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NUMERICAL INVESTIGATION OF THERMALLY STRATIFIED MHD FLUID FLOW WITH VISCOUS DISSIPATION AND HEAT SINK/SOURCE EFFECT

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Abstract

This study includes an unsteady MHD-free convective flow through a porous medium across a vertically inclined flat plate with varying temperatures. The combined effects of thermal radiation, heat absorption, and thermal stratification have also been discussed. The governing equations are transformed into a dimensionless form by applying the appropriate transformation and solved numerically using the Crank-Nicolson method. The graphical results have been achieved using Mathematica. The results demonstrate that radiation and heat absorption have a significant effect on the velocity and temperature profiles of thermally stratified fluids.

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Keywords and phrases: MHD Flow, Thermally stratified fluid, Viscous dissipation, Thermal radiation, Crank-nicolson method..

Nomenclature:

B_0 Strength of magnetic field
u' Dimensional velocity of plate in x-direction
v' Dimensional velocity of plate in y-direction
T' Dimensional Fluid temperature
u Dimensionless velocity
g Gravitational acceleration
β_T Coefficient of thermal expansion
α angle of inclination
σ Electrical conductivity
σ_s Stefan-Boltzmann Constant
ρ Fluid density
ν Kinematic viscosity
K' Dimensional permeability of porous medium
κ Thermal conductivity
k_e mean absorption coefficient
C_p Specific heat at constant pressure
μ viscosity of the fluid

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q_r Radioactive heat flux
Q_0 heat absorption coefficient
t' finite time
T_W wall temperature
A Constant buoyancy frequency
θ Non-dimensional temperature
M Magnetic parameter
P Pressure
T_∞ Fluid temperature far away from the plate
τ Skin friction

1. Introduction

The study of the magnetohydrodynamic (MHD) flow of electrically conductive fluid turns out to be highly significant in modern metallurgical and physical procedures. It addresses the impact of the magnetic field on the control of the boundary layer flow when combined with the heat transfer phenomenon in many engineering applications such as geophysics, astrophysics, etc., which is applicable in MHD generators, nuclear reactors, and geothermal energy extraction procedures. The quality of the end result is contingent upon the rate of heat transfer; hence, effective control of the cooling effect is necessary. The rate of cooling in an electrically conducting fluid can be regulated by the MHD flow investigated by Chakrabarti and Gupta [1]. The behavior of flow and heat transfer has been studied by numerous researchers. Grubka and Bobba [2] studied the characteristics of fluid flow and heat transfer on a stretching sheet under variable temperature conditions. Par Sparrow and Cess [3] examined temperature-dependent heat absorption on heat transfer and steady stagnation point flow. The impact of temperature-dependent heat sources during electrical heating on heat transfer in a porous medium has been investigated by Moalem [4]. In the presence of temperature-dependent heat generation or absorption effects, Vajravelu and Nayfeh [5] reported on hydromagnetic convection at a cone and a wedge. Recently, in his research on mixed convection in a channel filled with a porous medium, Chamkha [6] took temperature-dependent heat sources or sinks into consideration.

The effects of variable fluid properties and viscous dissipation on the transport phenomenon of magnetohydrodynamics viscoelastic fluid were recently studied by Megahed et al. [7] and Mahapatra and Gupta [8]. A porous stretching sheet with dissipation energy and stress work was used to demonstrate viscoelastic MHD flow, heat, and mass transfer by Khan et al. [9].

In a more recent study, Ali et al. [10] examined the impact of MHD on the fluctuating, unsteady-free convective flow of viscoelastic fluid with embedded dust particles. Chaudhary et al. [11] anticipate the viscous liquid flow past an exponentially extending sheet with radiation effects. Hamza et al. [12] focused on the effects of MHD flow in a vertical channel with a porous medium containing a chemically reacting fluid that is convectively heated. Vijayalakshmi et al. [13] demonstrated magnetohydrodynamics in porous media with a variety of effects. Reddy et al.'s [14] investigation focused on the MHD-free convection. Couette flow viscoelastic fluid embedded with dust particles in a rotating channel was examined by Bilal et al. [15]. The effects of radiation and heat absorption on MHD boundary layer flow along an accelerated infinite vertical plate were examined by Reddy et al. [16]. Javaherdeh et al. [17] used the Darcy model to perform a numerical study of 2D steady laminar natural convection flow with a moving vertical plate in a porous medium exposed to a transverse magnetic field. Moreover, the impact of radiation and mass transfer on MHD-free convection flow over an inclined plate has been investigated by Suneetha [18]. A drop in temperature as the radiation parameter value increases flow on an inclined porous heated plate was examined by Prasad and Vara [19]. The effects of thermal radiation and chemical reactions on unstable blood flow through a parallel and horizontal plate in a saturated and porous medium with an inclined magnetic field have been studied by Omamoke et al. [20]. In the context of viscous dissipation, researchers Barik et al. [21] examined the impact of thermal radiation on an unstable MHD flow past an inclined porous heated plate. In addition, Iranian D. [22] as addressed the effects of changing viscosity, thermal conductivity, and stratification parameters at different times with velocity and temperature profiles. Verma and Ansari [23] examined the effect of magnetic field in rotating porous channel.

The study has attempted to bridge the gap with the aforesaid literature work and uses an unsteady MHD flow over a temperature-varying vertically inclined plate to explore the effects of thermal stratification, radiation, and viscous dissipation.

2. Mathematical Formulation

This study analyzes the role of thermal stratification, radiation, and viscous dissipation in the incompressible, unstable, free convective heat transfer of viscous MHD flow through an inclined plate embedded in a porous medium. A normal to the plate is taken by the y-axis, and the x-axis is taken along the plate in a vertical upward direction. After a α inclination towards the vertical x-axis, the plate is oriented in the directions of x' and y'. B_0, the uniform magnetic field, is assumed to be normal to the flow direction. The physical model of the problem is shown in Figure 1. The fluid and the plate are initially in a resting position for a temperature T_∞ at $t' \leq 0$. After time t' the sudden jerk is given to the plate, which started accelerating linearly with time t' which caused its temperature to rise to T_w.

The induced magnetic field produced by the fluid motion is minimal in comparison to the applied magnetic field because the fluid is electrically conducting and has a very low magnetic Reynolds number. Since the fluid is incompressible, the equation of continuity in two dimensions will be:

$$\nabla \cdot v' = 0 \implies \frac{\partial v'}{\partial x'} + \frac{\partial v'}{\partial y'} = 0. \tag{2.1}$$

But the plate is infinite in the x' direction; therefore, the flow variables are only functions of y' and t', and thus equation (2.1) reduces to

$$\frac{\partial v'}{\partial y'} = 0. \tag{2.2}$$

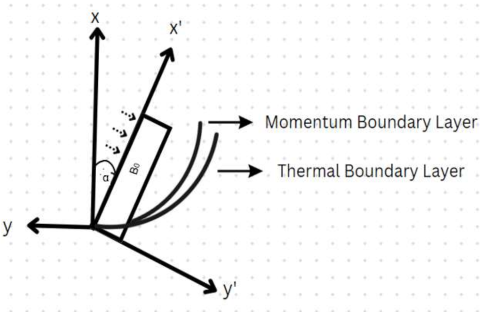

FIGURE 1. Configuration of the physical model of the problem

The governing boundary layer equations using Boussinesq's approximation under the above-mentioned assumptions are:

$$\frac{\partial v'}{\partial y'} = 0 \implies v' = -v_0, \tag{2.3}$$

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\beta_T (T' - T_\infty) cos\alpha - \frac{\sigma B_0^2 u'}{\rho} - \frac{\nu}{K'} u', \tag{2.4}$$

$$\frac{\partial T'}{\partial t'} = \frac{\kappa}{\rho C_p} \frac{\partial^2 T'}{\partial y'^2} - \gamma u' + \frac{\mu}{\rho C_p} (\frac{\partial u'}{\partial y'})^2 - \frac{1}{\rho Cp} \frac{\partial q_r}{\partial y'} - \frac{Q_0}{\rho C_p} (T' - T_\infty). \tag{2.5}$$

It is assumed that the fluid flow has the following initial and boundary conditions:

$$u'(y', 0) = 0, \;\; T'(y', 0) = T_\infty \;\; \forall \; y' > 0, \tag{2.6}$$

$$u'(0, t') = A\sqrt{A\nu}\, t', \;\; T'(0, t') = T_\infty + (T_w - T_\infty) e^{At'} \;\; \forall \; t' > 0, \tag{2.7}$$

,

$$u'(y', t') \to 0, \;\; T'(y', t') \to T_\infty \;\; as \;\; y' \to \infty, \tag{2.8}$$

,

where $\gamma = \frac{dT_\infty}{dz} + \frac{g}{C_P}$ is the static stability, here, the term thermal stratification is $\frac{dT_\infty}{dz}$ and the term $\frac{g}{C_P}$ is pressure work. The temperature of the plate is T_w and $A = \frac{{v_0}^2}{\nu}$ where v_0 is constant velocity. Thermal radiation is presumed to be present. Rosseland's estimate can be used to compute the radiative heat flow, represented by q_r,

$$q_r = -\frac{4\sigma_s}{3k_e}\frac{\partial T'^4}{\partial y'}. \tag{2.9}$$

If the temperature gradients within the flow are sufficiently low, we may obtain a linear version by putting T'^4 in a Taylor series around T_∞ by omitting higher-order components as-

$$T'^4 = 4{T_\infty}^3 T' - 3{T_\infty}^4. \tag{2.10}$$

The following non-dimensional quantities are introduced:

$$y = \sqrt{\frac{A}{\nu}}y', \quad u = \frac{u\ '}{\sqrt{A\nu}}, \quad t = At', \quad K = \frac{K'A}{\nu}, \quad Gr = \frac{g\beta_T(T_w - T_\infty)}{A\sqrt{A\nu}},$$
$$\theta = \frac{T' - T_\infty}{T_w - T_\infty}, \quad M = \frac{\sigma {B_0}^2}{\rho A}, \quad Pr = \frac{\mu C_P}{\kappa}, \quad \mu = \rho\nu, \quad S = \frac{\gamma\sqrt{A\nu}}{A(T_w - T_\infty)},$$
$$Q = \frac{Q_0}{\rho C_p A}, \quad R = \frac{k_e\kappa}{4\sigma_s {T_\infty}^3}, \quad Ec = \frac{A\nu}{C_p(T_w - T_\infty)}.$$

It is possible to simplify equations (2.4-2.10) using dimensionless values. Thus the non-dimensional form of equations (2.4-2.8) transforms as

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + Gr\theta cos\alpha - (M + \frac{1}{K})u, \tag{2.11}$$

$$\frac{\partial\theta}{\partial t} = \frac{1}{Pr}(1 + \frac{4}{3R})\frac{\partial^2\theta}{\partial y^2} - S\,u + Ec(\frac{\partial u}{\partial y})^2 - Q\theta. \tag{2.12}$$

The appropriate non-dimensional boundary conditions are:

$$u(y,0) = 0, \quad \theta(y,0) = 0, \quad \forall\ y > 0, \tag{2.13}$$

$$u(0,t) = t, \quad \theta(0,t) = e^t \quad \forall\ t > 0, \tag{2.14}$$

$$u(y,t) \to 0, \quad \theta(y,t) \to 0 \ \ as \ \ y \to \infty \quad \forall\ t > 0. \tag{2.15}$$

The value of skin friction and nusselt number can be estimated using equations (2.11-2.15) as

Skin Friction Skin friction is given by:

$$\tau = (\frac{\partial u}{\partial y})_{y=0}. \tag{2.16}$$

Nusselt Number Nusselt number is given by:

$$Nu = -(\frac{\partial \theta}{\partial y})_{y=0}. \tag{2.17}$$

3. Solution of the problem

The non-linear momentum and energy equations with boundary conditions (2.11-2.15) can be solved by using the implicit finite difference method of the Crank and Nicolson model after the appropriate initial and boundary conditions have been set up. To arrive at the appropriate finite difference equations, we adopt the Nicolson method as

$$\begin{aligned}\frac{u_{i,j+1} - u_{i,j}}{\Delta t} &= (\frac{u_{i+1,j+1} - 2u_{i,j+1} + u_{i-1,j+1} + u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{2(\Delta y)^2}) \\ &+Grcos(\alpha)(\frac{\theta_{i,j+1} + \theta_{i,j}}{2}) - (M + \frac{1}{K})(\frac{u_{i,j+1} + u_{i,j}}{2}),\end{aligned} \tag{3.1}$$

$$\begin{aligned}\frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta t} &= \frac{1}{Pr}(1 + \frac{4}{3R})(\frac{\theta_{i+1,j+1} - 2\theta_{i,j+1} + \theta_{i-1,j+1} + \theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}}{2(\Delta y)^2}) \\ &-S(\frac{u_{i,j+1} + u_{i,j}}{2}) + Ec(\frac{u_{i+1,j} - u_{i,j}}{\Delta y})^2 - Q(\frac{\theta_{i,j+1} + \theta_{i,j}}{2}).\end{aligned} \tag{3.2}$$

corresponding boundary conditions are:

$$u_{i,0} = 0, \;\; \theta_{i,0} = 0 \;\; \forall\ i, \tag{3.3}$$

$$u_{0,j} = j\Delta t, \;\; \theta_{0,j} = e^{j\Delta t} \;\; \forall\ j > 0, \tag{3.4}$$

$$u_{L,j} \to 0, \;\; \theta_{L,j} \to 0 \;\; as \;\; L \to \infty \;\; \forall\ j > 0. \tag{3.5}$$

Here the index i denotes space y and the index j denotes time t. Additionally, the mess sizes along the y-direction and the time t-direction, respectively, are represented by Δy and Δt. The finite difference equations (3.1-3.2) at each internal nodal point on a specific n-level constitute a tri-diagonal system of equations that are solved with the help of the Thomas algorithm. Therefore, at $t + \Delta t$, θ is known for all values of y. Replace these θ values in the equation and solve using the same process to solve for u until the desired time t, ensuring that the initial and boundary conditions are encountered.

4. Results and Discussion

Graphs are used to present the temperature and velocity profiles according to different flow parameter values. Figures (2-15) illustrate the graphic analysis of the effects of various parameters on the temperature field and velocity distribution, including the heat absorption parameter (Q), thermal stratification parameter (S), thermal Grashof number (Gr), Hartmann number (M), radiation parameter (R), Eckert number (Ec), and Prandtl number (Pr).

The angle of inclination α falls, the velocity increases, as seen in Figure [2]. Figure [3-5] depicts how velocity increases in proportion to increases in the Eckert number, Grashof number, and porosity parameter, respectively. As seen in Figure [6-10], velocity decreases as the values of the Hartmann number, Prandtl number, heat absorption parameter, radiation parameter, and thermal stratification parameter decreases, respectively. In figure [11], it can be seen that the temperature of the fluid increases with raising the value of the Eckert number. Further in figure [12-15], it shows that the temperature rises as the Prandtl number, heat absorption parameter, and stratification parameter fall, respectively.

The skin friction and nusselt number are presented in Table 1 and Table 2, respectively, where the effect of various parameters on skin friction and nusselt number is displayed.

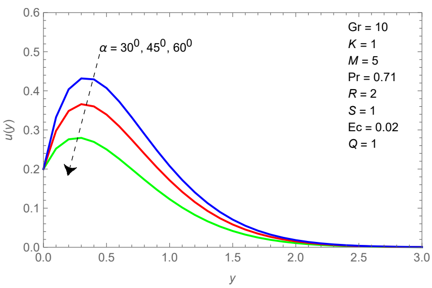

FIGURE 2. Velocity Profile for several values of α.

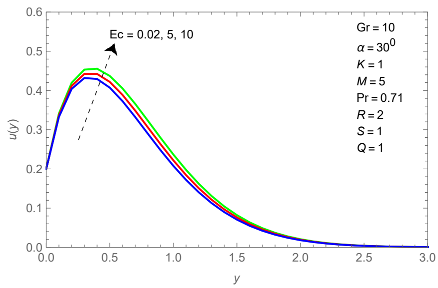

FIGURE 3. Velocity Profile for several values of Ec

5. Conclusion

An investigation of unsteady MHD-free convection of an incompressible electrically conducting fluid passing past an inclined plate while a uniform magnetic field is applied, as well as viscous dissipation with heat source/sink and radiation effects on thermally stratified fluid, is covered in this paper. Using the Crank-Nicolson method, the leading equations are solved numerically. The flow characteristics, such as temperature and velocity, are displayed in the results. The following conclusions are drawn

TABLE 1. Skin friction for different values of parameter

α	**Ec**	**Gr**	**K**	**M**	**Pr**	**Q**	**R**	**S**	τ
30^0	**0.02**	**10**	**1**	**5**	**0.71**	**1**	**2**	**1**	1.32585
45^0	0.02	10	1	5	0.71	1	2	1	0.978006
60^0	0.02	10	1	5	0.71	1	2	1	0.522929
30^0	**5**	10	1	5	0.71	1	2	1	1.36768
30^0	**10**	10	1	5	0.71	1	2	1	1.41218
30^0	0.02	**5**	1	5	0.71	1	2	1	0.375308
30^0	0.02	**15**	1	5	0.71	1	2	1	2.26784
30^0	0.02	10	**3**	5	0.71	1	2	1	1.38337
30^0	0.02	10	**10**	5	0.71	1	2	1	1.40413
30^0	0.02	10	1	**2**	0.71	1	2	1	1.60706
30^0	0.02	10	1	**3**	0.71	1	2	1	1.50664
30^0	0.02	10	1	5	**1**	1	2	1	1.1854
30^0	0.02	10	1	5	**1.5**	1	2	1	1.01183
30^0	0.02	10	1	5	0.71	**0.1**	2	1	1.37398
30^0	0.02	10	1	5	0.71	**2**	2	1	1.2758
30^0	0.02	10	1	5	0.71	1	**3**	1	1.26798
30^0	0.02	10	1	5	0.71	1	**5**	1	1.21382
30^0	0.02	10	1	5	0.71	1	2	**3**	1.28605
30^0	0.02	10	1	5	0.71	1	2	**5**	1.24752

TABLE 2. Nusselt number for different values of parameter

α	**Ec**	**Gr**	**K**	**M**	**Pr**	**Q**	**R**	**S**	**Nu**
30^0	**0.02**	**10**	**1**	**5**	**0.71**	**1**	**2**	**1**	-8.81772
45^0	0.02	10	1	5	0.71	1	2	1	-8.82698
60^0	0.02	10	1	5	0.71	1	2	1	-8.83923
30^0	**5**	10	1	5	0.71	1	2	1	-8.98288
30^0	**10**	10	1	5	0.71	1	2	1	-9.17016
30^0	0.02	**5**	1	5	0.71	1	2	1	-8.84324
30^0	0.02	**15**	1	5	0.71	1	2	1	-8.79308
30^0	0.02	10	**3**	5	0.71	1	2	1	-8.81619
30^0	0.02	10	**10**	5	0.71	1	2	1	-8.81563
30^0	0.02	10	1	**2**	0.71	1	2	1	-8.81024
30^0	0.02	10	1	**3**	0.71	1	2	1	-8.8129
30^0	0.02	10	1	5	**1**	1	2	1	-8.57458
30^0	0.02	10	1	5	**1.5**	1	2	1	-8.23474
30^0	0.02	10	1	5	0.71	**0.1**	2	1	-8.95532
30^0	0.02	10	1	5	0.71	**2**	2	1	-8.67434
30^0	0.02	10	1	5	0.71	1	**3**	1	-8.72064
30^0	0.02	10	1	5	0.71	1	**5**	1	-8.6259
30^0	0.02	10	1	5	0.71	1	2	**3**	-8.69429
30^0	0.02	10	1	5	0.71	1	2	**5**	-8.46148

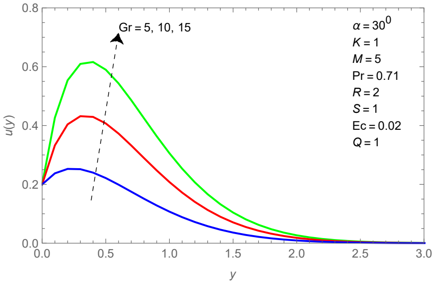

FIGURE 4. Velocity Profile for several values of Gr.

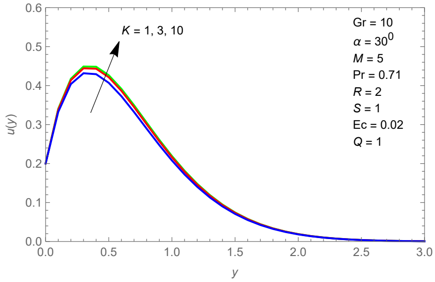

FIGURE 5. Velocity Profile for several values of K

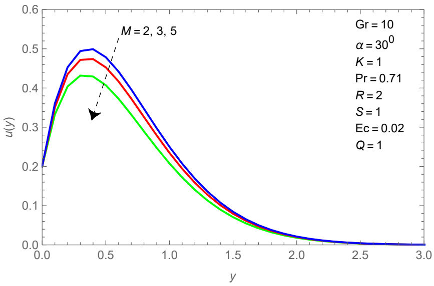

FIGURE 6. Velocity Profile for several values of M

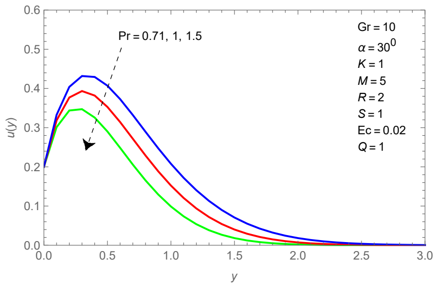

FIGURE 7. Velocity Profile for several values of Pr

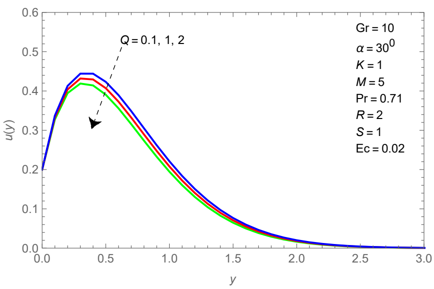

FIGURE 8. Velocity Profile for several values of Q.

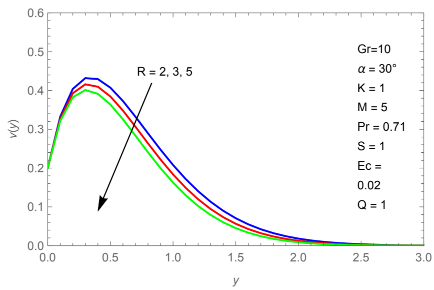

FIGURE 9. Velocity Profile for several values of R

from the flow analysis:

- When the angle of inclination α or magnetic parameter increases, consequently decreases the magnitude of velocity. For the Prandtl number, radiation parameter, stratification parameter, and heat absorption parameter, identical results are obtained.
- For increasing values of the porosity parameter, Grashof number, and Eckert number, the velocity rises in the flow domain.

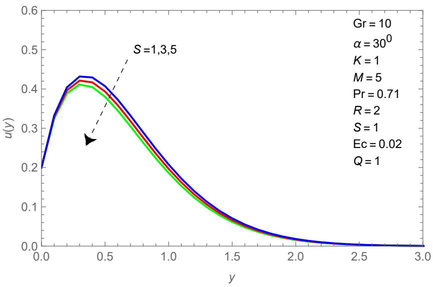

FIGURE 10. Velocity Profile for several values of S.

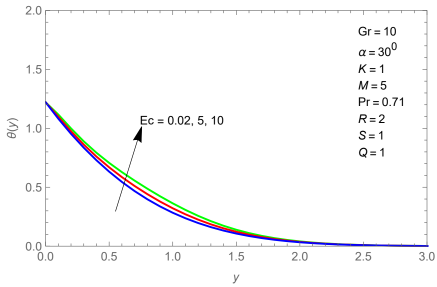

FIGURE 11. Temperature Profile for several values of Ec

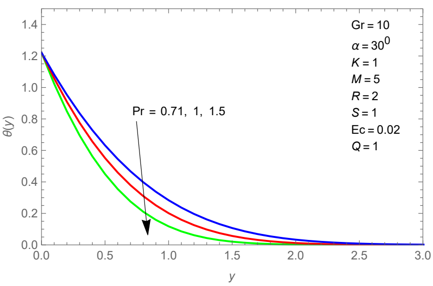

FIGURE 12. Temperature Profile for several values of Pr.

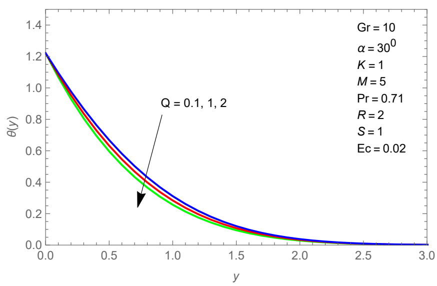

FIGURE 13. Temperature Profile for several values of Q

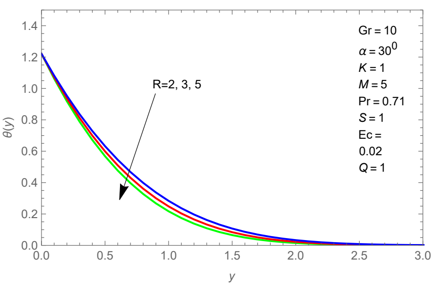

FIGURE 14. Temperature Profile for several values of R.

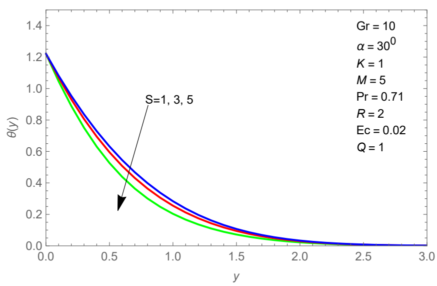

FIGURE 15. Temperature Profile for several values of S

- When the Eckert number increases, consequently increases the magnitude of temperature.
- With the increasing value of Prandtl number, radiation parameter, stratification parameter, and heat absorption parameter, the temperature decreases in the flow domain.

6. Declaration of competing interest

The authors state that they have no known financial conflicts of interest or personal ties that might have appeared to have an impact on the work presented in this study.

7. Declaration of generative AI in scientific writing

The writers did not use generative AI or AI-assisted technologies in the writing process while preparing this book.

8. Declaration and verification

The specified work is not being considered for publication anywhere, meaning it has not been published before.

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