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Effect of Radiation and Gravity Modulation on Unsteady MHD Free Convection Flow Through Porous Medium in Slip-Flow Regime with Entropy

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Abstract

The effect of radiation and periodic oscillation of the gravitational field on free-convection from a vertical plate is investigated. It is assumed that the gravity modulation is given by a harmonic function superimposed on a constant. The permeability and suction velocity is assumed to fluctuate with time. The transformed equations are solved by perturbation technique to investigate the effects of Prandtl number and gravity modulation parameter. The effect of gravity modulation on velocity, temperature, skin friction, penetration distance and entropy are discussed. It is observed that the Prandtl number and gravity modulation affect the shear stress and the rate of heat transfer considerably.

Keywords: Porous medium, MHD, heat transfer, entropy, gravity fluctuation, slip-flow

Introduction

The time-dependent gravitational field is of interest in space laboratory experiments, crystal growth, large scale convection of atmosphere and other related applications. Space technologies need special attention on forces involving vibrations that occur due to interaction of several phenomena, as in a spacecraft these fluctuating forces may originate from crew activities, vibrations from on-board equipment and structural oscillations. These cannot be totally eliminated from the space environment. Jules *et al*. [1] found that the international space station (ISS), was characterized by low mean accelerations which are $O(10^{-6})g_e$ - the gravity on earth, and fluctuations that were 2 or 3 order of magnitude above the mean. In space vehicles, there are transient perturbations to the gravity field at a point. An excellent account of this physical feature has been described by Duval and Jacqmin [2]. They studied g-jitter convection of 2 diffusing miscible liquids under an oscillating vertical gravitational field with zero mean.

Many experimenters seek to use the microgravity environment to avoid the unwanted effects of buoyancy as experienced under terrestrial conditions. As a result, there has been considerable interest in identifying and modeling residual acceleration effects on transport in directional solidification systems. Most recently, this interest has been motivated by the need for (i) acceleration requirements to be used in design considerations, (ii) quantitative assessment of residual acceleration effects and (iii) minimization of the impact of residual acceleration through an optimal choice of experiment operating conditions. The effect of gravity modulation on the onset of convection in a fluid and porous layer has been investigated by Malashetty and Padmavathi [3]. Zhao *et al*. [4] have studied the effects of g-jitter on experiments conducted in low-earth orbit.

Sharidan *et al*. [5] have studied the effect of g-jitter induced combined heat and mass transfer by mixed convection flow in microgravity for a simple system consisting of 2 heated vertical parallel infinite flat plates held at constant but different temperatures and concentrations. The effect of g-jitter on a free convection boundary layer with constant heat flux has been investigated by Sharidan and Amin [6]. Siddavaram and Homsy [7] studied the effect of g-jitter on fluid mixing. They predicted that g-jitter affects the mixing characteristics of 2 miscible fluids.

A numerical solution of the effect of a small fluctuating gravitational field characteristic of g-jitter was presented by Sharidan and Pop [8]. They considered the problem of free convection boundary layer flow near a three-dimensional stagnation point of attachment resulting from a step change in its constant surface temperature. Rees and Pop [9,10] investigated free convection near a stagnation point and boundary-layer flow in a porous medium with large-amplitude periodic variations in the gravitational acceleration. Deka and Soundalgekar [11] have studied gravity modulation effect on transient free - convection flow past an infinite vertical isothermal plate. They observed that transient velocity decreases with increasing frequency of gravity modulation or Prandtl number, but increases with increasing time. The g-jitter induced flows in microgravity under the influence of a transverse magnetic field between two parallel plates have been analyzed by Li [12]. In his analysis, a single component of time harmonic g-jitter was taken into account. General solutions were obtained for the velocity profile with a combined effect of oscillating g-jitter driving force and induced Lorentz force. He observed that the g-jitter frequency affects the convective flow. Chen and Chen [13] investigated the nature of instability occurring in a differentially heated vertical slot under a modified gravity field $g = g_0 + g_1 \cos(\omega^* t^*)$. They concluded that gravity modulation can stabilize or destabilize the flow.

Rajvanshi and Saini [14] considered the effect of gravity modulation on free convection magnetohydrodynamic (MHD) flow past a uniformly moving infinite vertical porous surface with time-dependent suction velocity and constant heat flux. Saini *et al*. [15] have studied the effect of gravity fluctuation on free convection flow past a uniformly moving infinite vertical porous plate maintained at a fluctuating temperature in a porous medium. They found that gravity modulation affects the skin friction and heat transfer coefficients considerably. Three-dimensional MHD free-convection flow past an infinite vertical porous plate with periodic suction and gravity modulation has been studied by Saini and Rajvanshi [16]. Rajvanshi and Wasu [17] investigated unsteady natural convection of viscous incompressible conducting fluid past a porous infinite flat plate placed in a porous medium under the influence of heat absorption, and gravity modulation g-jitter effect in flows past vertical flat plate under varying conditions have also been reported in [18-21].

In the present study, the influence of radiation and periodic oscillation of the gravitational field on free-convection flow past an infinite vertical porous plate is examined. The permeability of the porous medium is taken in the form $K^*(t^*) = K_0^*(1+\varepsilon B e^{i\omega^* t^*})$. The suction velocity is defined as $v^* = -v_0^*(1+\varepsilon A e^{i\omega^* t^*})$, where ω^* and t^* are frequency of oscillation and time respectively. Perturbation method has been used to evaluate the effects of pertinent parameters on velocity field, temperature distribution, skin friction, heat transfer coefficient, penetration distance and entropy generation. It has been noted that the effect of gravity modulation is significant.

Formulation of the problem

Two dimensional, unsteady, incompressible, electrically conducting fluid flow through a porous medium past a vertical porous plate with radiation and gravity modulation is considered. It is assumed that a semi-infinite porous region of variable permeability is bounded by a vertical porous plate. There exists a slip in velocity field and jump in temperature field at the boundary. The flow of fluid is taken along x^*-axis and y^*-axis is normal to the plate. A uniform magnetic field is introduced normal to the direction of flow. The magnetic Reynolds number is taken to be very small so that the induced magnetic field can be neglected in comparison to the applied magnetic field. The fluid properties are assumed to be constant. The temperature difference between the wall and the medium develops buoyancy force, which induces the basic flow.

Since the bounding surface is considered infinite in length along x^*-direction, all physical quantities are independent of x^* and are function of y^* and t^* only. Under these assumptions, flow is governed by the following set of equations;

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

$$\frac{\partial u^*}{\partial t^*} + v^* \frac{\partial u^*}{\partial y^*} = g\,\beta (T^* - T^*_\infty) + g\beta^* (C^* - C^*_\infty) + \bar{\upsilon}\, \frac{\partial^2 u^*}{\partial y^{*2}} - \upsilon \frac{u^*}{K^*(t^*)} - \frac{\sigma}{\rho} B_0^2 u^* \tag{2}$$

$$\frac{\partial T^*}{\partial t^*} + v^* \frac{\partial T^*}{\partial y^*} = \frac{\bar{\kappa}}{\rho C_p} \left(\frac{\partial^2 T^*}{\partial y^{*2}} \right) - \frac{1}{\rho C_p} \frac{\partial q^*}{\partial y^*} \tag{3}$$

$$\frac{\partial C^*}{\partial t^*} + v^* \frac{\partial C^*}{\partial y^*} = D \frac{\partial^2 C^*}{\partial y^{*2}} \tag{4}$$

where v^* is the suction velocity, u^* the fluid velocity, T^* the fluid temperature, T^*_∞ the fluid temperature in free stream, C^* the species concentration in the fluid, C^*_∞ the species concentration in free stream, β the coefficient of thermal expansion, β^* the coefficient of thermal expansion with concentration, g the acceleration due to gravity, D the chemical molecular diffusivity, C_p the specific heat at constant pressure, K^* the permeability of porous medium, $\bar{\kappa}$ the effective thermal conductivity in the porous medium, $\upsilon\ (= \mu/\rho^*)$ the kinematic viscosity of clear fluid, $\bar{\upsilon}\ (= \bar{\mu}/\rho^*)$ the effective kinematic viscosity of fluid in the porous medium, ρ^* the fluid density, σ the electric permeability, B_0 the magnetic field intensity and q^* the radiation heat flux. Viscous dissipation has been neglected in the energy equation.

The relevant boundary conditions are;

$$\text{at } y^* = 0: \quad u^* = L_1 \frac{\partial u^*}{\partial y^*}, \quad T^* = T^*_W + L_2 \frac{\partial T^*}{\partial y^*}, \ C^* = C^*_W, \tag{5a}$$

$$\text{as } y^* \to \infty: u^* \to 0, \quad T^* \to T^*_\infty, \quad C^* \to C^*_\infty. \tag{5b}$$

The suction velocity on the vertical plate is imposed in the form;

$$v^* = -v^*_0 (1 + \varepsilon A e^{i\omega^* t^*}). \tag{6}$$

The permeability of the porous medium is taken in the form;

$$K^*(t^*) = K^*_0 (1 + \varepsilon B e^{i\omega^* t^*}) \tag{7}$$

where v_0^* is the constant suction velocity of the fluid through the porous surface, A is the suction velocity amplitude, K_0^* is the constant permeability of porous medium and B is the permeability amplitude.

For an optically thin medium with relatively low density and very small absorption coefficient, Cogley *et al*. [22] have suggested a simplified radiative heat flux equation in the form;

$$\frac{\partial q_r}{\partial y^*} = 4(T^* - T_\infty^*)I \tag{8}$$

where I is the absorption coefficient. This depends on Plank's function. Grief *et al*. [23] have shown that in the optically thin limit, the fluid does not absorb its own emitted radiation. Therefore there is no self-absorption the fluid absorbs the radiation emitted by the boundaries.

The time-dependent gravitational acceleration is assumed in the form $g = g_0 + g_1 \cos \omega^* t^*$, where g_0 is the constant gravity level in the environment, g_1 is the amplitude of the oscillating component of acceleration and ω^* is the frequency of gravitational oscillation.

The gravitational acceleration is rewritten in the form;

$$g = g_0(1 + \varepsilon \alpha e^{i\omega^* t^*}) \tag{9}$$

where $g_1 = \varepsilon \alpha g_0$.

Eqs. (2) to (4) and (6) to (8) under the boundary conditions (5a) and (5b) are modified as;

$$\frac{\partial u^*}{\partial t^*} - v_0^*\left(1 + \varepsilon A e^{i\omega^* t^*}\right)\frac{\partial u^*}{\partial y^*} = \bar{\upsilon}\frac{\partial^2 u^*}{\partial y^{*2}} + \beta\ g_0(1 + \varepsilon \alpha e^{i\omega^* t^*})\ (T^* - T_\infty^*)$$

$$+ \beta^*\ g_0(1 + \varepsilon \alpha e^{i\omega^* t^*})\ (C^* - C_\infty^*) - \upsilon \frac{u^*}{K^*(t^*)} - \frac{\sigma}{\rho} B_0^2 u^* \tag{10}$$

$$\frac{\partial T^*}{\partial t^*} - v_0^*\left(1 + \varepsilon A e^{i\omega^* t^*}\right)\frac{\partial T^*}{\partial y^*} = \frac{\bar{\kappa}}{\rho^* C_p}\left(\frac{\partial^2 T^*}{\partial y^{*2}}\right) - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^*} \tag{11}$$

$$\frac{\partial C^*}{\partial t^*} - v_0^*\left(1 + \varepsilon A e^{i\omega^* t^*}\right)\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}}\ . \tag{12}$$

The following non-dimensional quantities are introduced into Eqs. (5a), (5b) and (10) to (12);

$$y = \frac{y^* v_0^*}{\upsilon}, \quad t = \frac{t^* v_0^{*2}}{\upsilon}, \quad \omega = \frac{\upsilon \omega^*}{v_0^{*2}}, \quad u = \frac{u^*}{v_0^*}, \quad C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*}, \quad \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},$$

Grashof Number $Gr = g_0 \beta \upsilon \dfrac{(T_w^* - T_\infty^*)}{v_0^{*3}}$, Prandtl Number $\Pr = \dfrac{\upsilon}{(\kappa / \rho C_p)}$, Magnetic parameter $M = \frac{B_0}{v_0^*}\sqrt{\frac{\sigma\upsilon}{\rho}}$, Schmidt number $Sc = \frac{\upsilon}{D}$,

Permeability parameter = $K_0 = \frac{v_0^{*2} K_0^*}{\upsilon^2}$, Radiation parameter $R = \frac{4\upsilon I}{\rho C_p v_0^{*2}}$,

Modified Grashof Number $Gc = g_0 \beta^* \upsilon \frac{(C_w^* - C_\infty^*)}{v_0^{*3}}$ (13)

where u is the dimensionless velocity of fluid, C the dimensionless species concentration in the fluid and θ, the dimensionless temperature.

The subscripts ∞ and w denote the free stream condition and wall conditions respectively.
Eqs. (10) to (12) take the following non-dimensional form.

$$\frac{\partial u}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial u}{\partial y} = \phi \frac{\partial^2 u}{\partial y^2} + (1+\varepsilon\alpha\, e^{i\omega t})(\theta\, Gr + C\, Gc) - M^2 u - \frac{u}{K_0(1+\varepsilon B e^{i\omega t})} \quad (14)$$

$$\frac{\partial \theta}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\left(\phi_1 \frac{\partial^2 \theta}{\partial y^2} - \Pr R\theta\right) \quad (15)$$

$$\frac{\partial C}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \quad (16)$$

where $\phi = \frac{\bar{\upsilon}}{\upsilon}$ and $\phi_1 = \frac{\bar{\kappa}}{\kappa}$

Boundary conditions take the following form.

$$u = h\frac{\partial u}{\partial y},\ \theta = 1 + h^*\frac{\partial \theta}{\partial y},\quad C = 1 \text{ at } y = 0.$$
$$u \to 0,\ \theta \to 0,\ C \to 0 \text{ as } y \to \infty \quad (17)$$

Solution of the problem

Since ε is small, so u, θ and C are assumed to be;

$$(u,\theta,C)(y,t) = (u_0,\theta_0,C_0)(y) + \varepsilon e^{i\omega t}(u_1,\theta_1,C_1)(y) \ . \quad (18)$$

Substituting (18) in (14) to (16) and separating steady and unsteady components;

$$\phi u_0'' + u_0' - \left(M^2 + \frac{1}{K_0}\right)u_0 = -Gr\theta_0 - GcC_0 \quad (19)$$

$$\phi u_1'' + u_1' - \left(\frac{i\omega}{4} + \frac{1}{K_0} + M^2\right)u_1 = -Au_0' - (Gr\theta_1 + GcC_1) - \alpha(Gr\theta_0 + GcC_0) - \frac{B}{K_0}u_0 \quad (20)$$

$$\phi_1 \theta_0'' + \Pr\theta_0' - R\Pr\theta_0 = 0 \tag{21}$$

$$\phi_1 \theta_1'' + \Pr\theta_1' - \Pr(R + i\omega)\theta_1 = -A\Pr\theta_0' \tag{22}$$

$$C_0'' + ScC_0' = 0 \tag{23}$$

$$C_1'' + Sc\,C_1' - i\omega ScC_1 = -ASc\,C_0' \tag{24}$$

are obtained, where prime denotes derivative with respect to y.

Boundary conditions are reduced to;

$$u_0 = hu_0',\ u_1 = hu_1',\ \theta_0 = 1 + h^*\theta_0',\ \theta_1 = h^*\theta_1',\ C_0 = 1,\ C_1 = 0 \quad \text{at} \quad y = 0$$
$$u_0 \to 0, \quad u_1 \to 0, \quad \theta_0 \to 0,\ \theta_1 \to 0, \quad C_0 \to 0, \quad C_1 \to 0, \qquad \text{as} \quad y \to \infty\ . \tag{25}$$

Finally;

$$C_0 = e^{-Scy} \tag{26}$$
$$C_1 = A_2(e^{-m_1 y} - e^{-Scy}) \tag{27}$$
$$\theta_0 = A_3 e^{-m_3 y} \tag{28}$$
$$\theta_1 = A_4 e^{-m_4 y} + A_5 e^{-m_3 y} \tag{29}$$
$$u_0 = A_6 e^{-m_5 y} - A_7 e^{-m_3 y} - A_8 e^{-Scy} \tag{30}$$
$$u_1 = A_1 e^{-m_2 y} - B_1 e^{-m_1 y} + B_2 e^{-Scy} + B_3 e^{-m_3 y} - B_4 e^{-m_4 y} + B_5 e^{-m_5 y} \tag{31}$$

where A_1 to A_8, B_1 to B_5 and m_1 to m_5 are constants which have not been recorded here for the sake of brevity.

Discussion

In order to understand the physical solution, the numerical values of the velocity, temperature, skin friction, Nusselt number, penetration distance and entropy have been calculated. These are shown graphically for different values of permeability parameter K_0, magnetic parameter M, velocity slip parameter h, temperature jump parameter h^*, Grashof number Gr, modified Grashof number Gc, Prandtl number $\Pr$, radiation parameter R, permeability amplitude B, suction velocity amplitude A and gravity modulation parameter $\varepsilon\alpha = g_1 / g_0$. Numerical solution has been done by taking $\phi_1 = 1$.

Figure 1 shows the velocity profiles for $R = 1, \quad M = 0.2, \quad A = 0.4, \quad B = 0.2$, $\phi = 1$ and $\varepsilon\alpha = 10$. It is noted that velocity profiles increase with increase in permeability parameter K_0, velocity slip parameter *h*, Grashof number Gr and modified Grashof number Gc, but velocity profiles decrease with increase in temperature jump parameter h^*. It is also observed that the velocity is at maximum near the plate and decreases exponentially.

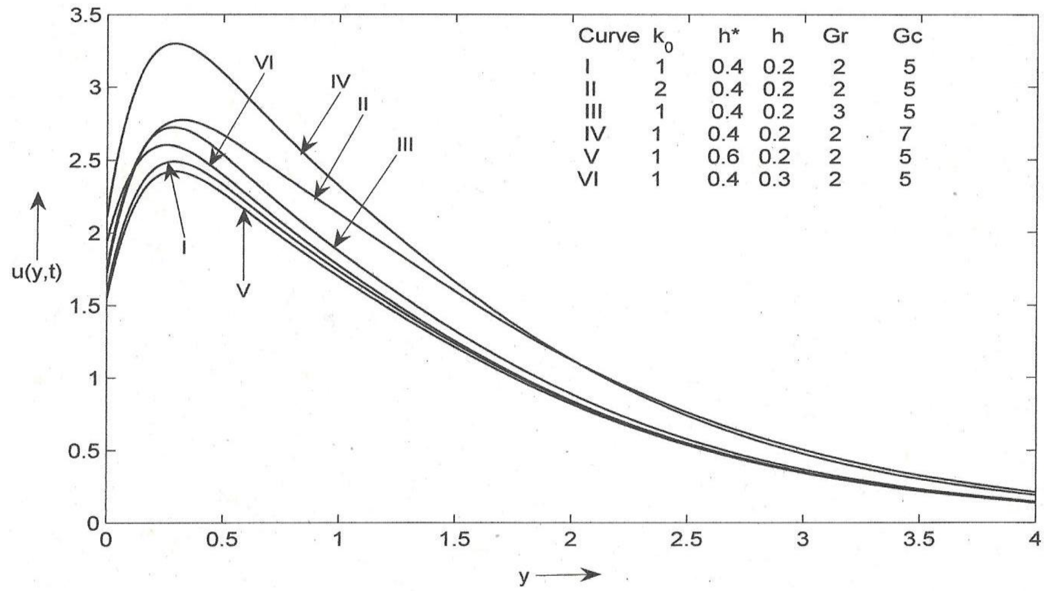

Figure 1 Velocity profiles for R = 1, M = 0.2, A = 0.4, B = 0.2, ϕ = 1 and $\varepsilon\alpha$ = 10.

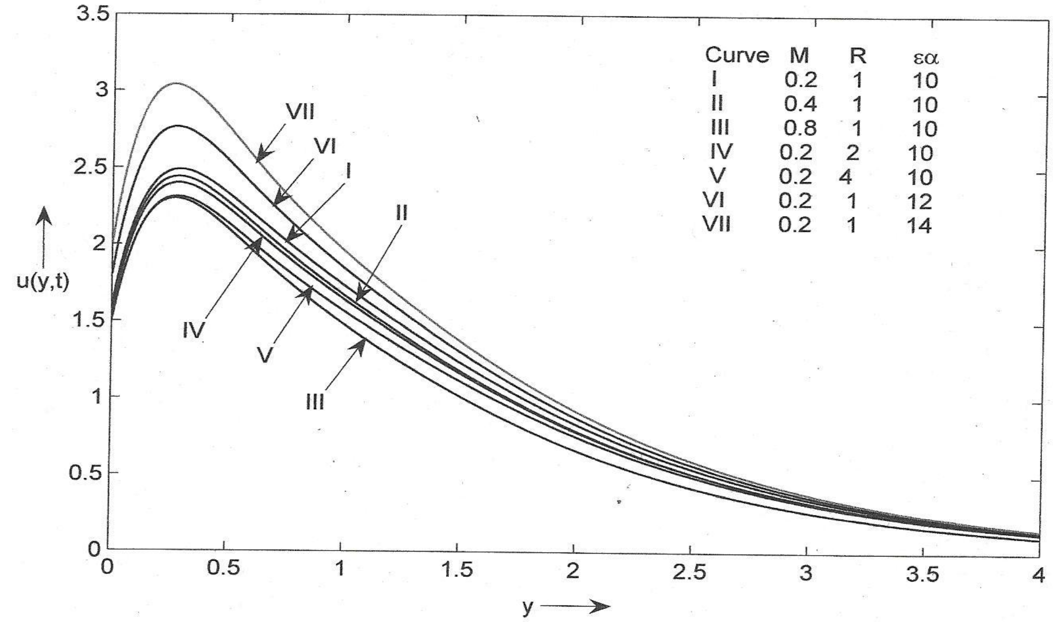

Figure 2 Velocity profiles for Gr = 2, Gc = 5, K_0 = 1, h = 0.2, ϕ = 1 and h^* = 0.4.

Figure 2 depicts the effect of magnetic parameter *M*, Radiation parameter R and gravity modulation parameter $\varepsilon\alpha$ on velocity profiles for $Gr = 2, Gc = 5, h = 0.2, h^* = 0.4$, $\phi = 1$ and $K_0 = 1$. It is observed that velocity profiles decrease with increase in magnetic parameter M and radiation parameter R , while these increase with increase in gravity modulation parameter $\varepsilon\alpha$. **Figure 3** shows that velocity profiles decrease with increase in the value of Pr and Sc . The effect of ϕ on the velocity profiles has been shown in **Figure 4**. Velocity profiles decrease with increase in the value of ϕ .

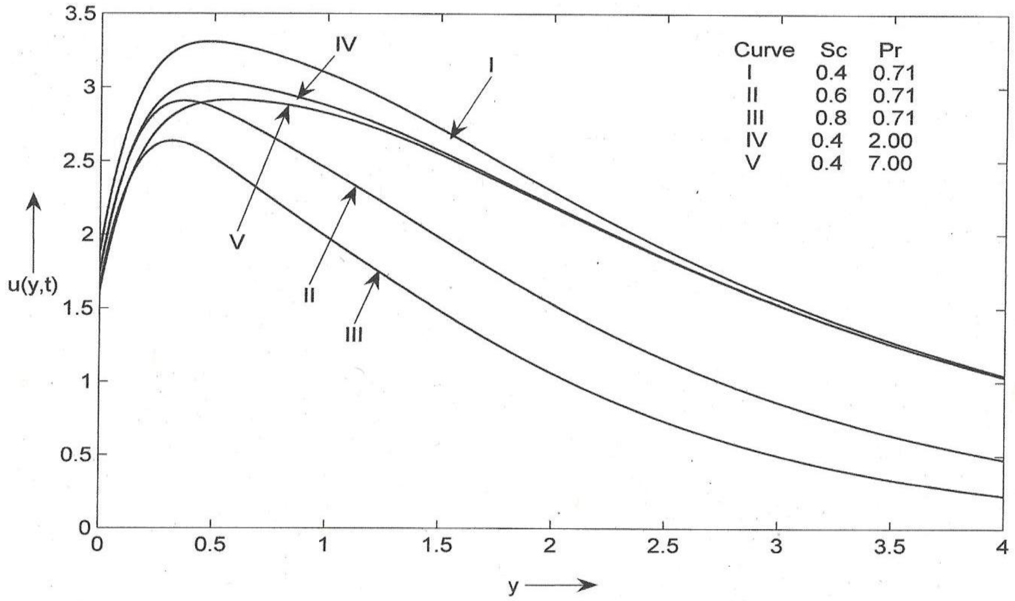

Figure 3 Velocity profiles for R = 1, M = 0.2, Gr = 2, Gc = 5, ϕ = 1 and εα = 10.

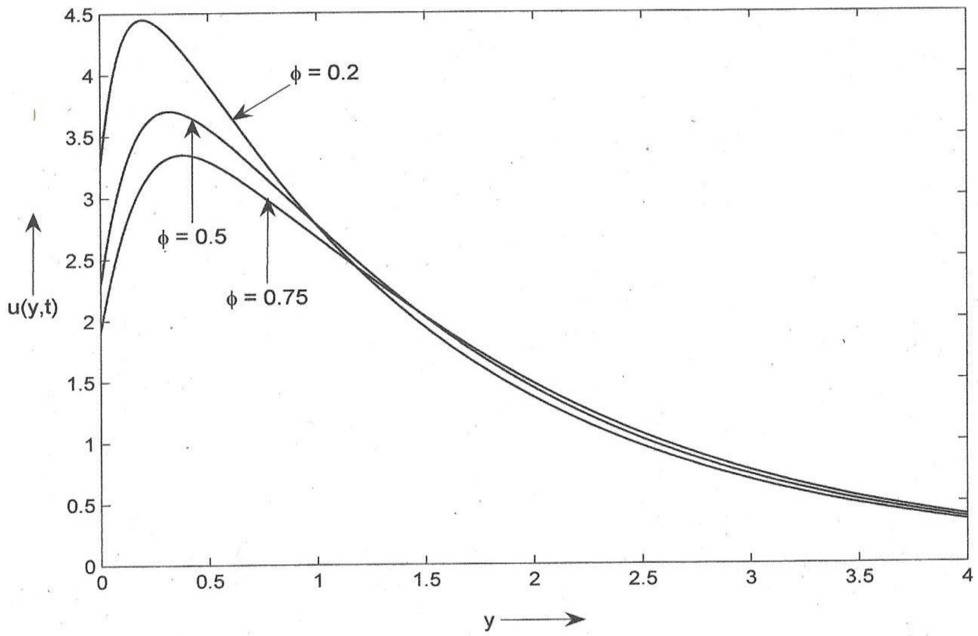

Figure 4 Velocity profiles for R = 1, M = 0.2, A = 0.4, B = 0.2 and εα = 10.

The temperature distribution is shown graphically in **Figure 5** for $Gr = 2, Gc = 5, K_0 = 1, \quad A = 0.4$ and $B = 0.2$. It is observed that temperature profiles decrease with increase in temperature jump parameter h^*, Prandtl number $\Pr$ and Radiation parameter R. It is also observed that gravity modulation has no impact on temperature profiles.

Figure 6 represents the effect of Schmidt number Sc on concentration profiles. The values of Schmidt number Sc are taken for Hydrogen $(Sc = 0.22)$, Helium $(Sc = 0.30)$, water vapour $(Sc = 0.60)$ and Ammonia $(Sc = 0.78)$. It is noted that concentration profiles decrease with increase in the value of Schmidt number Sc.

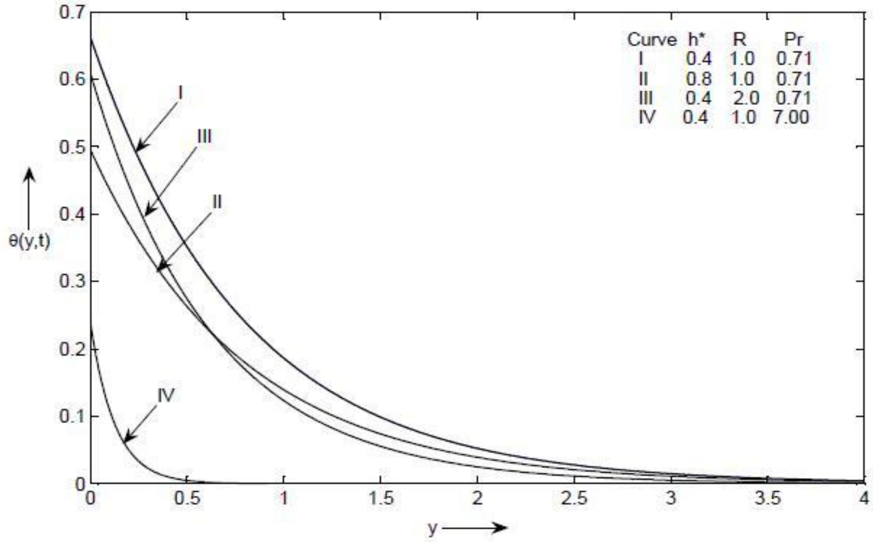

Figure 5 Temperature profiles for Gr = 2, Gc = 5, K_0 = 1, A = 0.4 and B = 0.2.

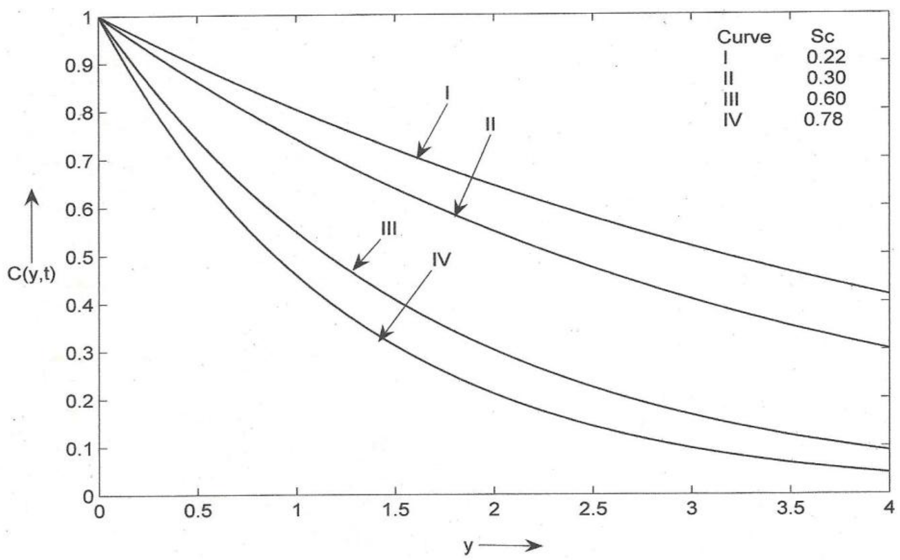

Figure 6 Concentration profiles due to variation in Schmidt number Sc.

Skin friction

The non-dimensional skin friction τ at the plate is given by;

$$\tau = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -m_5 A_6 + m_3 A_7 + ScA_8 + \varepsilon\, e^{i\omega t}\left[-m_2 A_1 + m_1 B_1 - ScB_2 - m_3 B_3 + m_4 B_4 - m_5 B_5\right] \qquad (32)$$

Figure 7 shows the effect of various parameters on skin-friction τ for $R = 1$, $M = 0.2$, $A = 0.4$, $B = 0.2$, $\phi = 1$ and $\varepsilon\alpha = 10$ versus K_0. It is observed that skin friction decreases with increase in velocity slip parameter h and temperature jump parameter h^*. It is also noted that velocity slip parameter h has more impact on τ as compared to temperature jump parameter h^*. Figure also depicts that skin friction τ increases with increase in Grashof number Gr and modified Grashof number Gc.

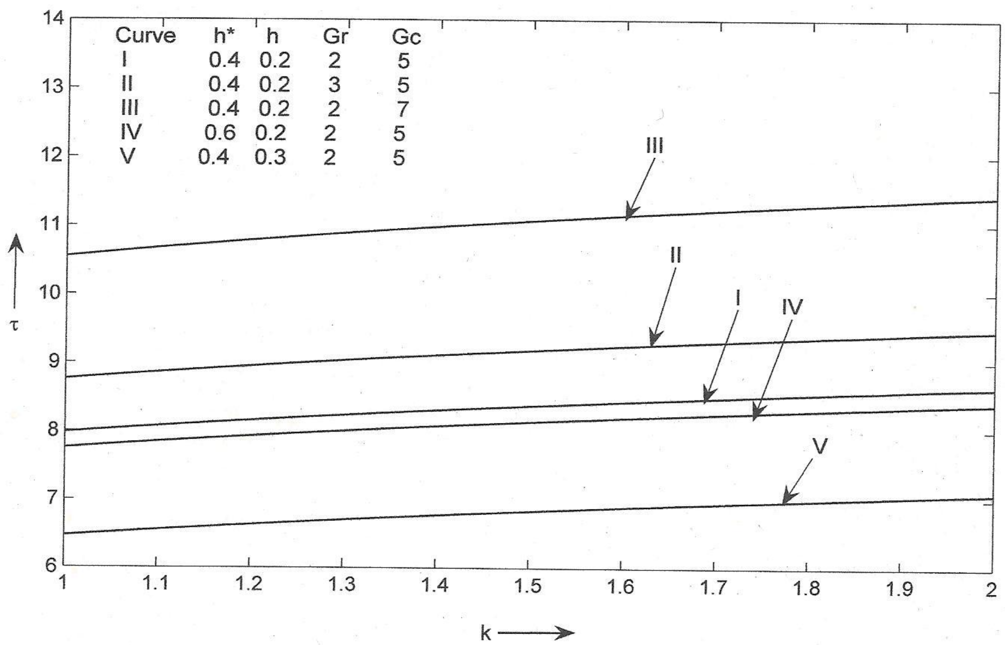

Figure 7 Skin friction for R = 1, M = 0.2, A = 0.4, B = 0.2, ϕ = 1 and εα = 10.

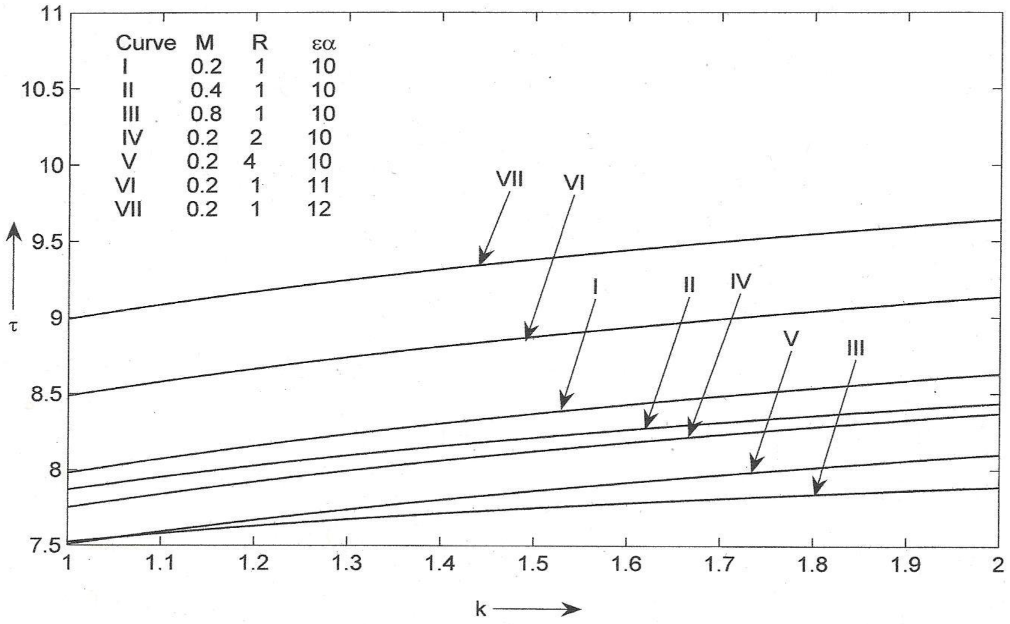

Figure 8 Skin friction profiles for Gr = 2, Gc = 5, K_0 = 1, h = 0.2, ϕ = 1 and h^* = 0.4.

Figure 8 shows the effect of magnetic parameter M, Radiation parameter R and gravity modulation parameter $\varepsilon\alpha$ on τ for $Gr = 2, Gc = 5, h = 0.2$, $\phi = 1$ and $h^* = 0.4$. It is observed that skin friction τ decreases with increase in magnetic parameter M and radiation parameter R, while it increases with increase in gravity modulation parameter $\varepsilon\alpha$. It is noted that gravity modulation parameter $\varepsilon\alpha$ has a significant effect on skin-friction.

Coefficient of heat transfer

The heat transfer coefficient on the vertical plate in dimensionless form is given by;

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0} = -m_3A_3 + \varepsilon e^{i\omega t}\left(-m_4A_4 - m_3A_5\right). \quad (33)$$

Table 1 represents the numerical values of Nusselt number Nu for variation in radiation parameter *R*, temperature jump parameter h^*, Prandtl number Pr and suction velocity amplitude *A*. It is observed that $|Nu|$ increases with increase in the value of *R*, Pr and *A*, while it decreases with increase in temperature jump parameter h^*. It is noted that suction velocity amplitude *A* has much less impact on $|Nu|$ as compared to other parameters.

Table 1 Values of Nusselt number $|Nu|$.

R	A	h^*	Pr	$\|Nu\|$
0	0.4	0.4	0.71	0.5531
0.5	0.4	0.4	0.71	0.7389
1.0	0.4	0.4	0.71	0.8420
0.5	0.8	0.4	0.71	0.7390
0.5	0.4	0.6	0.71	0.6437
0.5	0.4	0.8	0.71	0.5703
0.5	0.4	0.4	7.00	1.8734

Penetration distance

Penetration distance was studied to understand the effect of gravity modulation and radiation on the transition from conduction to convection. The penetration distance of the point from the leading edge is defined as;

$$X_p = \int_0^t u(y,t)\,dt \tag{34}$$

Penetration distance has been evaluated for $Gr = 2, Gc = 5, k_0 = 1, h = 0.2, h^* = 0.4$ and $\phi = 1$. It is noted from **Figure 9** that transition from conduction to convection is delayed as gravity modulation parameter $\varepsilon\alpha$ increases, but transition becomes faster as M and R increase.

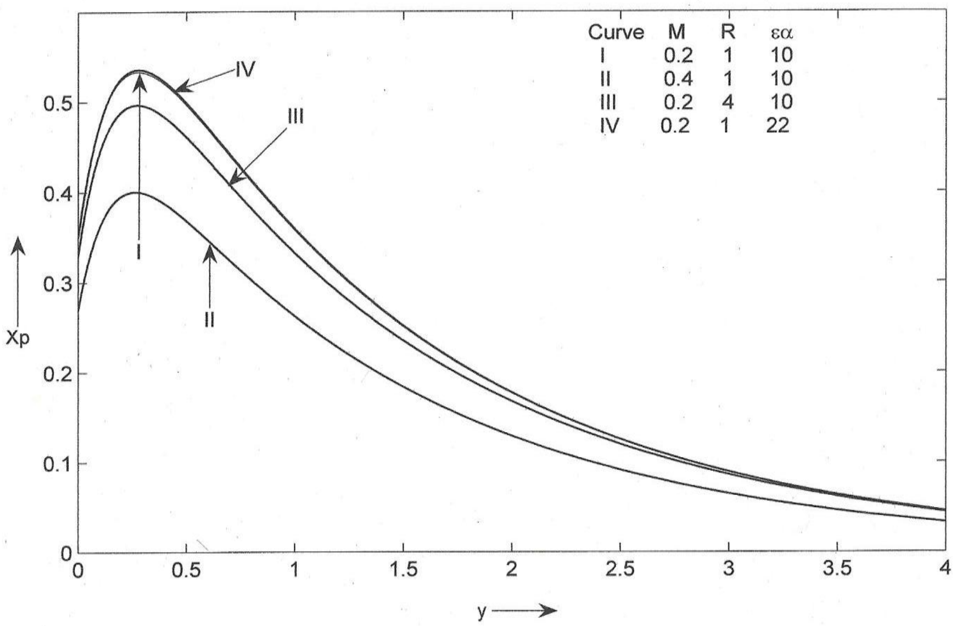

Figure 9 Penetration distance for Gr = 2, Gc = 5, K_0 = 1, h = 0.2, ϕ = 1 and h^* = 0.4.

Entropy generation

Entropy generation in a thermal system is associated with thermodynamic irreversibility. The irreversible nature of heat transfer, viscous effects and magnetic fields lead to the continuous generation of entropy in the system. It exists in all type of heat transfer processes. The entropy destroys available work, and thus reduces the efficiency of a thermal system. The minimization of entropy generation may lead to improvements of efficiency in thermal systems. The velocity components, heat transfer and magnetic field provide a basis for calculation of entropy. Entropy generation has been studied in [24-28] for various systems.

The entropy generation in the present study is written as;

$$S = \frac{k}{T_0^{*2}}\left(\frac{\partial T^*}{\partial y^*}\right)^2 + \frac{1}{T_0^*}\sigma B_0^2 u^{*2} + \frac{1}{T_0^*}\left[\frac{\mu}{K^*}\left(u^{*2}+v^{*2}\right)+\bar{\mu}\left(\frac{\partial u^*}{\partial y^*}\right)^2\right] \tag{35}$$

where T_0^* is a reference temperature.

Volumetric entropy generation in dimensionless form is defined as;

$$Ns = \frac{S'''}{S_0'''} \tag{36}$$

where

$S_0''' = \frac{k\, v_0^{*2}}{\upsilon^2}\frac{1}{T_0}$ is the reference volumetric entropy generation and

$T_0 = \frac{T_0^*}{T_w^* - T_\infty^*}$ is the dimensionless reference temperature.

Using the Eqs. (6), (7) and (13) in (35) - (36) the dimensionless form of the total local entropy generation is written as the sum of local entropy generation due to heat transfer irreversibility (Ns_1), local entropy generation due to fluid friction irreversibility (Ns_2) and local entropy generation due to magnetic effect (Ns_3) in the following manner;

$$Ns = Ns_1 + Ns_2 + Ns_3 \tag{37}$$

where

$$Ns_1 = \frac{1}{T_0}\left(\frac{\partial\theta}{\partial y}\right)^2 \tag{38}$$

$$Ns_2 = N_{Br}\left[\frac{1}{k_0(1+\varepsilon B e^{i\omega t})}\left\{u^2 + (1+\varepsilon A e^{i\omega t})^2\right\} + \phi\left(\frac{\partial u}{\partial y}\right)^2\right] \tag{39}$$

$$Ns_3 = M^2 N_{Br}\, u^2 \tag{40}$$

and where $N_{Br} = \dfrac{\mu v_0^{*2}}{k(T_w^* - T_\infty^*)}$ is the Brinkman number.

Figure 10 depicts the entropy generation due to heat transfer irreversibility Ns_1 for $\Pr = 0.71$, $M = 0.5$ and $\varepsilon\alpha = 10$. There is increase in entropy generation due to increase in radiation parameter R near the plate, and it shows reversible behavior as it moves away from the plate. Entropy generation due to fluid friction irreversibility Ns_2 is shown in **Figure 11**. It is seen that entropy generation decreases with increase in the value of ϕ. Profiles show maximum increase near the plate and a gradual decrease. Similar behavior is seen on the entropy generation due to magnetic field, as shown in **Figure 12**. The total entropy generation Ns is analyzed in **Figure 13** corresponding to y. It decreases with increasing the values of ϕ.

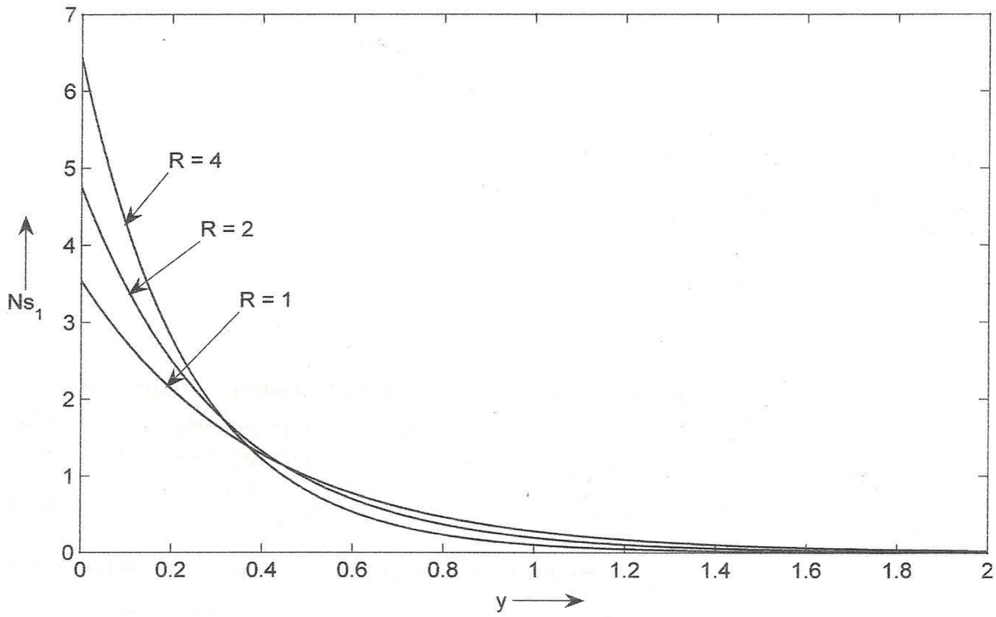

Figure 10 Ns_1 versus y for Pr = 0.71, M = 0.5 and εα = 10.

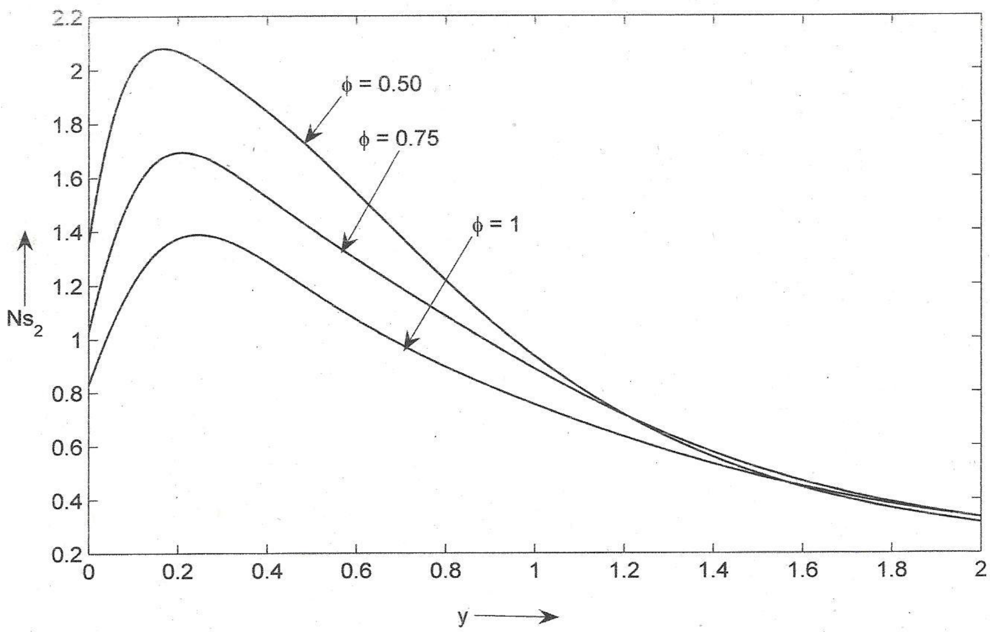

Figure 11 Ns_2 versus y for R = 1, M = 0.5, Pr = 0.71 and εα = 10.

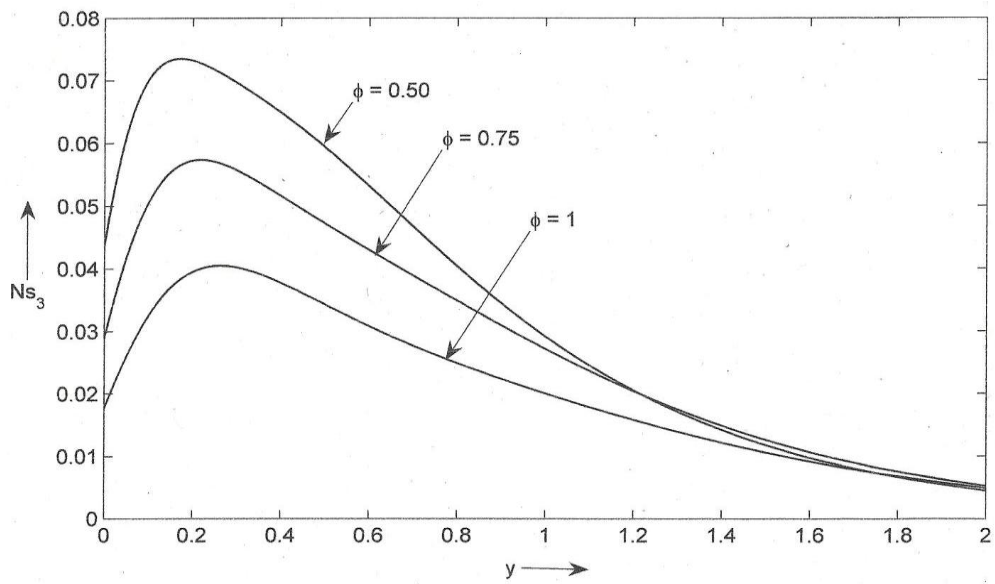

Figure 12 Ns_3 versus y for R = 1, M = 0.5, Pr = 0.71 and εα = 10.

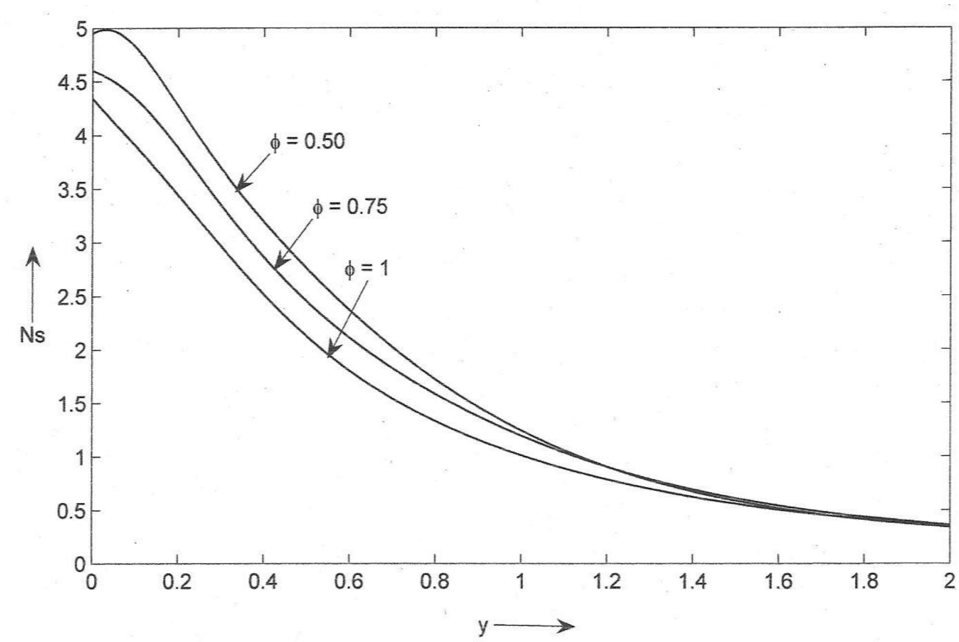

Figure 13 Ns versus y for R = 1, M = 0.5, Pr = 0.71 and $\varepsilon\alpha$ = 10.

With a view to understand the entropy generation mechanism of convective heat transfer, an irreversibility distribution ratio Φ is defined as;

$$\Phi = \frac{Ns_2 + Ns_3}{Ns_1}. \tag{41}$$

It is noted that heat transfer irreversibility is dominant for $0 < \Phi < 1$; fluid friction and magnetic effect dominate for $\Phi > 1$. When $\Phi = 1$, the contribution of heat transfer to entropy generation is equal to the sum of fluid friction and magnetic effects. The variation of irreversibility distribution parameter Φ is shown in **Table 2**. It is observed that the irreversibility distribution parameter decreases by increasing the values of ϕ, R, h^* and y.

Table 2 Variation of irreversibility distribution parameter Φ.

y	ϕ	R	M	h^*	Φ
0.2	0.50	1	0.2	0.4	1.0043
0.2	0.75	1	0.2	0.4	0.8206
0.2	0.50	2	0.2	0.4	0.9525
0.2	0.50	1	0.8	0.4	1.2136
0.2	0.50	1	0.2	0.8	0.9206
0.4	0.50	1	0.2	0.4	0.9034

Conclusions

The velocity profiles decrease with increase in magnetic parameter M and radiation parameter R, and increase with increase in gravity modulation parameter $\varepsilon\alpha$. Increase in temperature jump parameter and radiation parameter decreases the temperature profiles. Skin friction decreases with increase in magnetic parameter and radiation parameter, while it increases with increase in gravity modulation parameter $\varepsilon\alpha$. The total entropy generation Ns decreases with increasing values of ϕ.

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