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Unsteady Magnetohydrodynamic Flow in the Presence of Permeable Medium through an Upstanding Channel with Persistent Suction and Heat Source

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ABSTRACT

The present study explores unsteady magnetohydrodynamic, incompressible viscous fluid flow through upstanding equidistant plates in the presence of permeable media, persistent heat flux and heat source. The flow is constrained due to the flow between two equidistant plates, one of which is moving and other is at rest, and the occurrence of free convection because of the stationary wall with persistent temperature while heat flux is persistent on the wall with a uniform upstanding motion in its self plane. The fluid is considered emitting/absorbing but medium is non-scattering, so taking it as grey and to describe the radiative heat flux with persistent suction we used the Rosseland approximation. Numerical results for the velocity and temperature distribution for various physical parameters as well as the local skin friction coefficient and local Nusselt number are discussed numerically and shown through graphs.

Keywords: Chemical reaction; Free-convection; Heat source; Magnetohydrodynamic; Radiation

1. Introduction

Due to the growth of technology in the last few decades, magnetohydrodynamic free convection and heat transfer with chemical reaction has become important in engineering and research. It has many industrial applications such as geothermal energy recovery, oil extraction,

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thermal energy storage, flow through filtering devices, production of glass, design of furnace, thermonuclear fusion, casting and levitation, etc. In the study of boundary layer problems, magnetohydrodynamics (MHD) plays a major role. In boundary layer formation, suction or blowing through the wall is supreme phenomena. An increment in suction velocity may show a delay in the formation of a boundary layer and an increment in blowing may show a decrement in the skin friction at the plate which, in turn, may diminish in the rate of heat transfer at the plate.

Verma and Bansal [1] studied flow of a viscous incompressible fluid between two equidistant plates, one in uniform motion and the other at rest with uniform suction at the stationary plate. Cogley, Vincenti and Gill [2] obtained differential estimation for radiative transfer in a non-gray gas near equipoise. Hassanien and Mansour [3] studied unsteady MHD flow through a permeable media between two infinite equidistant plates. Bansal [4] presented magnetofluiddynamics of viscous fluids. Attia and Kotb [5] obtained MHD flow between two equidistant plates with heat transfer. El-Hakiem [6] analyzed MHD oscillatory flow on free-convection radiation through a permeable media with persistent suction velocity. Chung [7] presented Computational Fluid Dynamics. Cookey et al. [8] discussed impact of viscous dissipation and radiation on unsteady MHD free-convection flow past an infinite heated upstanding plate in a permeable media with time-dependent suction. Makinde [9] explained free-convection flow with thermal radiation and mass transfer past a moving upstanding permeable plate. Sharma, Gaur and Sharma [10] studied steady laminar flow and heat transfer of a fluid which is non-Newtonian through a linear equidistant permeable channel in the presence of a heat source. Alam et al. [11] described MHD free convective heat and mass transfer flow past an inclined surface with heat generation.

Ganesh and Krishnambal [12] presented MHD flow of viscous fluid between two equidistant permeable plates. Sharma and Sharma [13] obtained effect of oscillatory suction and heat source on temperature and concentration profile in MHD flow along an upstanding moving permeable plate bounded by permeable medium. Sharma and Singh [1] studied unsteady MHD free convective flow and heat transfer along an upstanding permeable plate with fluctuating suction and inner heat generation. Jha and Ajibade [14] analyzed free convective flow of heat generation/absorbing fluid between upstanding permeable plates with periodic heat input. Narahari [15] described effects of thermal radiation and free convection currents on the unsteady Couette flow between two upstanding equidistant plates with persistent heat flux at one boundary. Jha and Apere [16] presented MHD free convective Couette flow with suction and injection. Kesavaiah, Satyanarayana and Venkataramana [17] discussed radiation absorption, chemical reaction and magnetic field effects on the free convection and mass transfer flow through permeable media where suction and heat flux both are persistent. Manna, Das and Jana [18] derived effects of radiation on unsteady MHD free convective flow past an oscillating upstanding permeable plate immersed in a permeable media with fluctuating heat flux. Sharma and Dadheech [19] obtained the effect of volumetric heat generation/absorption on convective heat and mass transfer in permeable media in between two upstanding plates. Kesavaiah et al. [20] presented effects of radiation and free convection currents on unsteady Couette flow between two upstanding equidistant plates with persistent heat flux and heat source through permeable medium. Kirubhashankar and Ganesh [21] studied unsteady MHD flow of a Casson fluid in a equidistant plate channel with heat and mass transfer of chemical reaction. The aim of the present paper is to study unsteady MHD flow of an incompressible viscous fluid between two upstanding equidistant plates embedded with permeable medium in the presence of radiation and free convection with persistent suction and heat source. Equations of momentum and energy, which govern the fluid flow and heat transfer are solved by using the method of perturbation. The effects of various physical parameters on fluid velocity, temperature, skin friction coefficient and Nusselt number at the plates are derived, discussed numerically and shown through graphs.

2. Mathematical analysis

Consider the unsteady MHD free-convective Couette flow of an incompressible viscous radiating fluid between two infinite upstanding equidistant plates in the presence of persistent suction and heat source. The distance between the plates is d. The y^*-axis is taken normal to the plate and the x^*-axis is taken in the direction of the plate (when $y^* = 0$). Initially, at time $t^* \leq 0$ the plates and the fluid both are assumed to be stationary and at the same temperature T_0. At time $t^* > 0$, the plate (when$y^* = 0$) starts moving in its own plane with time dependent velocity $U_0\left(1+\varepsilon\, e^{n^* t^*}\right)$ and is heated by supplying heat at persistent rate whereas the plate (at $y^* = d$) is stationary with time dependent temperature $T_0 + \frac{qd}{\kappa}\left(1+\varepsilon\, e^{n^* t^*}\right)$. It is also assumed that in the x^*-direction, the radiative heat flux is insignificant as compared to that in the y^*-direction. As the length of plates are infinite, the velocity and temperature fields both are taken as functions of y^* and t^* only. Under the above assumptions and usual approximation of Boussinesq the governing equations of motion and heat transfer are given by

$$\frac{\partial v^*}{\partial y^*} = 0, \tag{2.1}$$

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = g\beta\left(T^* - T_0\right) + \upsilon \frac{\partial^2 u^*}{\partial y^{*2}} - \frac{\sigma_e {B_0}^2}{\rho} u^* - \frac{\upsilon}{K^*} u^*, \tag{2.2}$$

$$\left(\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*}\right) = \frac{\kappa}{\rho C_p} \frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho C_p} \frac{\partial q_r}{\partial y^*} - \frac{Q_0}{\rho C_p}\left(T^* - T_0\right) + \frac{\sigma_e {B_0}^2}{\rho C_p} u^{*2}, \tag{2.3}$$

where u^* and v^* are the components of velocity in x^* and y^*-directions, t^* the time, T^* the temperature of fluid, β the coefficient of the thermal expansion, υ the kinematic viscosity, B_0 the magnetic field strength, σ_e the electric conductivity, ρ the fluid density, K^* the permeable medium permeability, C_p the specific heat at persistent pressure, κ the thermal conductivity, q_r the radiative heat flux in the y^*-direction and Q_0 the heat generation/absorption constant.

The boundary conditions for the present discussion are given by

$$y^* = 0 : u^* = U_0\left(1+\varepsilon\, e^{n^* t^*}\right),\ \frac{\partial T^*}{\partial y^*} = -\frac{q}{\kappa};$$
$$y^* = d : u^* = 0,\ T^* = T_0 + \frac{qd}{\kappa}\left(1+\varepsilon\, e^{n^* t^*}\right). \tag{2.4}$$

From Eq. (2.1), it is noted that the suction velocity at the plate may be a persistent or may be a function of time only. Here, we assumed the suction velocity which is normal to the plate in the following form

$$v^* = V_0. \tag{2.5}$$

By using the Rosseland approximation the term of radiative heat flux is taken as

$$q_r = -\frac{4\sigma_e}{3k^*}\frac{\partial T^{*4}}{\partial y^*}. \tag{2.6}$$

T^{*4} can be expressed as a linear function of temperature because it is assumed that the difference of temperature with the flow is very small. Then by expanding T^{*4} in a Taylor series about T_0 and neglecting terms of higher order, the following approximation is given

$$T^{*4} = 4{T_0}^3 T^* - 3{T_0}^4. \tag{2.7}$$

Using Eqs. (2.6) and (2.7) in Eq. (2.3), we obtain

$$\left(\frac{\partial T^*}{\partial t^*} + v^*\frac{\partial T^*}{\partial y^*}\right) = \frac{\kappa}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{16\sigma_e}{3k^*}\frac{{T_0}^3}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{Q_0}{\rho C_p}(T^* - T_0) + \frac{\sigma_e {B_0}^2}{\rho C_p}u^{*2}. \tag{2.8}$$

Introducing the following non-dimensional quantities

$$\begin{aligned} y &= \frac{y^*}{d}, & t &= \frac{t^*\upsilon}{d^2}, & u &= \frac{u^*}{U_0}, \\ \theta &= \frac{T^* - T_0}{(qd/\kappa)}, & n &= \frac{d^2 n^*}{\upsilon}, & Gr &= \frac{g\beta d^3 q}{U_0 \kappa \upsilon}, \\ Ha^2 &= \frac{\sigma_e B_0^2 d^2}{\rho\upsilon}, & K^2 &= \frac{d^2}{K^*}, & S &= \frac{Q_0 d^2}{\upsilon\rho C_p}, \\ \Pr &= \frac{\upsilon\rho C_p}{\kappa}, & R &= \frac{\kappa k^*}{4\sigma_e {T_0}^3}, & Su &= \frac{V_0 d}{\upsilon}, \\ Ec &= \frac{{U_0}^2\kappa}{C_p q d} \end{aligned} \tag{2.9}$$

into Eqs. (2.2) and (2.8), we get

$$\frac{\partial^2 u}{\partial y^2} - Su\frac{\partial u}{\partial y} - \frac{\partial u}{\partial t} - \left(Ha^2 + K^2\right)u = -Gr\theta, \tag{2.10}$$

$$\left(\frac{3R+4}{3R\Pr}\right)\frac{\partial^2\theta}{\partial y^2} - Su\frac{\partial\theta}{\partial y} - \frac{\partial\theta}{\partial t} - S\theta = -Ha^2 Ec\, u^2, \tag{2.11}$$

where u is non-dimensional velocity along x-axis, t the non-dimensional time, y non-dimensional coordinate axis normal to the plates, θ non-dimensional temperature, Su Suction parameter, Ha Hartmann number, K parameter for permeability, Gr Grashof number, Pr Prandtl number, R Radiation parameter, S heat source parameter and Ec Eckert number.

The non-dimensional boundary conditions are given by

$$\begin{aligned} y = 0 &: \; u = \left(1 + \varepsilon\, e^{nt}\right), \; \frac{\partial\theta}{\partial y} = -1; \\ y = 1 &: u = 0, \; \theta = \left(1 + \varepsilon\, e^{nt}\right). \end{aligned} \tag{2.12}$$

3. Method of Solution

For solving Eqs. (2.10) and (2.11) under the boundary conditions (2.12) we assume

$$\begin{aligned} u(y,t) &= u_0(y) + \varepsilon\, e^{nt} u_1(y) + O\left(\varepsilon^2\right), \\ \theta(y,t) &= \theta_0(y) + \varepsilon\, e^{nt}\theta_1(y) + O\left(\varepsilon^2\right). \end{aligned} \tag{3.1}$$

Using (3.1) in Eqs. (2.10) and (2.11), equating the coefficients of the harmonic and non-harmonic terms and neglecting the coefficients of ε^2, we obtain

$$\frac{\partial^2 u_0}{\partial y^2} - Su\frac{\partial u_0}{\partial y} - \left(Ha^2 + K^2\right)u_0 = -Gr\theta_0, \tag{3.2}$$

$$\frac{\partial^2 u_1}{\partial y^2} - Su\frac{\partial u_1}{\partial y} - \left(Ha^2 + K^2 + n\right)u_1 = -Gr\theta_1, \tag{3.3}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_0}{\partial y^2}-Su\frac{\partial\theta_0}{\partial y}-S\theta_0=-Ha^2Ec\,u_0{}^2, \tag{3.4}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_1}{\partial y^2}-Su\frac{\partial\theta_1}{\partial y}-(S+n)\,\theta_1 = -2Ha^2Ec\,u_0u_1. \tag{3.5}$$

Now, the corresponding boundary conditions are reduced to

$$\begin{aligned} &y=0: u_0=1,\ \frac{\partial\theta_0}{\partial y}=-1;\ u_1=1,\ \frac{\partial\theta_1}{\partial y}=0,\\ &y=1: u_0=0,\ \theta_0=1; u_1=0,\ \theta_1=1. \end{aligned} \tag{3.6}$$

The Eqs. (3.2) to (3.5) are coupled second order ordinary differential equations. Since the Eckert number Ec is too small for the fluid which is incompressible, therefore u_0,u_1, θ_0 and θ_1 can be expanded in the powers of Eckert number Ec and given as

$$\begin{aligned} &u_0=u_{00}+Ec\,u_{01}; u_1=u_{10}+Ec\,u_{11};\\ &\theta_0=\theta_{00}+Ec\,\theta_{01}; \theta_1=\theta_{10}+Ec\,\theta_{11}. \end{aligned} \tag{3.7}$$

Substituting (3.7) into the Eqs. (3.2) to (3.5), equating the coefficients of same powers of Ec and neglecting terms of $O\left(Ec^2\right)$, we get the following equations:

Zeroth order equations

$$\frac{\partial^2u_{00}}{\partial y^2}-Su\frac{\partial u_{00}}{\partial y}-\left(Ha^2+K^2\right)u_{00}=-Gr\theta_{00}, \tag{3.8}$$

$$\frac{\partial^2u_{10}}{\partial y^2}-Su\frac{\partial u_{10}}{\partial y}-\left(Ha^2+K^2+n\right)u_{10}=-Gr\theta_{10}, \tag{3.9}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_{00}}{\partial y^2}-Su\frac{\partial\theta_{00}}{\partial y}-S\theta_{00}=0, \tag{3.10}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_{10}}{\partial y^2}-Su\frac{\partial\theta_{10}}{\partial y}-(S+n)\,\theta_{10}=0. \tag{3.11}$$

First order equations

$$\frac{\partial^2u_{01}}{\partial y^2}-Su\frac{\partial u_{01}}{\partial y}-\left(Ha^2+K^2\right)u_{01}=-Gr\theta_{01}, \tag{3.12}$$

$$\frac{\partial^2u_{11}}{\partial y^2}-Su\frac{\partial u_{11}}{\partial y}-\left(Ha^2+K^2+n\right)u_{11}=-Gr\theta_{11}, \tag{3.13}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_{01}}{\partial y^2}-Su\frac{\partial\theta_{01}}{\partial y}-S\theta_{01}=-Ha^2u_{00}{}^2, \tag{3.14}$$

$$\left(\frac{3R+4}{3R\,\mathrm{Pr}}\right)\frac{\partial^2\theta_{11}}{\partial y^2}-Su\frac{\partial\theta_{11}}{\partial y}-(S+n)\,\theta_{11} = -2Ha^2u_{00}u_{10}. \tag{3.15}$$

Now, the corresponding boundary conditions are given accordingly

$$\begin{aligned} y=0: u_{00}&=1,\quad u_{10}=1,\quad \tfrac{\partial\theta_{00}}{\partial y}=-1,\\ \tfrac{\partial\theta_{10}}{\partial y}&=0,\quad u_{01}=0,\quad u_{11}=0,\\ \tfrac{\partial\theta_{01}}{\partial y}&=0,\quad \tfrac{\partial\theta_{11}}{\partial y}=0,\\ y=1: u_{00}&=0,\quad u_{10}=0,\quad \theta_{00}=1,\\ \theta_{10}&=1,\quad u_{01}=0,\quad u_{11}=0,\\ \theta_{01}&=0,\quad \theta_{11}=0. \end{aligned} \tag{3.16}$$

Eqs. (3.8) to (3.15) are ordinary second order differential equations and solved under the boundary conditions (3.16). Through straightforward calculations $u_{00}(y)$, $u_{01}(y)$, $u_{10}(y)$, $u_{11}(y)$, $\theta_{00}(y)$, $\theta_{01}(y)$, $\theta_{10}(y)$ and $\theta_{11}(y)$ are calculated. Thus, the expressions for velocity and temperature are given by

$$u(y,t)=u_{00}+Ec\,u_{01}+\varepsilon\,e^{nt}\left(u_{10}+Ec\,u_{11}\right), \tag{3.17}$$

$$\theta(y,t)=\theta_{00}+Ec\,\theta_{01}+\varepsilon\,e^{nt}\left(\theta_{10}+Ec\,\theta_{11}\right). \tag{3.18}$$

The dimensionless stress tensor in terms of skin-friction coefficient at both plates (when $y=0$ and $y=1$) are given by

$$C_f=\frac{du}{dy}=\frac{du_{00}}{dy}+Ec\frac{du_{01}}{dy}$$

$$+\varepsilon e^{nt}\left(\frac{du_{10}}{dy}+Ec\frac{du_{11}}{dy}\right). \quad (3.19)$$

Hence, skin-friction coefficient at both plates (when $y = 0$ and $y = 1$) is calculated. The dimensionless rate of heat transfer in terms of the Nusselt number at the plate (when $y = 1$) is also calculated as

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right) = -\left(\frac{d\theta_{00}}{dy}+Ec\frac{d\theta_{01}}{dy} + \varepsilon e^{nt}\left(\frac{d\theta_{10}}{dy}+Ec\frac{d\theta_{11}}{dy}\right)\right). \quad (3.20)$$

4. Results and Discussion

The effects of radiation and free convection on unsteady MHD flow of an incompressible viscous fluid through a permeable medium between two upstanding equidistant plates in the presence of persistent heat flux and heat source with uniform suction are investigated. Equations of momentum and energy, which govern the fluid flow and heat transfer are solved by using the perturbation method. The effects of various physical parameters on fluid velocity, temperature, concentration, skin friction coefficient and Nusselt number at the plates are observed, discussed numerically and shown through graphs.

The velocity distribution of fluid is described through Figs. 1 to 8. It is observed from Figs. 1 to 3 that the velocity of fluid rises with the increase of Grashof number, suction parameter or Eckert number. It is noted from Figs. 4 to 8 that the velocity of fluid reduces for Prandtl number, Hartmann number, permeability parameter, radiation parameter or heat source parameter.

The temperature profiles are illustrated through Figs. 9 to 16. It is noted from Figs. 9 to 12 that the temperature of fluid rises due to an increment in Grashof number, suction parameter, Eckert number or Hartmann number. It is observed from Figs. 13 to 16 that the velocity of fluid reduces as Prandtl number, permeability parameter, radiation parameter or heat source parameter increases.

It is observed from Table 1 that the skin-friction coefficient at the plate (when $y = 0$) rises as the values of Grashof number or Eckert number, while it reduces due to increase in the values of suction parameter, Prandtl number, Hartmann number, permeability parameter, radiation parameter or heat source parameter. The skin-friction coefficient at the plate (when $y = 1$) rises due to increase of Prandtl number, Hartmann number, permeability parameter, radiation parameter or heat source parameter, while it reduces due to increase of Grashof number, suction parameter or Eckert number.

From Table 2 it is observed that the Nusselt number at the plate (when $y = 1$) rises due to an increment in Grashof number, suction parameter, Eckert number or Hartmann number, while it reduces as Prandtl number, permeability parameter, radiation parameter or heat source parameter increases.

5. Conclusions

1. The fluid velocity and fluid temperature both increase as the Grashof number, suction parameter or Eckert number increase.

2. The velocity and temperature of the fluid decrease as the Prandtl number, permeability parameter, radiation parameter or heat source parameter increase.

3. As the Hartmann number rises the fluid velocity decreases, while fluid

Table 1. Numerical values of skin friction coefficient at the plates for various values of physical parameters.

Gr	Su	Ec	Pr	Ha	K	R	S	Cf_0	Cf_1
10	1	0.05	0.71	1	0.2	2	4	3.2036	-6.5302
5	1	0.05	0.71	1	0.2	2	4	1.1332	-3.9359
15	1	0.05	0.71	1	0.2	2	4	5.3055	-9.153
10	2	0.05	0.71	1	0.2	2	4	3.0659	-8.0795
10	3	0.05	0.71	1	0.2	2	4	2.8979	-9.8126
10	1	0.001	0.71	1	0.2	2	4	3.1573	-6.491
10	1	0.01	0.71	1	0.2	2	4	3.1658	-6.4982
10	1	0.05	3	1	0.2	2	4	0.8615	-4.2591
10	1	0.05	7	1	0.2	2	4	0.1085	-3.1748
10	1	0.05	0.71	2	0.2	2	4	1.8973	-5.1519
10	1	0.05	0.71	3	0.2	2	4	0.3617	-3.828
10	1	0.05	0.71	1	1	2	4	2.7027	-5.986
10	1	0.05	0.71	1	2	2	4	1.4608	-4.7616
10	1	0.05	0.71	1	0.2	1	4	3.7316	-6.9811
10	1	0.05	0.71	1	0.2	3	4	2.9626	-6.3203
10	1	0.05	0.71	1	0.2	2	1	5.4049	-8.365
10	1	0.05	0.71	1	0.2	2	2	4.452	-7.576

Table 2. Numerical values of Nusselt number at the plate (when $y = 1$) for various values of physical parameters.

Gr	Su	Ec	Pr	Ha	K	R	S	Nu_1
10	1	0.05	0.71	1	0.2	2	4	-0.5806
5	1	0.05	0.71	1	0.2	2	4	-0.594
15	1	0.05	0.71	1	0.2	2	4	-0.5623
10	2	0.05	0.71	1	0.2	2	4	-0.4902
10	3	0.05	0.71	1	0.2	2	4	-0.3342
10	1	0.001	0.71	1	0.2	2	4	-0.6075
10	1	0.01	0.71	1	0.2	2	4	-0.6026
10	1	0.05	3	1	0.2	2	4	-3.3042
10	1	0.05	7	1	0.2	2	4	-6.4873
10	1	0.05	0.71	2	0.2	2	4	-0.5378
10	1	0.05	0.71	3	0.2	2	4	-0.516
10	1	0.05	0.71	1	1	2	4	-0.5846
10	1	0.05	0.71	1	2	2	4	-0.5925
10	1	0.05	0.71	1	0.2	1	4	-0.2083
10	1	0.05	0.71	1	0.2	3	4	-0.764
10	1	0.05	0.71	1	0.2	2	1	0.8182
10	1	0.05	0.71	1	0.2	2	2	0.2328

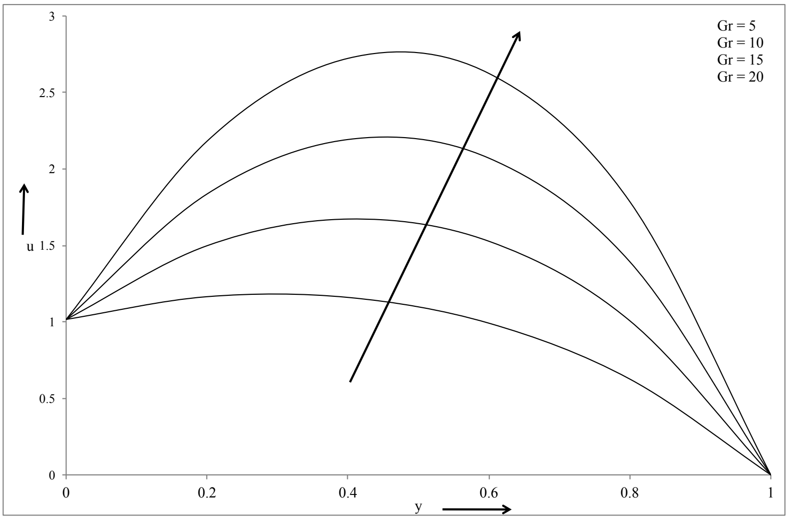

Fig. 1. Graph between velocity profile and y for various values of Gr when $\Pr = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

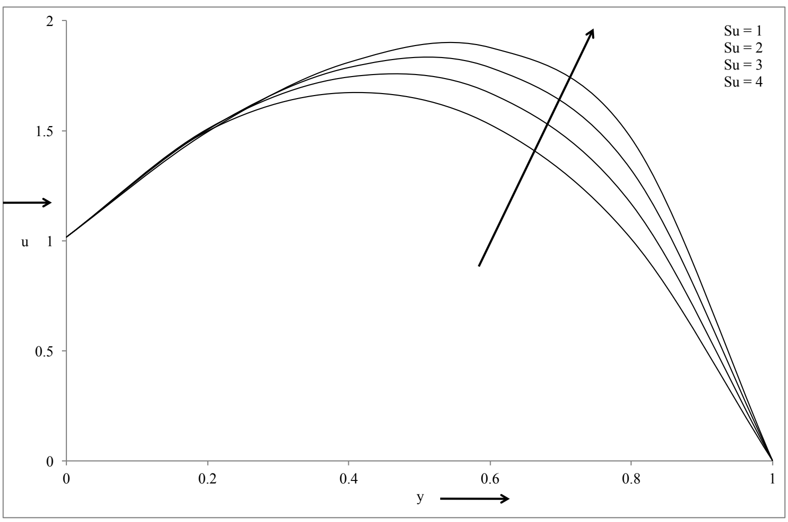

Fig. 2. Graph between velocity profile and y for various values of Su when $Gr = 10$, $\Pr = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

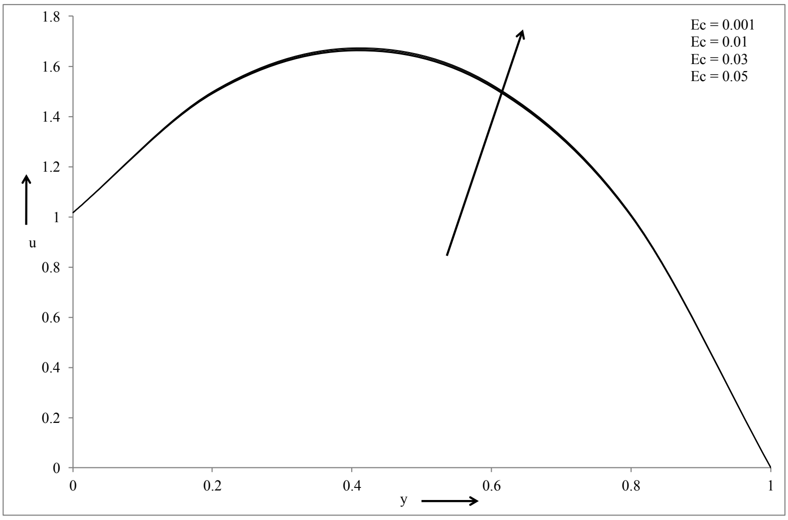

Fig. 3. Graph between velocity profile and y for various values of Ec when $Gr = 10$, $\mathrm{Pr} = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $\varepsilon = 0.01$, $t = 0.5$.

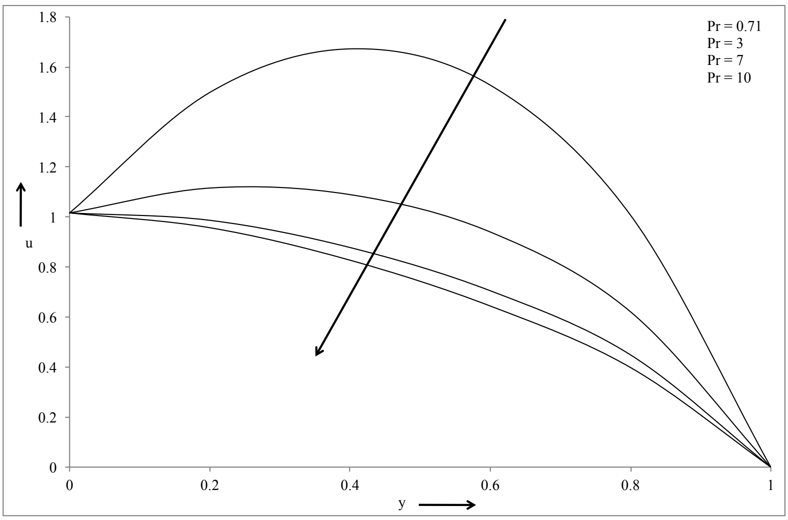

Fig. 4. Graph between velocity profile and y for various values of Pr when $Gr = 10$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

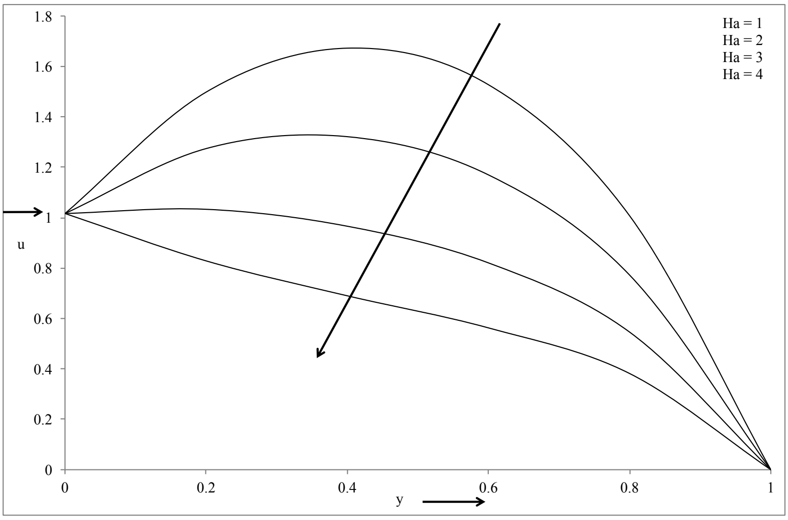

Fig. 5. Graph between velocity profile and for various values of when $Gr = 10$, $\mathrm{Pr} = 0.71$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

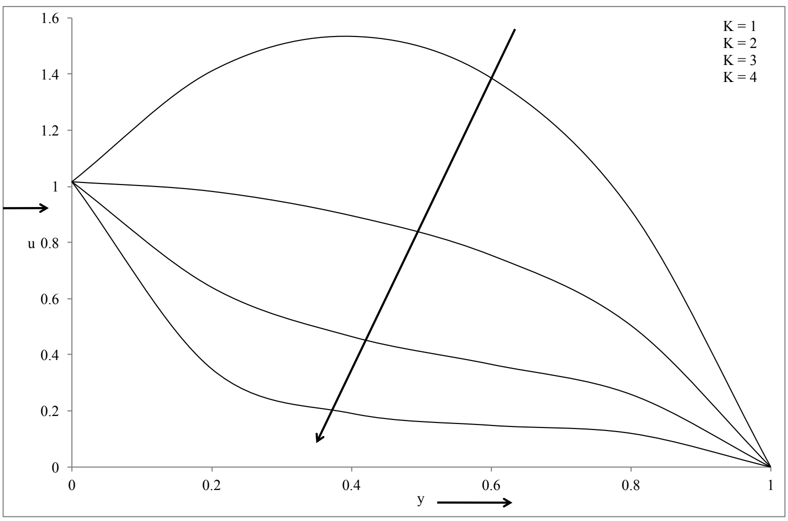

Fig. 6. Graph between velocity profile and for various values of when $Gr = 10$, $Pr = 0.71$, $Ha = 1$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

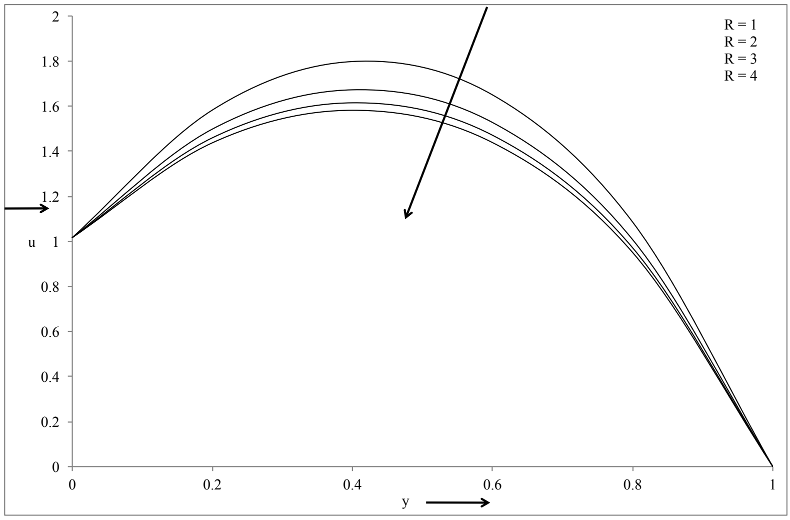

Fig. 7. Graph between velocity profile and y for various values of R when $Gr = 10$, $\Pr = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

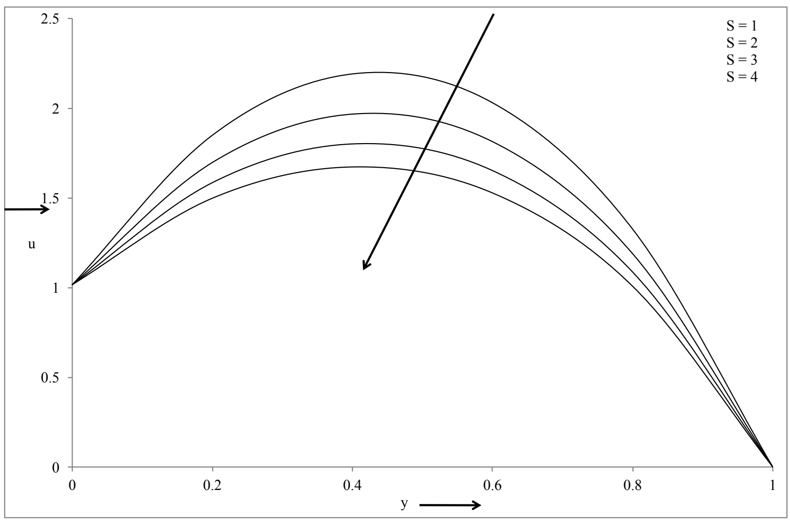

Fig. 8. Graph between velocity profile and y for various values of S when $Gr = 10$, $\Pr = 0.71$, $Ha = 1$, $K = 0.2$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

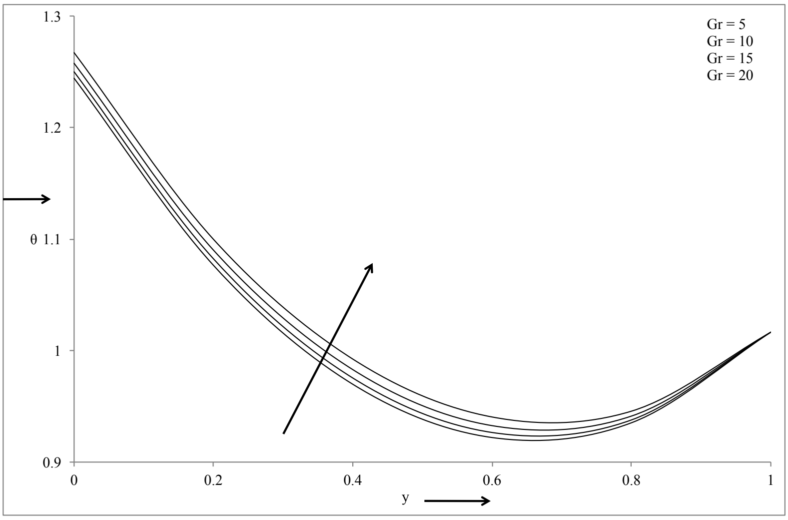

Fig. 9. Graph between velocity profile and y for various values of Gr when $\mathrm{Pr} = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

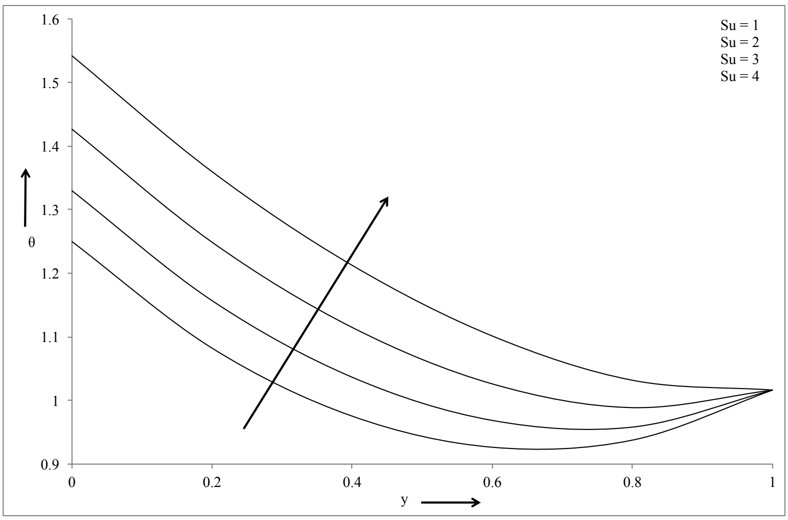

Fig. 10. Graph between velocity profile and y for various values of Su when $Gr = 10$, $\mathrm{Pr} = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

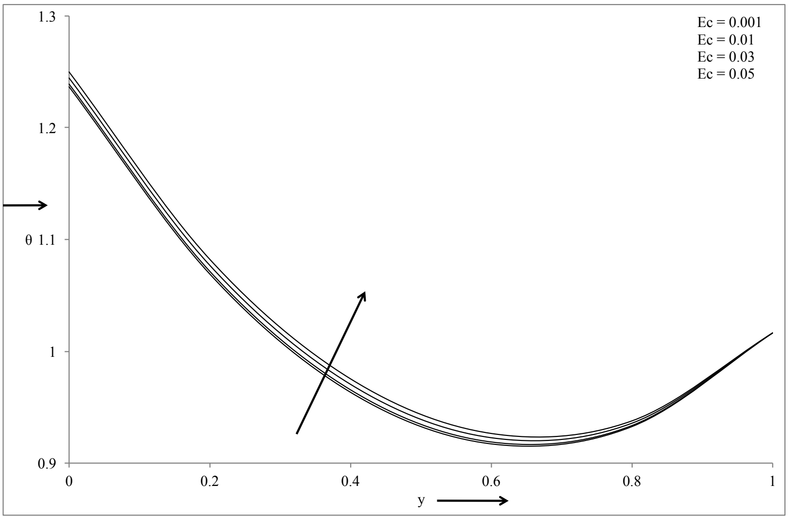

Fig. 11. Graph between temperature profile and y for various values of Ec when $Gr = 10$, $\Pr = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $\varepsilon = 0.01$, $t = 0.5$.

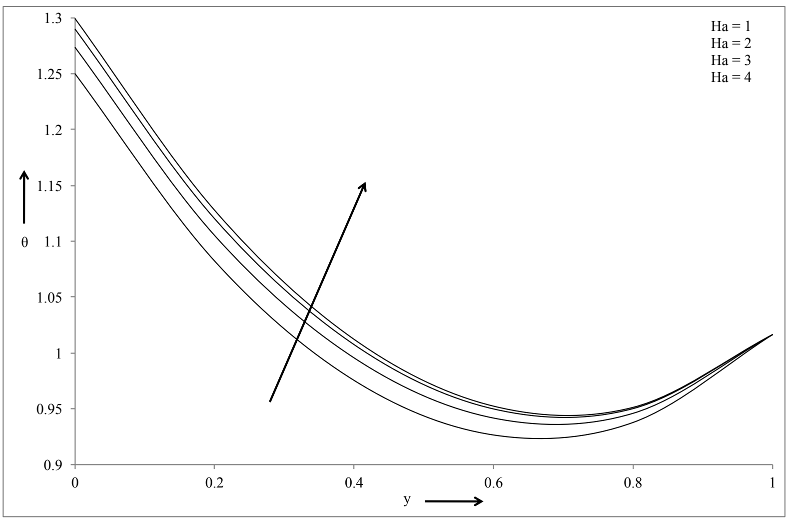

Fig. 12. Graph between temperature profile and y for various values of Ha when $Gr = 10$, $\Pr = 0.71$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

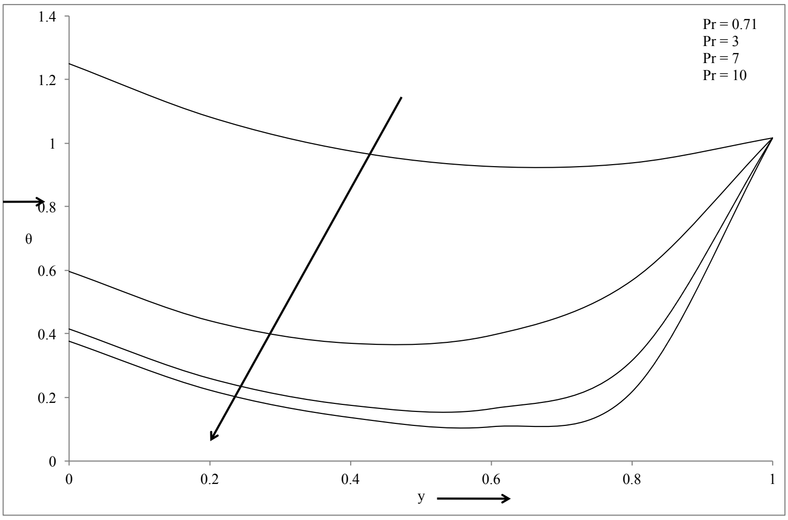

Fig. 13. Graph between temperature profile and for various values of when $Gr = 10$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

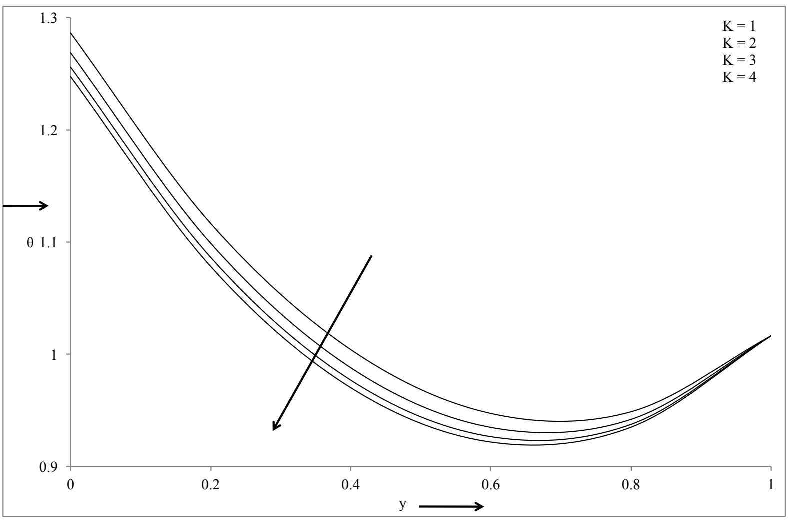

Fig. 14. Graph between temperature profile and y for various values of K when $Gr = 10$, $\Pr = 0.71$, $Ha = 3$, $S = 4$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

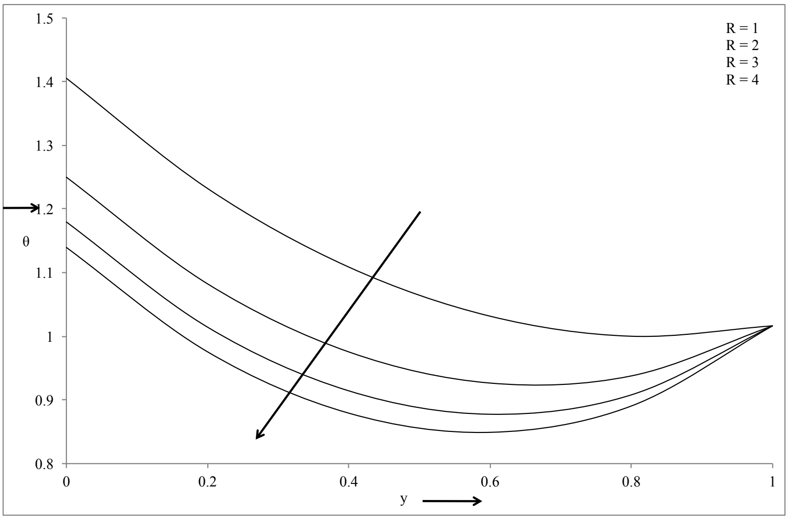

Fig. 15. Graph between temperature profile and y for various values of R when $Gr = 10$, $\mathrm{Pr} = 0.71$, $Ha = 1$, $K = 0.2$, $S = 4$, $Su = 1$, $n = 1$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

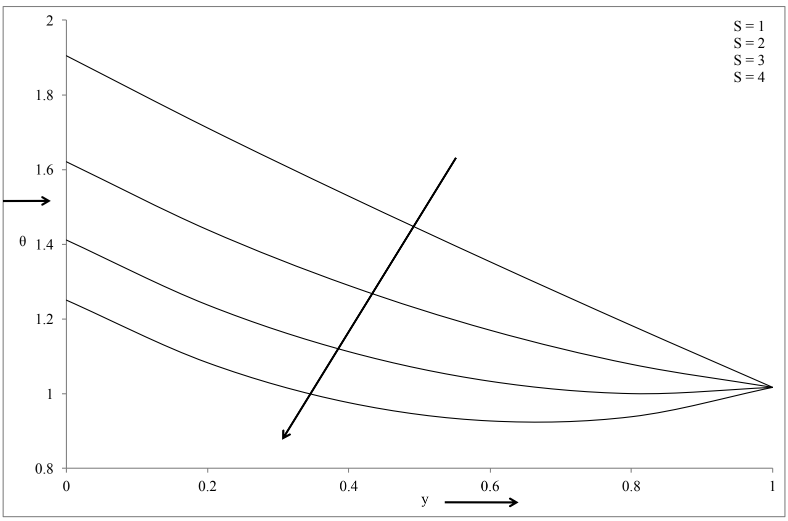

Fig. 16. Graph between temperature profile and y for various values of R when $Gr = 10$, $\mathrm{Pr} = 0.71$, $Ha = 1$, $K = 0.2$, $Su = 1$, $n = 1$, $R = 2$, $Ec = 0.05$, $\varepsilon = 0.01$, $t = 0.5$.

temperature increases.

4. As the Grashof number or Eckert number rises the skin-friction coefficient increases at the plate (when $y = 0$) and decreases at the plate (when $y = 1$).

5. An increase in Prandtl number, Hartmann number, permeability parameter, radiation parameter or heat source parameter causes a reduction in skin-friction coefficient at the plate (when $y = 0$).

6. The skin-friction coefficient at both the plates reduces as suction parameter increases.

7. The skin-friction coefficient at the plate (when $y = 1$) increases with the increase of the Prandtl number, Hartmann number, permeability parameter, radiation parameter or heat source parameter.

8. As the Grashof number, suction parameter, Eckert number or Hartmann number increases the Nusselt number increases at the plate (when $y = 1$)

9. The Nusselt number at the plate (when $y = 1$) decreases as number, permeability parameter, radiation parameter or heat source parameter increases.

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