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EFFECT OF RADIATION AND HEAT DISSIPATION ON MHD CONVECTIVE FLOW IN PRESENCE OF HEAT SINK[†]

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The paper examines heat and mass transfer in MHD convective flow across a vertical porous plate in presence of radiation, heat sink, and dissipation of heat. A strong magnetic field is applied perpendicular to the plate and directed into the fluid area. The governing non-dimensional equations are solved using MATLAB built-in bvp4c solver technique. With the use of mathematical software, the findings are computed, and the effect of the various non-dimensional parameters entering into the problem on the velocity, temperature and concentration profiles are displayed in graphical formats. It has been noted that the application of the magnetic field slows down fluid velocity. Additionally, both the thermal radiation effect and the Prandtl number are fully applicable to the fluid temperature. It is significant to notice that the heat sink dramatically reduces fluid temperature and fluid velocity. The current work is utilized in many real life applications, such as chemical engineering, industrial processes, a system may contain multiple components, each of whose concentrations varies from one point to the next in a number of different circumstances.
Keywords: *Heat and mass transfer; MHD; Heat dissipation; Porous medium; bvp4c*
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INTRODUCTION

Buoyancy force is the outcome of the variation in density brought on by a change in concentration or temperature in a flowing fluid. The flow induced by buoyancy forces is called free convective or natural flow. Natural convection also, known as free convection, is a mechanism, or type of mass and heat transport. In chemical engineering and industrial processes, there are several where a system contains more than one component whose concentrations differ from one point to the next. Mass transfer operations are concerned with the transfer of matter from one stream to another. As a result, a mass transfer occurs, which is the movement of one ingredient from a high-concentration zone to a low-concentration zone. That is to say, mass transfer is the mass in transient due to the concentration gradient. Furthermore, heat transfer is defined as the movement of heat across the border of system due to difference in temperature between the system and its surroundings. Studies pertaining to coupled heat and mass transfer due to free convection has got wide applications in different realms, such as, mechanical, geothermal, chemical sciences, etc. and many industrial and technological, physical set up such as nuclear reactors, food processing, polymer production, etc. MHD refers to the study of the magnetic properties and behavior of electrically conducting fluids. As a result, it is a mix of electromagnetic and fluid dynamics fields. Magnetohydrodynamics (MHD) attracts the attention of many authors due to its applications in geophysics, in the study of steller and solar structures, inter steller matter, radio propagation through the ionosphere etc.

Despite all these important investigations, there are few investigations in porous medium taking dissipation into account. It is worth mentioning that heat dissipation through a porous medium has been conventionally considered as combined that heat flows, such as thermal conduction along its solid matrix, thermal radiation across internal pores, and either thermal convection by or conduction through gases filling the pores. Heat and mass transfer in wet porous media are coupled in a very complicated way. Alfven [1], Cowling [2], Shercliff [3] and many other authors have studied and presented in the form MHD, and various problems of MHD. Raptis and Massals [4] and Hossain and Alim [5] studied the radiation effect on free and forced convection flows passed a vertical plate including various physical aspects. MHD free convection flows has been studied by Ferraro and Plumption [6]. Chen [7] studied the problem of combined heat and mass transfer of an electrically conducting fluid in MHD natural convection, adjacent to vertical surface with Ohmic heating. Based on the significance of heat and mass transfer problems, several authors geometrical and physical situations. Ahmed and Choudhury [8], Raptis and Perdikis [9], and others are among them.

Kim [10] discussed unsteady MHD free convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. Senapati *et.al* [11] have studied magnetic effect on mass and heat transfer of a hydromagnetic flow past a vertical oscillating plate in presence of chemical reaction. Shekhawat *et.al* [12], have been discussed the Dissipation heat and mass transfer in porous medium due to continuously moving pate. Rajesh [13] used the Crank-Nicolson type finite difference method to investigate the chemical reaction and radiation effects of a transient MHD natural convective dissipation flow through a porous plate in the presence of ramped wall temperature. Ahmed and Dutta [14] extended the work Rajesh [13]. The heat and mass transfer dissipative flow in the presence of porous medium have been studied Ahmed and Chamuah [15] very recently.

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Reddy et al. [16] investigated the magneto-hydrodynamic boundary layer flow with the influence of thermal radiation, ramped plate temperature, and heat absorption. Sedki [17] studied the combined impact of chemical reaction, thermal radiation, thermophoresis, and Brownian motion on mixed convective heat and mass transfer within the boundary layer of a moving magnetonanofluid adjacent to a permeable stretching surface, considering heat generation through a porous medium. Basant et al. [18] investigated the effects of heat source/sink on magnetohydrodynamic free convective flow in a channel filled with nanofluid. Matta et al. [19] analyzed the effects of viscous dissipation on magnetohydrodynamic (MHD) free convection flow past a semi-infinite moving vertical porous plate with heat sink and chemical reaction. Manvi et al. [20] investigated the influence of radiation on magnetohydrodynamic (MHD) Eyring-Powell fluid flow past a stretching sheet with non-uniform heat source/sink. Bhaskar et al. [21] examined the impact of heat generation and thermal radiation on steady hydromagnetic fully developed natural convection flow in a vertical micro-porous channel in the presence of viscous dissipation. Andreeva et al. [22] conducted a theoretical investigation into the stability of a rotating and heated-from-below horizontal cylindrical layer of a viscous, incompressible liquid with free boundaries. Andrieieva et al. [23] carried out a theoretical investigation of convective mass transfer in a cylindrical viscous incompressible conductive fluid layer. The study focused on the presence of an inhomogeneous temperature field and an external magnetic field resulting from the vacuum arc current passing through the fluid layer.

This paper deals with the study of heat dissipation in presence of porous medium due to continuously moving plate in presence of magnetic field and heat and mass flux. Governing equation is retained in vector form as readers will be able to generalize the problem without much difficulty. In the existing literature, there are few papers dealing with the above-mentioned aspects. However, in the current work, a comparison with an already published paper has been shown to ensure the accuracy of our current problem.

BASIC EQUATIONS

The following vector equations describe how a viscous, electrically conducting, stable, incompressible, radiating fluid moves in the presence of a uniform magnetic field:
Equation of continuity:

$$\vec{\nabla}.\vec{q} = 0 \tag{1}$$

Gauss's law of magnetism:

$$\vec{\nabla}.\vec{B} = 0 \tag{2}$$

Ohm's law:

$$\vec{J} = \sigma\left(\vec{E} + \vec{q} \times \vec{B}\right) \tag{3}$$

Momentum equation:

$$\rho\left(\vec{q}.\vec{\nabla}\right)\vec{q} = \rho\vec{g} - \vec{\nabla}p + \vec{J} \times \vec{B} + \mu\nabla^2\vec{q} - \frac{\mu\vec{q}}{K'} \tag{4}$$

Energy equation:

$$\rho C_p\left(\vec{q}.\vec{\nabla}\right)T = k\nabla^2 T + \varphi + \frac{\vec{J^2}}{\sigma} + Q'(T - T_\infty) - \vec{\nabla}.\vec{q_r} \tag{5}$$

Species continuity equation:

$$\left(\vec{q}.\vec{\nabla}\right)C = D_M\nabla^2 C + \bar{K}c(C_\infty - C) \tag{6}$$

Equation of state:

$$\rho_\infty = \rho\left[1 + \beta(T - T_\infty) + \bar{\beta}(C_\infty - C)\right] \tag{7}$$

Those equations are identified by nomenclature.

MATHEMATICAL ANALYSIS

We introduced the electrically conducting two-dimensional natural convective flow of a viscous, steady, incompressible, and radiating fluid through a porous vertical plate with uniform suction in the presence of a uniform strong magnetic field. The current theoretical inquiry is carried out to idealize the mathematical model, the investigation is based on the following basic assumptions.

1. All of the fluid's properties are constant, with the exception of density.
2. The plate has a surface that is electrically insulated.
3. The system is not subjected to any external electrical field.
4. The plate is parallel to the flow of fluid.

Presenting a Cartesian coordinate systems ($\mathbf{x}'$, $\mathbf{y}'$, $\mathbf{z}'$) with $\mathbf{x}'$-axis upward vertical direction along the plate, $\mathbf{y}'$-axis normal to the plate and directed into the fluid region, and $\mathbf{z}'$-axis along the plate's width, and the induced magnetic field is insignificant. The physical model of the problem is shown in Figure 1.

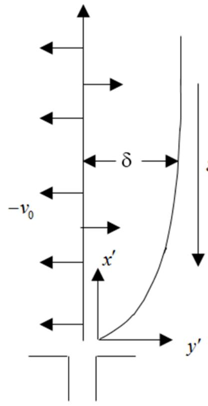

Figure 1. Physical Configuration of the problem.

Cogley *et al.* [24] demonstrated that the following form represents the radiative heat flux for a Gray gas near equilibrium in the optically thin limit:

$$\frac{\partial q_r}{\partial y'} = 4(T - T_\infty)I. \tag{8}$$

Where $I = \int K_{\lambda w} \frac{\partial e_{b\lambda}}{\partial T^*} d\lambda$, is the wall absorption coefficient, and $e_{b\lambda}$ is the Planck's function.

Given by Equation (7), the preceding principles, and the normal boundary layer approximations, the basic equations take the following forms:

$$\frac{\partial v'}{\partial y'} = 0 \tag{9}$$

$$v'\frac{\partial u'}{\partial y'} = g\beta(T - T_\infty) + g\bar{\beta}(C - C_\infty) + \vartheta\frac{\partial^2 u'}{\partial^2 y'} - \frac{\sigma B_o{}^2 u'}{\rho} - \frac{\vartheta u'}{K'}, \tag{10}$$

$$\rho C'_p\frac{\partial T}{\partial y'} = k\frac{\partial^2 T}{\partial^2 y'^2} + \mu\left(\frac{\partial u'}{\partial y'}\right) + \sigma B_o{}^2 u'^2 - \frac{\partial q_r}{\partial y'} - Q'(T - T_\infty) - \frac{\mu}{k'}u^2, \tag{11}$$

$$v'\frac{\partial C}{\partial y'} = D'_M\frac{\partial^2 C}{\partial^2 y} + \bar{k}C(C_\infty - C). \tag{12}$$

The boundary conditions that are relevant are

$$y' = 0:\ u' = U,\ \frac{\partial T}{\partial y'} = -\frac{q^*}{k},\ C = C_w, \tag{13}$$

$$y' \to \infty:\ u' \to 0,\ T \to T_\infty,\ C \to C_\infty. \tag{14}$$

Equation (9) gives,

$$v' = \text{a constant} = -V_o(V_o > 0). \tag{15}$$

The following non-dimensional parameters are introduced

$$y = \frac{v_o y'}{v}, u = \frac{u'}{U}, \theta = \frac{T - T_\infty}{\frac{q^* v}{k v_o}}, \varphi = \frac{(C - C_\infty)}{C_w - C_\infty},\ G_r = \frac{v^2 g\beta q^*}{kUv_o{}^3}, E = \frac{\rho U^2 v_o}{q^*},\ P_r = \frac{\mu C_p}{k},$$

$$K_c = \frac{\bar{k}c\vartheta}{v_o{}^2},\ G_m = \frac{g\bar{\beta}\,\vartheta}{Uv_o{}^2}(C_w - C_\infty),\ S_c = \frac{\vartheta}{D_M},\ M = \frac{\sigma B^2{}_o\vartheta}{\rho v_o{}^2},\ R = \frac{4\vartheta I}{\rho C_p v_o{}^2 q^*},\ \ Q = \frac{Q'\vartheta}{\rho v_o{}^2 C_p}.$$

The governing equations in dimensionless form are as follows:

$$\frac{d^2 \mathrm{u}}{dy^2} + \frac{du}{dy} - \lambda\, u = -\, G_r\theta - G_m\varphi, \tag{16}$$

$$\frac{d^2\theta}{dy^2} - P_r\frac{d\theta}{dy} - \lambda_1\theta = -\mathrm{E}\left(\frac{du}{dy}\right)^2 - \mathrm{EMu}^2 - \frac{E}{K}u^2, \tag{17}$$

$$\frac{d^2\varphi}{dy^2} + S_c\frac{d\varphi}{dy} - \lambda_2\,\varphi = 0\,. \tag{18}$$

Where, $\lambda = M + \frac{1}{K}$, $\lambda_1 = P_r\,(R+Q)$, and $\lambda_2 = S_c K_c$, with boundary conditions

$$y = 0 : \; u = 1, \; \frac{\partial \theta}{\partial y} = -1, \; \varphi = 1, \tag{19}$$

$$y \to \infty : u \to 0, \; \theta \to 0, \; \varphi \to 0. \tag{20}$$

METHOD OF SOLUTION

In this paper, the numerical method "MATLAB built-in bvp4c solver technique" is used to solve the ordinary differential equations [(16)-(18)] along with the boundary conditions [(19), (20)].

The set of boundary ordinary differential equations are converted into a set of first order differential equations as follows:

Let,

$$u = y(1), u' = y(2), \theta = y(3), \theta' = y(4), \varphi = y(5), \varphi' = y(6).$$

Next, we have the set of first order differential equations shown below:

$$\begin{aligned} y'(2) &= -y(2) + \left(M + \frac{1}{K}\right) - Gr\,y(3) - Gm\,y(5) \\ y'(4) &= \Pr y(4) + \Pr\left(R+Q\right)y(3) - E\,y(2)y(2) - M\,Ey(1)y(1) - \left(\frac{E}{K}\right)y(1)y(1) \\ y'(6) &= -Sc\,y(6) + Sc\,Kc\,y(5) \end{aligned} \tag{5}$$

The resulting ordinary differential equations' boundary conditions can be reduced to the following forms

$$y0(1)-1, \;\; y0(4)+1, \;\; y0(5)-1, \;\;\; y1(1)-1, \;\; y1(3)-0, \;\; y1(5)-0\,.$$

RESULT AND DISCUSSION

In this paper, the effect of the parameters as magnetic parameter M, thermal radiation R, heat sink Q thermal Grashof number G_r, solutal Grashof number G_m, Prandtl number P_r, chemical reaction parameter K_c, Schmidt number S_c on the velocity u, temperature field θ and concentration field φ have been studied and shown by means of graphs. The graphs of velocity, temperature and concentration are taken with respect to y. The Prandtl number P_r is set to 0.71, which corresponds to air at 290K and 1 atm. Moreover, we have taken Eckert number E = 0.001, S_c = 0.90, P_r = 0.71, K_c = 2, K=1, M = 10, R = 5, Q = 5, G_r = 10, G_m = 10.

Velocity profiles: The velocity profiles are depicted in Figures 2-8. Figure-2 shows that the fluid velocity decreases with the increase of magnetic parameter M. Figure 2 illustrates that as the magnetic parameter increases, the velocity profile decreases. This phenomenon occurs because the magnetic field generates a Lorentz force that opposes the fluid motion, leading to a reduction in fluid velocity. Therefore, the velocity decreases with an increase in the magnetic field strength. Figure 3 demonstrates the influence of the thermal radiation parameter on the velocity profile. It is evident that as the radiation parameter increases, the velocity of fluid particles decreases. This behavior can be attributed to the fact that increased radiation leads to enhanced heat transfer, causing a reduction in fluid velocity.

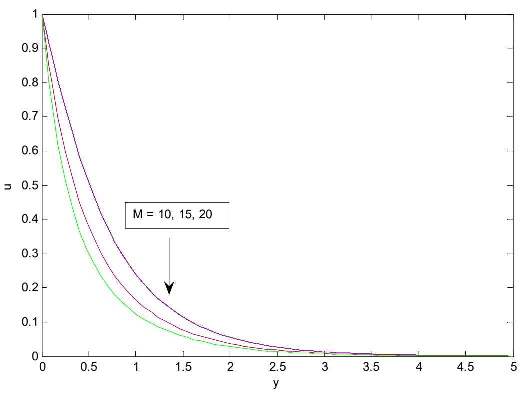

Figure 2. Velocity *u* versus *y* for the variation M

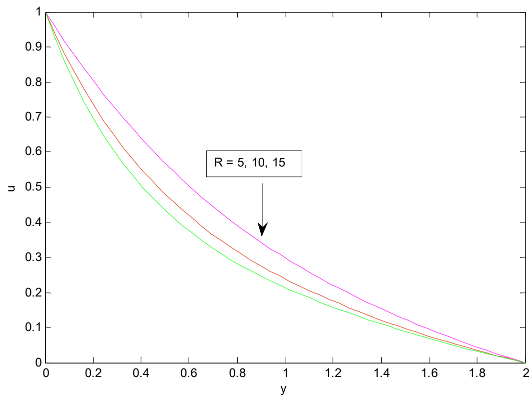

Figure 3. Velocity *u* versus *y* for the variation R

Figure-4 shows the impact of heat sink on velocity profile. It is observed that the fluid velocity decreases with the increase of heat sink Q. Figure-5 shows how fluid velocity changes with thermal Grashof number G_r. It is observed that as the thermal Grashof number increases, the velocity profile also increases. This can be explained by the fact that an increase in Grashof number corresponds to an increase in temperature gradients, which in turn leads to an augmentation in the velocity distribution within the flow.

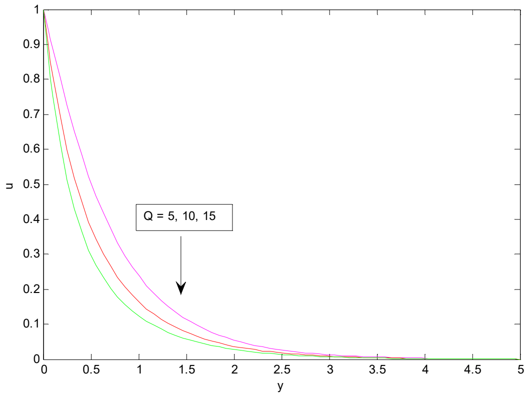

Figure 4. Velocity u versus y for the variation Q

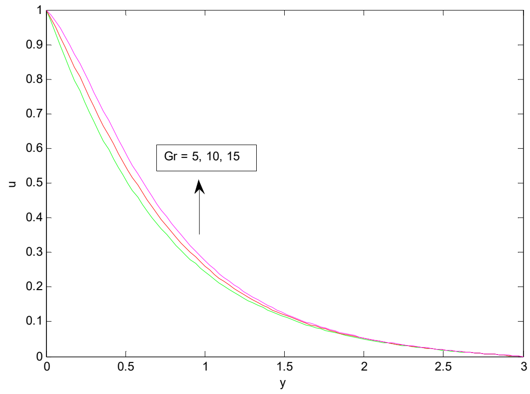

Figure 5. Velocity u versus y for the variation G_r

Figure-6 shows the impact of solutal Grashof number G_m on the fluid velocity. It is observed that the fluid velocity increases with G_m. The velocity field increases significantly due to the thermal and solutal buoyancy forces. This is caused by the direct correlation between buoyant force and Grashof numbers. Figure-7 depicts the effect of Prandtl number P_r on velocity profile. It is seen that an elevation in the Prandtl number P_r is directly associated with a decrease in the fluid velocity. This can be attributed to the nature of higher Prandtl numbers leading to weakened convection currents, thereby qualitatively diminishing the temperature gradients and ultimately resulting in a decreased fluid velocity. In Figure 8, it can be observed that the fluid velocity increases as the porosity parameter rises. This phenomenon occurs because higher porosity values, provide the fluid with more space to flow. As a result, the fluid velocity experiences an increase.

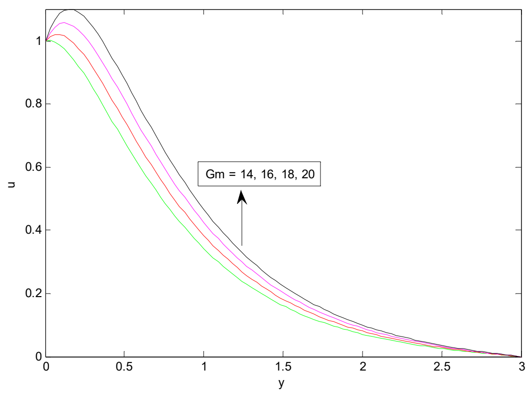

Figure 6. Velocity u versus y for the variation G_m

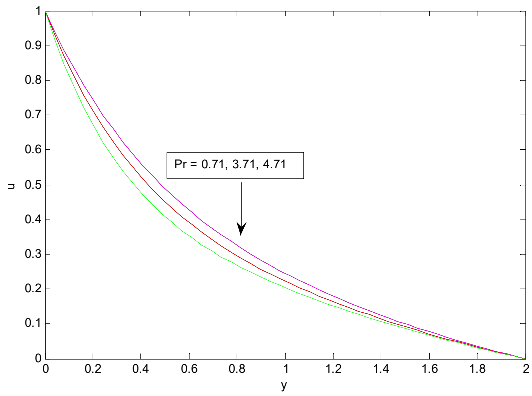

Figure 7. Velocity u versus y for the variation P_r

Temperature Profile: The temperature profiles are depicted in Figures 9-11. Figure-9 demonstrates how temperature profile changes with heat sink Q. It is observed that the temperature decreases with the increase in Q. Figure 10 demonstrates that the temperature decreases as the Prandtl number increases. This behavior is attributed to the reduction in the thermal diffusivity of the fluid with higher Prandtl numbers. As a consequence, the thermal boundary layer thickness is diminished, leading to the observed decrease in temperature. The impact of the radiation parameter on the temperature profile is depicted in Figures 11. The trend observed indicates that as the radiation parameter increases, the temperature of the fluid decreases.

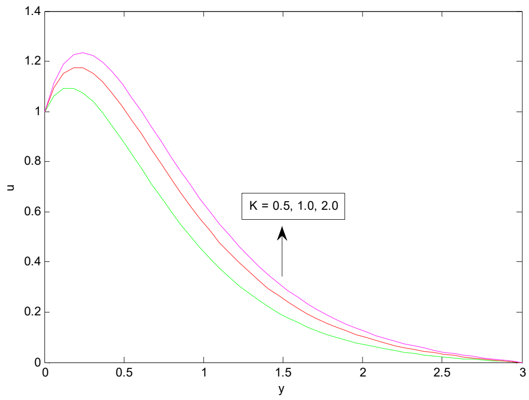

Figure 8. Velocity u versus y for the variation K

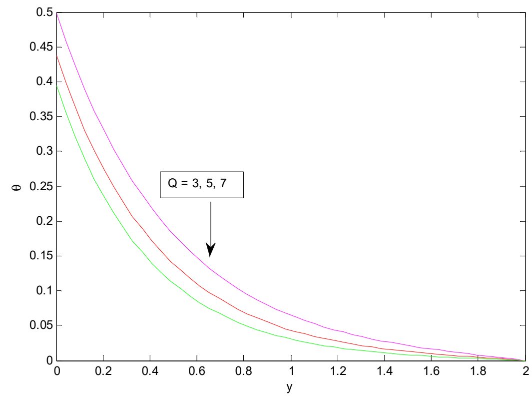

Figure 9. Temperature $\boldsymbol{\theta}$ versus y for the variation Q

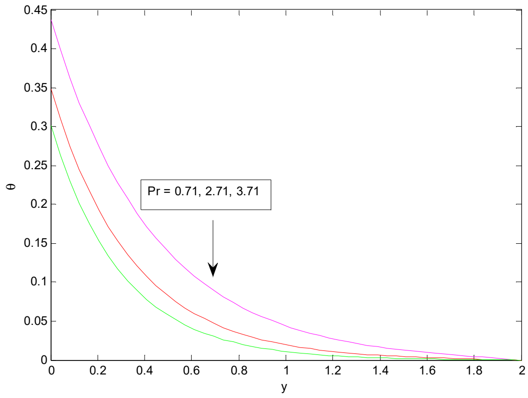

Figure 10. Temperature θ versus y for the variation P_r

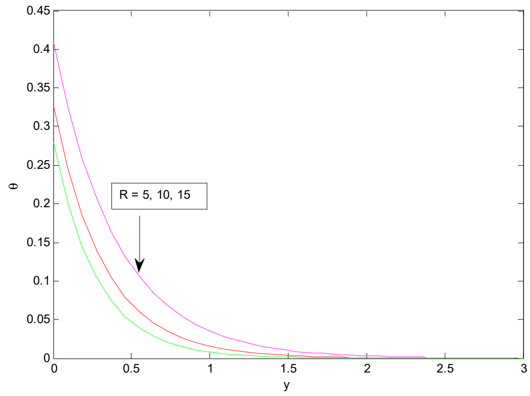

Figure 11. Temperature θ versus y for the variation R

Concentration Profile: The concentration profiles are depicted in Figures12-13. Figure-12 depicts how concentration profile changes with Schmidt number $\mathbf{S_c}$. It can be inferred that an increase in the Schmidt number corresponds to a decrease in solute diffusivity, leading to a shallower penetration of solutal effects. Consequently, the concentration decreases with an increase in the Schmidt number. Figure-11 shows how fluid concentration changes with chemical reaction parameter K_c .The concentration profile slows down with an increase in K_c. This effect is logical as higher values of the chemical reaction parameter lead to a decrease in the molecular diffusivity of the chemical species.

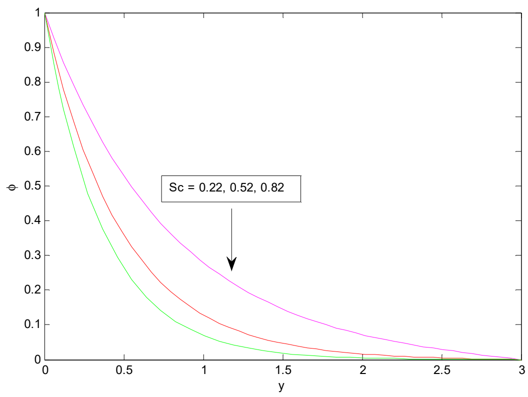

Figure 12. Concentration φ versus y for different S_C

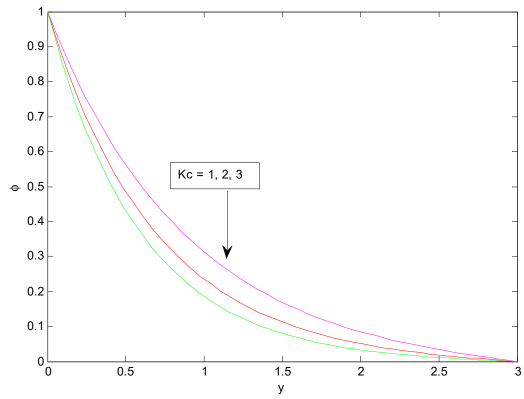

Figure 13. Concentration φ versus y for different K_c

CONCLUSIONS

In this study, the impact of radiation and heat dissipation on magnetohydrodynamic (MHD) convective flow in the presence of a heat sink has been examined. The governing equations were numerically solved to obtain velocity, temperature, and concentration profiles, utilizing the MATLAB built-in bvp4c solver technique. The key findings of this investigation can be summarized as follows:

1. The transverse magnetic field's imposition causes fluid velocity to be delayed.
2. Thermal radiation consistently shows a propensity to reduce the atmosphere's temperature.
3. The plate's fluid concentration decreases as a result of decreased mass diffusivity.
4. The concentration of species decreases as a result of species eating.
5. With the use of a strong magnetic field in operation, the frictional resistance can be successfully inhibited.
6. As the porosity parameter increases, there is a corresponding increase in the fluid velocity.

Nomenclature

$\vec{q}$	Fluid velocity	U	Velocity of free stream
ρ	Fluid density	K	Porosity parameter
ϑ	Kinematic viscosity	q^*	Heat flux
$\vec{J}$	Current density	$\vec{q}_r$	Radiation heat flux
$\vec{g}$	Acceleration vector due to gravity	T	Fluid temperature
$\vec{B}$	Magnetic flux density vector	C	Concentration
k	Thermal conductivity	C_w	Plate species concentration
k^*	Mean absorption coefficient	E	Eckert number
φ	Energy viscous dissipation per unit volume	C_∞	Free stream concentration
p	Fluid pressure	σ	Electrical conductivity

$\vec{E}$	Electrical field
B	Thermal expression coefficient
$\bar{\beta}$	Solutal expansion coefficient
T_∞	Free stream concentration
C_∞	Free stream concentration
B_0	Applied magnetic field strength
M	Viscosity coefficient
Θ	Non-dimensional temperature
Φ	Non-dimensional concentration
P_r	Prandtl number
Q	Heat sink
S_c	Schmidt number
G_r	Thermal Grashof number
M	Magnetic parameter
G_m	Solutal Grashof number
R	Radiation

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ВПЛИВ ВИПРОМІНЮВАННЯ ТА РОЗСІЮВАННЯ ТЕПЛА НА МГД КОНВЕКТИВНИЙ ПОТІК ЗА НАЯВНОСТІ ТЕПЛОВІДВОДУ

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У статті розглядається тепломасообмін у МГД-конвективному потоці через вертикальну пористу пластину за наявності випромінювання, тепловідводу та розсіювання тепла. Сильне магнітне поле прикладене перпендикулярно до пластини і спрямоване в область рідини. Керівні безвимірні рівняння розв'язуються за допомогою вбудованого в MATLAB методу вирішувача bvp4c. Результати обчислюються за допомогою математичного програмного забезпечення, а вплив різних безрозмірних параметрів, що входять у задачу, на профілі швидкості, температури та концентрації відображається в графічних форматах. Було відзначено, що застосування магнітного поля сповільнює швидкість рідини. Крім того, як ефект теплового випромінювання, так і число Прандтля повністю застосовні до температури рідини. Важливо зауважити, що радіатор різко знижує температуру та швидкість рідини. Поточна робота використовується в багатьох реальних програмах, таких як хімічна інженерія, промислові процеси, система може містити кілька компонентів, кожна з яких концентрація змінюється від однієї точки до іншої в ряді різних обставин.

Ключові слова: *тепломасообмін; МГД; розсіювання тепла; пористе середовище; bvp4c*