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Time-dependent hydromagnetic convective transport upon a vertical perforated sheet with heat production and viscous dissipation effects

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ABSTRACT

This research analysed the theoretical influences of viscous dissipation and heat production on an unstable hydromagnetic free convective transference upon a vertical porous sheet. The converted conservation equations are resolved numerically with suitable boundary conditions by exerting the similarity techniques. Then the coupled ODEs is resolved by inserting the finite difference method (FDM). The influences of the working dimensionless numbers or parameters on the flow, concentration and temperature fields, the mass transmission rate, the coefficient of local skin friction, and the heat transmission rate examined and discussed quantitatively with the aid of graphs. The findings show that as the Eckert number rises, the temperature and fluid velocity both advance along with the heat generation parameter. The f′(0) increases by around 8% and 12% due to uprising amounts of the heat generation parameter from 1.0 to 2.0, and the Eckert number from 0.5 to 2.5, respectively. Growing amounts of the heat generation parameter from 1.0 to 2.0 and Eckert number from 0.5 to 2.5, the heat transmission rate lessens by around 63% and 52%, respectively. The comparable outcomes are good coincided with a published article.

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KEYWORDS
Heat generation; MHD; permeability; heat and mass transfer; viscous dissipation

Nomenclature

MHD	Hydromagnetic
C	fluid concentration
T_w	wall temperature
g	acceleration due to gravity
C_w	wall concentration
C_∞	free stream concentration
k	thermal conductivity
v(t)	suction velocity
D_m	mass diffusivity coefficient
k_T	thermal diffusion ratio
σ	similarity parameter
G_r	local Grashof number
M	Magnetic force parameter
Df	Dafour number
Sc	Schmidt number
τ	Shear stress
S_h	Sherwood number
$\theta(\eta)$	non-dimensional temperature
Ec	Eckert number
Q	internal heat production/absorption parameter
$f'(0)$	local skin friction coefficient
u	velocity component in the *x*-axis
FDM	Finite difference method
T	the temperature of the fluid
B	uniform magnetic field
ρ	fluid density
T_∞	free stream temperature
υ	kinematic viscosity
C_p	specific heat at constant pressure
$U_0(t)$	uniform surface velocity
T_m	fluid mean temperature
C_s	concentration susceptibility
v_0	suction and blowing
G_m	modified local Grashof number
Pr	Prandtl number
Sr	Soret number
t	Time
N_u	Nusselt number
$f(\eta)$	non-dimensional velocity
$\phi(\eta)$	non-dimensional concentration
Q_0	dimensional heat production/absorption coefficient
$\theta'(0)$	heat transfer rate
$\phi'(0)$	mass transfer rate
v	velocity component in the *y*-axis,

1. Introduction

Hydromagnetic (MHD) free convective flow has devoted a lot of studies owing to its applications in numerous engineering sites in plasma studies, storage of radioactive nuclear waste materials, boundary layer flow control, cooling of electronic components, boundary layer flow control, and MHD generators and pumps. A lot of technological problems and natural phenomena are amenable to MHD analysis. Geophysics encounter MHD properties in the interactions of magnetic fields and conducting fluids. Engineers use MHD principles in the design of flow metres and heat exchange pumps, thermal protection,

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in creating naval power generating systems, in space vehicle propulsion, and braking etc. From a technical perspective, MHD convection flow problems are also of great importance in planetary magnetospheres and stellar, electronics, aeronautics, and chemical engineering. The application of MHD principles in biology and medicine are of paramount interest due to their significance in bio medical engineering in general and in the treatment of various pathological state in particular. Applications in biomedical engineering include ECG, cardiac MRI, etc. MHD is also utilised in stabilising a flow against the transition from laminar to turbulent flow and in the reduction of turbulent drag and suppression of flow separation. Some model studies of the above phenomena of MHD convection have been made by many. Many researchers (Ahmed, Sarmah, and Kalita 2011; Aldoss et al. 1995; Cramer 1963; Gupta 1962; Hasanuzzaman, Azad, and Hossain 2021; Helmy 1998; Hossain 1986; Kim 2000; Kuiken 1970; Pop 1969; Takhar, Roy, and Nath 2003; Wilks 1976) have been studied in this fields. Primarily, Pavlov (1974) the hydromagnetic fluid movement imposed to the deformity of the sheet. The lesson of heat production or absorption effect on heat pathway is very important due to these influences are conclusive in the heat transfer. Many researchers have examined the effect of heat- producing or heat-absorbing fluids for different flow regimes. Taiwo and Dauda (2019) investigated the time-dependent flow of MHD heat absorbing or generating viscous fluid. These results reported that improving the heat production parameter resulted in an improvement in temperature and thus enhanced the motion. Besides, an opposite characteristic is found in a fluid which absorbs heat. The role of uniform heat production or absorption on the natural convective movement of hydromagnetic fluid crossing by annular gap shaped by two cylinders has been explored by Gambo et al. (2021).

For all fluid properties, viscosity needs to be considered the most in the research of fluid flow. L Prandtl (1904) analysed a field of fluid dynamics by taking into account viscosity and in this way combining theoretical hydraulics and hydrodynamics in the twentieth century. The effect of such heat dissipation terms on a time-dependent state is often neglected. The role of the viscous dissipation function may not be ignored from a practical side as it is important in various flow problems. The predominance of heat dissipation on the temperature field is relatively small for much lower velocity methods. A dynamic temperature-related approach cannot ignore the impact of viscous dissipation which is comparable to the temperature difference. The theory of boundary layer has been used to explore the heat dissipation influence for both compressible and incompressible flows. Fonsho (2004) investigated the influences of the dissipation role upon the unstable MHD radiating gas movement past a vertical plate. The role of fixed transpiration on an unstable free convection elastics' viscous fluid motion upon a porous sheet was analysed by Sen (1977). Uwanta, Isah, and Ibrahim (2011) studied the impact of heat dissipation on viscoelastic fluid motion on an infinite sheet. The influences of heat dissipation on the mixed convective transport of heat-producing or absorbing fluid with the wall conduction were theoretically studied by Ajibade and Umar (2019). In very recent time, Hasanuzzaman et al. (2023) deliberated the roles of Eckert number and thermal radiation on unstable MHD conductive transport across a vertical porous plate.

Many researchers have hypothesised that free convection flows happen in nature as well as in engineering practice which is very broad due to their usages in engineering, industry, and geosciences like gas-particle trajectories, foam hydrology, combustion, turbine blades, and petrology. The circulation potential is very complex in nature when heat-mass transmission occur concurrently within the flux. In addition to mass gradients, temperature gradients also contribute to energy flux. The temperature gradients may supply mass fluxes. We refer to this as thermal diffusion or Soret influence. The heat fluxes occured from the concentration gradients. We refer to this as the mass diffusion or Dufour influence. In a changeable permeability medium, Postelnicu (2004) investigated the impact of mass and heat diffusion on an unstable MHD free convective fluid motion on a vertical sheet. The implications of the Dufour and Soret on the mixed convection fluid flow on a vertical porous sheet in a permeable medium were examined by Alam and Rahman (2006). Kumar, Goud, and Malga (2020) examined the impact of thermal-diffusion upon MHD free convective transference flowing over a porous plate that is moving vertically. Gangadhar, Shashidhar Reddy, and Wakif (2023) focused the effect of the thermal characteristics on the magnetised hybrid nanofluids and the wall jet fluid flow through the moving flat surface. The free convection flow phenomenon on magnetised second-grade nanofluid over a nonlinear elongating surface has been modelled by Gangadhar, Sujana Sree, and Thumma (2024) under the assumptions of generalised Fick's and Cattaneo–Christov heat flux relations. Reddy et al. (2022) investigated the effects of thermal radiation and viscous dissipation on the bioconvection MHD stream of Maxwell nanoliquid including nanoparticles and gyrotactic microorganisms. The flow and heat transport impacts of copper-water and titania-water nanofluid with nanoparticles aggregation has been examined by Swain et al. (2023). In very recent time, Hasanuzzaman, Ahamed, and Miyara (2022) and Hasanuzzaman, Sharin et al. (2022) explored Hasanuzzaman, Azad, and Hossain (2021) study by taking chemical reactions and, radiative and heat production, respectively. Now, we prolonged Hasanuzzaman, Azad, and Hossain (2021) and Hasanuzzaman, Sharin et al. (2022) by addition of the additional term which is viscous dissipation.

According to the above literature reviews, we focus our attention to discuss the influences of heat production or absorption, and Eckert number on unstable MHD convective transmission past a upright permeable plate. The main innovation of this investigation is further prolonged by assuming the heat absorption or generation and the Eckert number under the FDM which is not investigated yet. The comparison of the current results with a earlier available article is one more novel feature of this paper. The numerical result is obtained graphically by using the FDM with the shooting technique in MATLAB software. The tabular representations additionally include the mass transmission rate, the local skin friction coefficient, and the heat transmission rate.

2. Model and governing equations

It is supposed that there is an incompressible, viscous, electrically conducting fluid flowing in an unsteady 2D hydromagnetic convective boundary layer over a vertical permeable plate

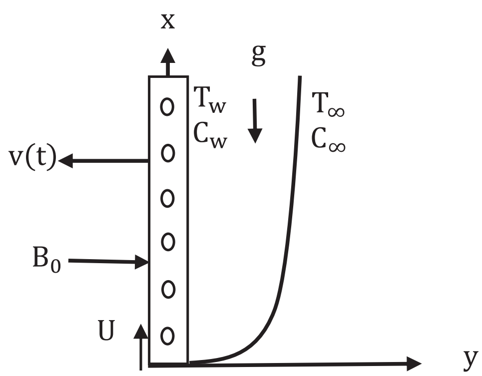

Figure 1. The coordinates system along with flow configuration.

immersed in a permeable medium. The plate is placed across the *x*-axis. The vertical porous plate and the free-stream velocity are thought to be parallel. It is believed that the vertical porous sheet is normal along the y-axis. A uniform magnetic field of strength $\mathbf{B} = (0, B_0)$ is applied transversely along the flow. Here, C_w and T_w respectively represent the fluid concentration and temperature at the wall. For $t > 0$, the perforated surface inaugurates passing emotively with velocity U in its proper surface. We believe there is an infinite permeable plate. Consequently, $\frac{\partial u}{\partial x} \to 0$ as $x \to \infty$. The fluid velocity vector is hence $\mathbf{q} = u(y, t)\mathbf{i} + v(y, t)\mathbf{j}$. The fluid density remains uniform throughout the whole simulation, based on the Boussinesq approximation. Figure 1 shows the coordinates system along with flow configuration.

From the above concept, the fluid is govern by the following equations.

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

$$\frac{\partial u}{\partial t} + v\frac{\partial u}{\partial y} = \upsilon\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) - \left(\frac{\sigma' B_0^2}{\rho} + \frac{\upsilon}{K}\right)u + g\beta^*(C - C_\infty) - \frac{b}{K}u^2 \tag{2}$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y} = \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} + \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} - \frac{\upsilon}{\rho c_p}\left(\frac{\partial u}{\partial y}\right)^2 + \frac{Q_0}{\rho C_p}(T - T_\infty) \tag{3}$$

$$\frac{\partial C}{\partial t} + v\frac{\partial C}{\partial y} = D_m\frac{\partial^2 C}{\partial y^2} + \frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

The associate boundary conditions are given by

$$u = U(t),\ T = T_w,\ C = C_w,\ v = v(t)\ \text{at}\ y = 0 \tag{5}$$

$$u = 0,\ T \to T_\infty,\ C \to C_\infty,\ v = 0\ \text{at}\ y \to \infty \tag{6}$$

where kinematic viscosity is υ, fluid temperature is T, the fluid density is ρ, wall temperature is T_w, the velocity component in the y-axis is v, wall concentration is C_w, thermal conductivity is k, the velocity component in the x-axis is u, dimensional heat production or absorption coefficient is Q_0, thermal diffusion ratio is k_T, the permeability of the porous plate is K, the fluid mean temperature is T_m, mass diffusivity coefficient is D_m, T_∞ is the fluid temperature in the free stream, fluid concentration is C, and gravitational acceleration is*g*.

We utlised the similarity parameter as.

$$\sigma = \sigma(t) \tag{7}$$

where σ denotes the unstable length scale.

The following solution in terms of σ is found from the Equation (1):

$$v = -v_0\frac{\upsilon}{\sigma} \tag{8}$$

At the porous plate, the dimensionless normal velocity is v_0. When $v_0 < 0$ then the blowing is happened and when $v_0 >$ 0then the suction is happened in the computational domain.

The similarity variables are:

$$\eta = \frac{y}{\sigma},\ f(\eta) = \frac{u}{U},\ \phi(\eta) = \frac{C - C_\infty}{C_w - C_\infty},\quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty} \tag{9}$$

By taking into account the previously mentioned Equations (7)–(9), the Equations (1)–(4) are transformed into the subsequent dimensionless coupled ODEs:

$$f''(\eta) + 2\xi f'(\eta) + G_r\theta(\eta) + G_m\phi(\eta) - Mf(\eta) - \frac{ReFs}{Da}f^2(\eta) - \frac{1}{Da}f(\eta) = 0 \tag{10}$$

$$\theta''(\eta) + Pr\{2\xi\,\theta'(\eta) - Ec\,(f'(\eta))^2 + Df\,\phi''(\eta) + Q\,\theta(\eta)\} = 0 \tag{11}$$

$$\phi''(\eta) + 2\xi Sc\phi'(\eta) + ScSr\theta''(\eta) = 0 \tag{12}$$

The converted boundary conditions are:

$$\theta(\eta) = 1,\ f(\eta) = 1,\ \phi(\eta) = 1 \quad \text{at}\ \eta = 0 \tag{13}$$

$$\theta(\eta) = 0,\ f(\eta) = 0,\ \phi(\eta) = 0 \quad \text{as}\ \eta \to \infty \tag{14}$$

where Magnetic force parameter is $M = \frac{\sigma' B_0^2\sigma^2}{\rho\upsilon}$, Schmidt number is $S_c = \frac{\upsilon}{D_m}$, local Grashof number is $Gr = \frac{g\beta(T_w - T_\infty)\sigma^2}{U_0\upsilon}$, Prandtl number is $Pr = \frac{\rho\upsilon C_p}{k}$, $Da = \frac{K}{\sigma^2}$ is the Darcy number, Soret number is $Sr = \frac{D_m k_T(T_w - T_\infty)}{\upsilon T_m(C_w - C_\infty)}$, the Reynolds number is $Re = \frac{U\sigma}{\upsilon}$, thermal radiation parameter is $R = \frac{16\sigma^* T_W^2}{3K^* K}$, $Gm = \frac{g\beta^*(C_w - C_\infty)\sigma^2}{U_0\upsilon}$ is the modified local Grashof number, the Dufour number is $D_f = \frac{D_m k_T(C_w - C_\infty)}{C_s C_p\upsilon(T_w - T_\infty)}$, the Forchheimer number is $Fs = \frac{b}{\sigma}$, and $\xi = \eta + \frac{v_0}{2}$, and $Q = \frac{Q_0}{\rho C_p}$ is the internal heat generation or absorption parameter,

The physical parameters are the shear stress (τ), the local Sherwood number (*Sh*), and the local Nusselt number (*Nu*) which can be written as:

$$\tau \propto f'(0),\ Sh \propto -\phi'(0),\ Nu \propto -\theta'(0), \tag{15}$$

3. Numerical solution

The primary goal of this research is to utilise the Finite Difference Methods (FDM) to the solutions of ODEs (10)–(12), taking into account the boundary conditions (13)–(14). For solving numerous problems, this method has shown to be exact and successful (Ali, Sameh, and Abdulkareem 2010) and (Cheng and Lin 2008). The FDM discretises the solution domain space.

We have taken grid size $\Delta\eta = h > 0$ in η-direction and $\Delta\eta = \frac{1}{N}$, with $\eta_i = ih$, where $i = 0,1,2,\ldots, N$. The term f_i is defined by $f_i = f(\eta_i), \theta_i = \theta(\eta_{i,})$ and $\phi_i = \phi(\eta_i)$.

The numerical quantities of f, θ, and ϕ are F_i, $\Theta_{i,}$ and Φ_i, respectively at the i^{th} node. Hence, we suppose:

$$f'|_i = \frac{f_{i+1} - f_{i-1}}{2h}, \quad \theta'|_i = \frac{\theta_{i+1} - \theta_{i-1}}{2h}, \phi'|_i = \frac{\phi_{i+1} - \phi_{i-1}}{2h} \tag{16}$$

$$f''|_i = \frac{f_{i+1} - 2f_i + f_{i-1}}{h^2}, \theta''|_i = \frac{\theta_{i+1} - 2\theta_i + \theta_{i-1}}{h^2},$$
$$\phi''|_i = \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{h^2} \tag{17}$$

The key step is to discretise the set of ODES (22)–(25) with the aid of FDM. For this, we substitute the Equations (16)–(17) into (10)–(12) and neglect the truncation errors. Hence the resultant algebraic equations produce the following form (where $i = 0,1,\ldots,N$):

$$F_{i+1} - 2F_i + F_{i-1} + \xi h(F_{i+1} - F_{i-1}) + G_r\Theta_i + G_c\Phi_i$$
$$- Mh^2F_i - \frac{F_i}{Da}(1 + ReFsF_i) = 0 \tag{18}$$

$$\Theta_{i+1} - 2\Theta_i + \Theta_{i-1} + Pr[\xi h(\Theta_{i+1} - \Theta_{i-1})$$
$$+ D_f(\Phi_{i+1} - 2\Phi_i + \Phi_{i-1}) - Ec(F_{i+1} - F_{i-1})^2 + Q\Theta_i] = 0 \tag{19}$$

$$\Phi_{i+1} - 2\Phi_i + \Phi_{i-1} + Sc[\xi h(\Phi_{i+1} - \Phi_{i-1}) + S_r(\Theta_{i+1}$$
$$- 2\Theta_i + \Theta_{i-1})] = 0 \tag{20}$$

Also, the boundary conditions are.

$$F_0 = 1,\ \Theta_0 = 1, \Phi_0 = 1, F_N = 0,\ \Theta_N = 0, \Phi_N = 0 \tag{21}$$

The Equations (18)–(20) signify the nonlinear set of algebraic equations in F_i, Θ_i, andΦ_i. In our computation, we use MATLAB program with a good primary solution and the Newton iteration approach.

4. Results and discussions

The unstable hydromagnetic free convective transmission upon a vertical permeable sheet with heat production and viscous dissipation roles has been analysed numerically in this study. The ODEs (10)–(12) are solved numerically by using the FDM. The dimensionless fluid temperature, concentration, and velocity fields for separate amounts of the nodimensional numbers or parameters are exhibited in Figures 2–18. The heat transmission rates $(-\theta'(0))$, the local skin friction coefficient($f'(0)$), and the mass transmission rates $(-\phi'(0))$ are presented in Tables 1–5. The static values of the numbers or parameter are $Ec = 0.5, Gm = 10.0, M = 0.5, Pr = 0.71, Sr = 2.0,\ Sc = 0.22,\ Da = 0.5,\ G = 10.0,\ Df = 0.5$, and $Q = 0.5$.

4.1. Velocity fields $(f(\eta))$

The velocity fields for numerous amounts of the dimensionless numbers or parameters are revealed in Figures 2–11. For improving amounts of the Eckert number (Ec), it is evident from Figure 2

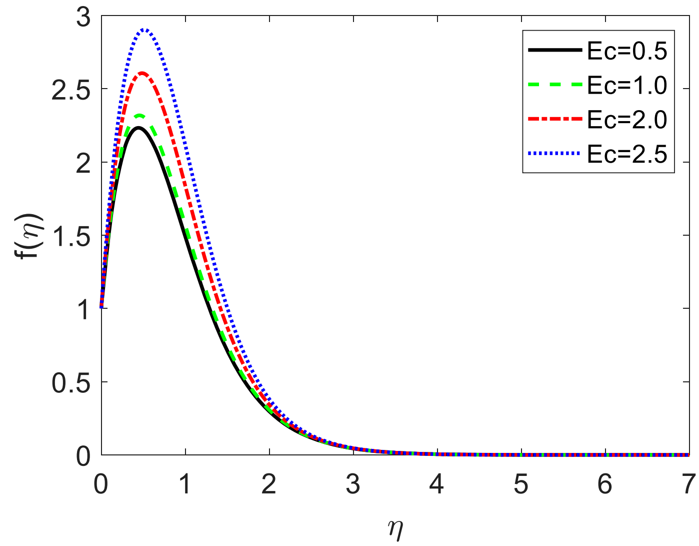

Figure 2. f(η) for Ec.

that f(η) goes up. This is because by including the consequence of Ec, mechanical energy is transferred into thermal energy. So, the fluid becomes thinner and consequently, its velocity is improved. It is noticed from Figure 3 that owing to the generation of heat ($Q > 0$), the buoyancy force enhances which in turn provides higher fluid motions in the border layer. Besides, the buoyancy force reduces causing the fluid motion to diminish for heat absorption ($Q < 0$). The fluid motion goes down when magnetic parameter (M) improves, as shown in Figure 4. That may be inferred from the figure that the velocity of the fluid reduces to rise on this magnetic parameter. This magnetic field acts on the opposition contributed to this magnetic pressure field component by Lorentz force. That noted reduction in the velocity of the fluid by the magnetic field raises because the transverse magnetic field provides the damping or retarding force by this model on Lorentz force. As this value of magnetic parameter develops, this concerning body force improves and this velocity decreases regularly. The importance of this performance by Lorentz force was the frictional resistive force that takes on the fluid motion and regularly decreases this velocity into the fluid flow. Below this scheme, this boundary layer thickness is a massive strong magnetic field. As a consequence, the $f'(0)$ lessens at the wall for rising values of M. This result demonstrates that M can be utilised for regulating the flow. It is found in Figure 5 that the fluid motion retards quickly with the improvement of v_0. This result indicates that the suction attends to obstruct the convective of the fluid motion. The $f'(0)$ reduces for improving values of v_0. The hydrodynamic boundary layer thickness goes down with an improvement of v_0 significantly exhibiting the common fact that suction stagnates the boundary layer growth.

With an enhance in the Darcy Number (Da), the fluid moton improves as shown in Figure 6. The Darcy Number measures the permeabiliity of the plate. As the permeability of the plate improves the values of Da enhance. Therefore, the fluid motion goes up for growing values of Da. This is because the fluid gets larger space to flow for the large permeability of the plate. Thus, the fluid speed exacerbates. The fluid speed enhances due to

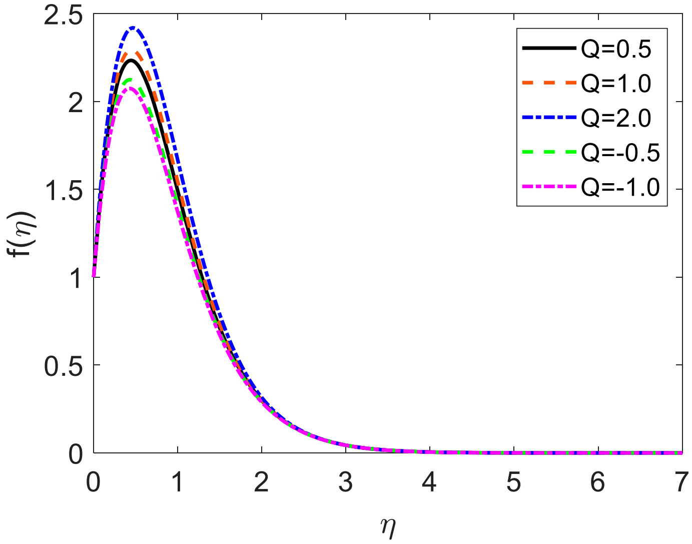

Figure 3. f(η) for Q.

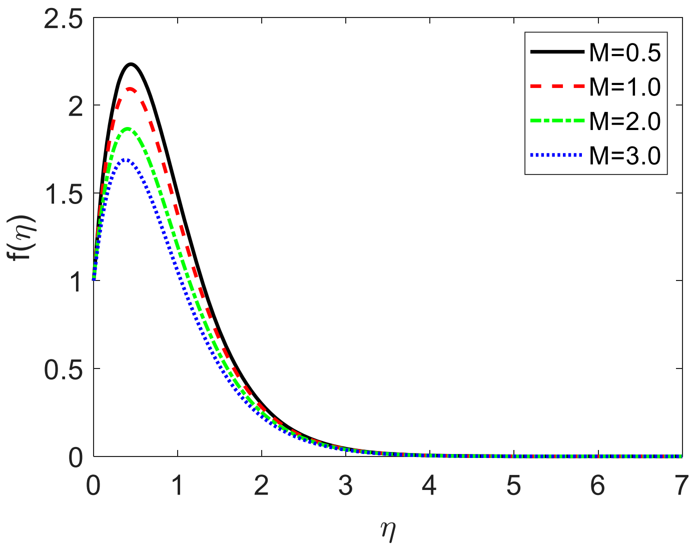

Figure 4. f(η) for M.

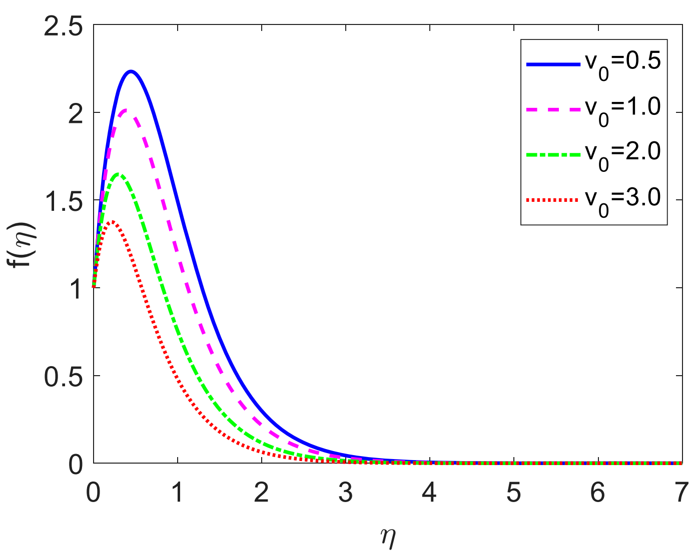

Figure 5. f(η) for v_0.

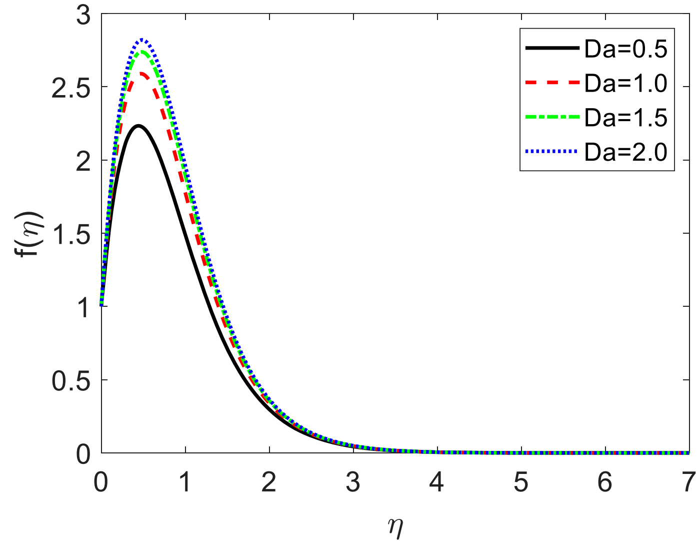

Figure 6. f(η) for Da.

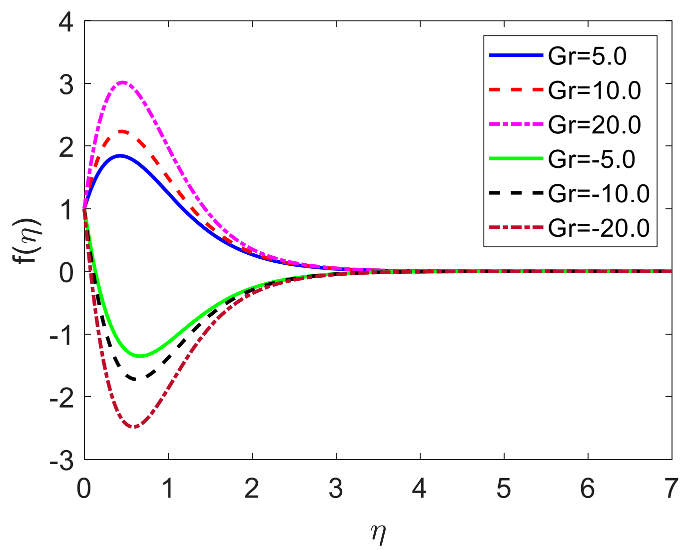

Figure 7. f(η) for Gr.

the increasing the local Grashof number (Gr) as shown in Figure 7. The positive value of Gr $>$ 0 shows the system is heated. It means that increasing values of Gr in the heating plate improves the fluid velocity. The momentum boundary layer diminishes for growing quantities of Gr. We have observed the cooling system for Gr $<$ 0. It means that the cooling plate decays the fluid motion for uplifting values of Gr. The symmetrical shape is found for the combined values of (Gr $>$ 0) and (Gr $<$ 0). The same characteristic is noticed for the local modified Grashof number (Gm) as shown in Figure 8.

The fluid motion goes down for uplifting quantities of Prandtl number (Pr) as revealed in Figure 9. We know that the mathematical relation is $Pr = \frac{\rho \upsilon C_p}{k}$. The Prandtl number directly varies with the kinematic viscosity. The viscous forces tend to improve the buoyancy forces as Pr goes up. These forces produce slow velocity in the boundary layer. That is why, fluid movement is not so easy in the computational area. Hence the fluid motion is observed to lessen and the boundary layer thickness is found

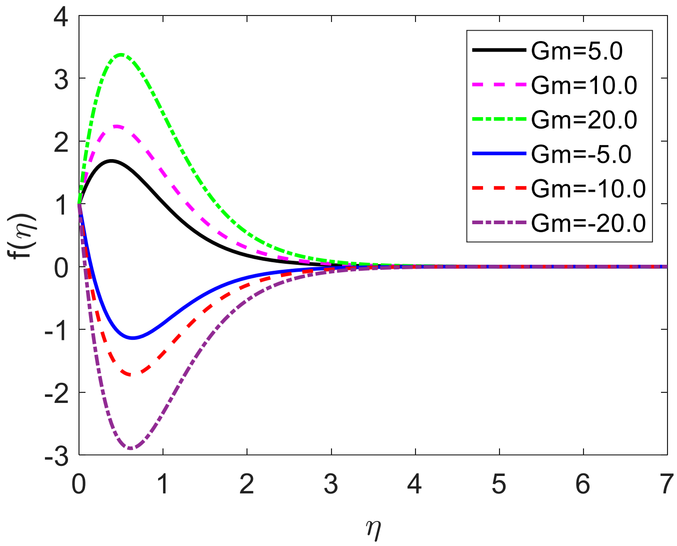

Figure 8. f(η) for Gm.

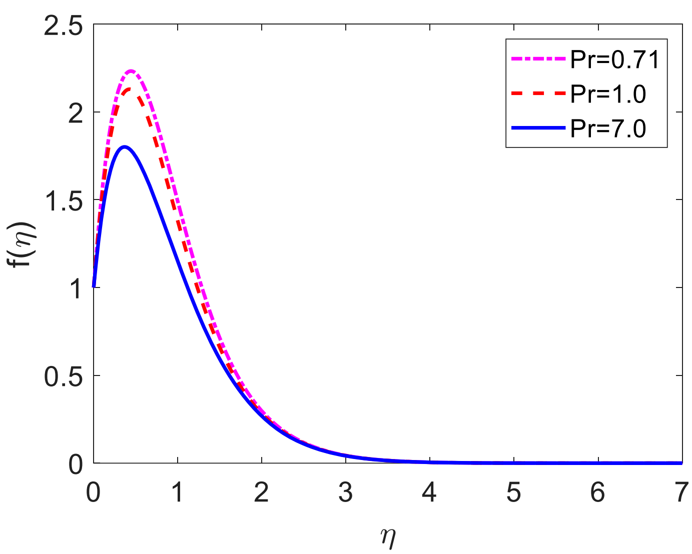

Figure 9. f(η) for Pr.

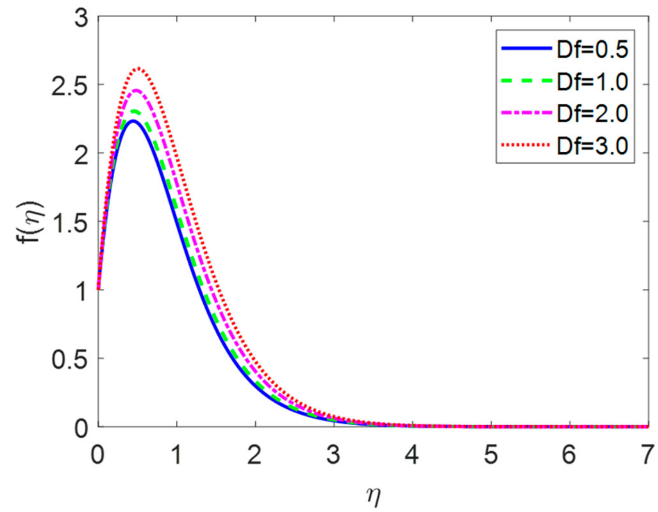

Figure 10. $f(\eta)$ for Df.

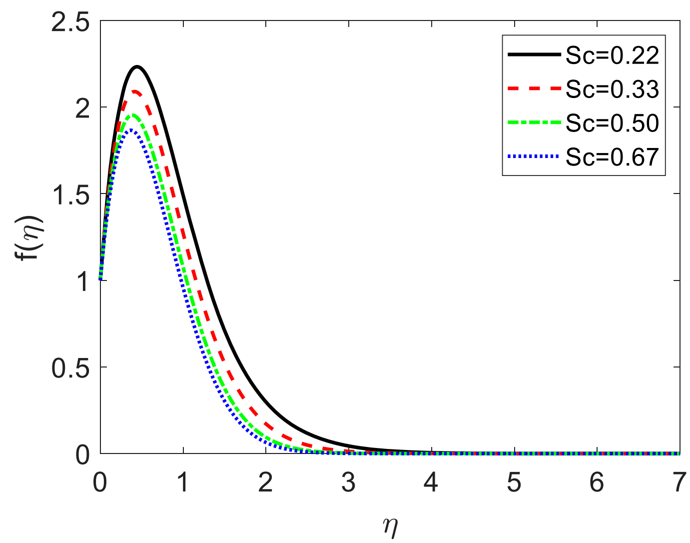

Figure 11. $f(\eta)$ for Sc.

to decay for growing amounts of Pr. This is inferred from Figure 10 that as Df is augmented, the fluid's velocity rise. The Dufour number fluctuates inversely as the kinematic viscosity (μ). The value of μ goes down when Df improves. The kinematic viscosity diminishes means the frictional force reduces. On account of this, the fluid particle moves freely in the domain of computation. Therefore, the fluid speed quickens for upward amounts of Df. With the improve in Schmidt number, the fluid velocity goes down as demonstrated in Figure 11. Since the Schmidt number (Sc) varies with the viscosity. The fluid viscosity enhances the rising values of Sc. The $f'(0)$ goes down as Sc increases.

4.2. Temperature fields

Figures 12–16 depict the impactes of the non-dimensional parameters/numbers upon the temperature distributions. The fluid temperature improves within the border layer with the enhancement in the Eckert number as shown in Figure 12. The Eckert number (Ec) is a significant part of studying the thermal behaviour of fluid flow. Therefore, the thermal border layer becomes denser and lessens heat dissipation. This is because by including the viscous dissipation effect of Ec, the mechanical energy is changed into thermal energy. This thermal energy improves the temperature field. On the fluid, energy yield into increase by Eckert number being on frictional heating that solution on improving the temperature. It is found from Figure 13 that the temperatures do indeed increase as the internal heat generation ($Q > 0$) increases is corroborated in Figure 13. When heat production happens in the fluid, then the fluid temperature will improve in the thermal boundary layer. Usually, the heat production is acting as a heat generator in the system. Therefore, on account of the presence of heat production releases energy or heat to the flow. This type of energy helps to go up the solute and thermal boundary layer thickness. So, the opposite behaviour is found for absorption as portrayed in Figure 13. The heat absorbed from the system is called heat absorption ($Q < 0$). As heat absorption levels improve, the fluid's temperature drops. The Prandtl number (Pr) inversely varies with the

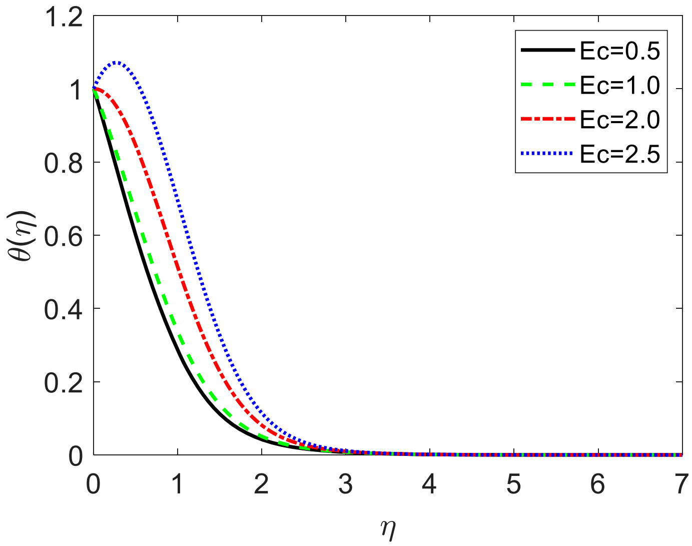

Figure 12. $\theta(\eta)$ for Ec.

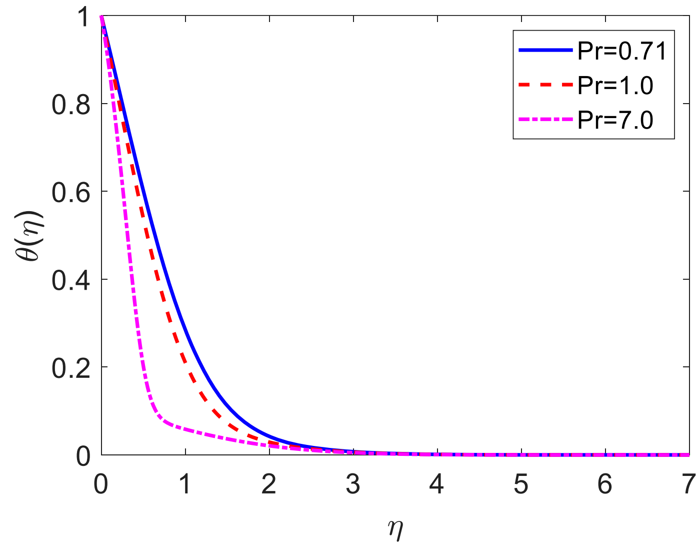

Figure 14. $\theta(\eta)$ for Pr.

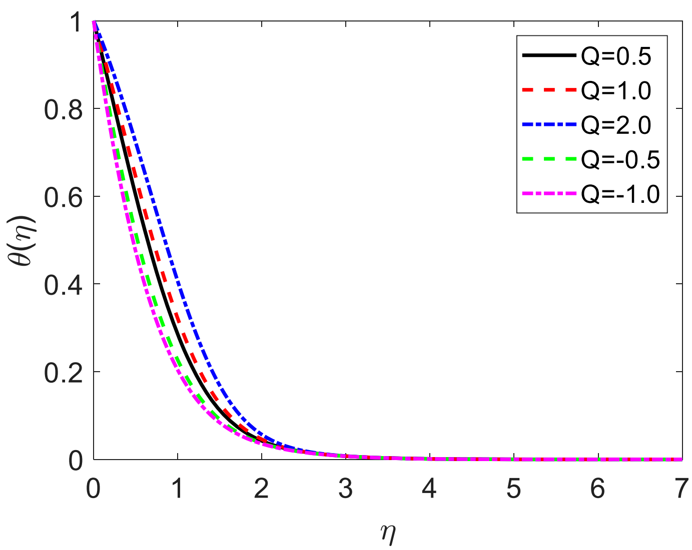

Figure 13. $\theta(\eta)$ for Q.

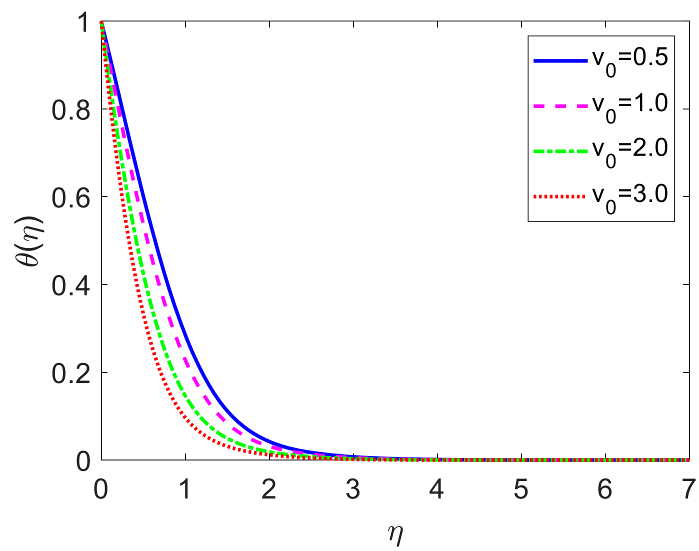

Figure 15. $\theta(\eta)$ for v_0.

thermal diffusion. With an enhancement in Pr, the thermal diffusion lessens. Consequently, the thermal boundary layer gets thinner. Physically, the fluid with a larger Pr gives a higher heat capacity.

This higher heat capacity improves the heat transference rate. Therefore, the temperature of the fluid diminishes for rising quantities of Pr as portrayed in Figure 14. Improving values of the suction parameter (v_0) implies the temperature goes down as depicted in Figure 15. The removal of fluid particles from the computational domain is indicated by the suction. When the fluids are sucked from the domain then the heat transfer rate improved. So, the temperature diminishes for growing quantities of v_0. The suction decayed fluid particles through the perforated plate to reduce the thermal boundary layers. The temperature goes up for growing values of the Dufour number (Df) as plotted in Figure 16. The Dufour number indicates the influence of mass gradient in Equation (3). The Dufour number generates the heat or energy in the movement of fluid. As Df changes, so does the heat conductivity. When Df improves then the rate of heat transmission decays. Therefore, the thermal border layer thickness uplifts significantly in the influence of durable Dufour impacts. So, the fluid temperature improves owing to improving Df.

4.3. Concentration fields

The characteristics of the nondimensional parameters or numbers on the concentration fields are portrayed in Figures 17–18. Figure 17 demonstrates how the suction velocity reduces as the species concentration gets higher. The values $-\phi'(0)$ raise for upward amounts of the suction parameter (v_0). Figure 18 signifies the properties of the various amounts of Schmidt number (Sc) on $\phi(\eta)$. The Schmidt number varies inversely as the molecular (species) diffusivity. Figure 18 reveals that the concentration field goes down for growing amounts of Sc. The allied lessening in the mass diffusivity provides a slight strong mass transmission that diminishes the density gradient. Consequently, the density boundary layer thickness reduces for Sc. This is the reason

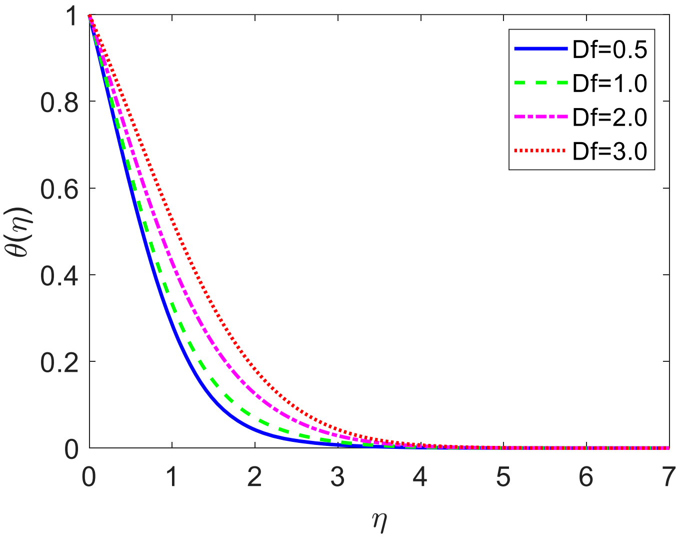

Figure 16. $\theta(\eta)$ for Df.

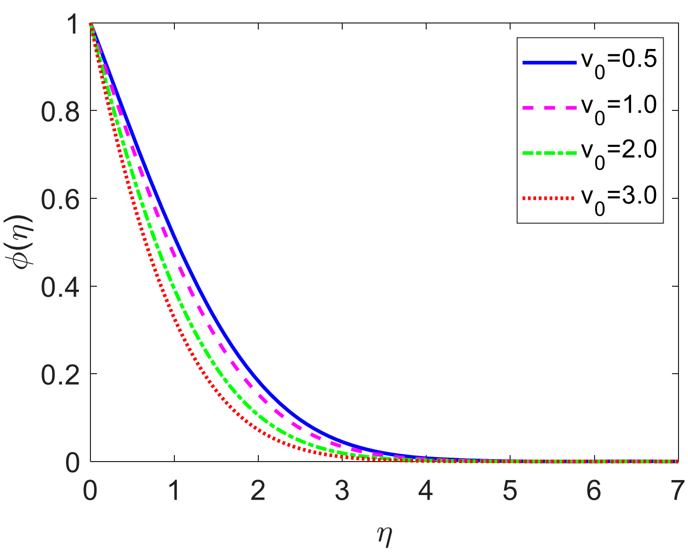

Figure 17. $\phi(\eta)$ for v_0.

the mass transmission uses the interplay with the concentration distribution, and the velocity profile of the material can be dominated via the Sc.

The flow parameters like the heat transmission rate ($-\theta'(0)$), the coefficient of local skin friction ($f'(0)$), and the mass transmission rate ($-\phi'(0)$) are further arranged in tabular pattern to explain the innermost behaviour of the fluid movement.

Table 1 depicts the impact of numerous quantities of Eckert number (Ec) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$. The value of $f'(0)$ advances but $-\theta'(0)$ decays for upward quantities of Ec. The

Table 1. Influence of various amounts of Eckert number (Ec) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$.

Ec	$f'(0)$	$-\theta'(0)$	$-\phi'(0)$
0.5	6.47127400108620	0.781821521565587	0.507185477218282
1.0	6.65400893314410	0.651393913555926	0.507185477218282
2.0	7.01863928373015	0.455441021203235	0.507185477218282
2.5	7.19881836032756	0.380959781248542	0.507185477218282

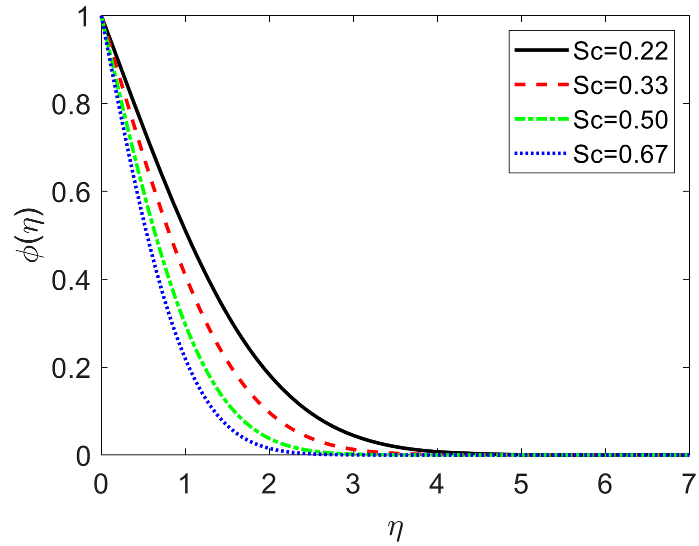

Figure 18. $\phi(\eta)$ for Sc.

increases by about 12% and the $-\theta'(0)$ lessens by around 52% for rising amounts of Ec (0.5-2.5). Hence, the fluid motion and temperature accelerate owing to increased values of Ec.

Table 2 displays the properties of $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$ for various amounts of heat generation and absorption (Q). The value of $f'(0)$ reduces for growing values of absorption but increases for growing values of heat production. But

Table 2. Effects of several amounts of internal heat production and absorption parameter (Q) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$.

Q	$-\theta'(0)$	$f'(0)$	$-\varphi'(0)$
0.5	0.781821521565587	6.47127400108620	0.507185477218282
1.0	0.582285539277967	6.73385102134690	0.507185477218282
2.0	0.212943633128381	7.25960585159191	0.507185477218282
−0.5	1.096929155993250	6.09340035164640	0.507185477218282
−1.0	1.228002606458990	5.95027410740542	0.507185477218282

Table 3. Impact of several amounts of Prandtl number (Pr) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$.

Pr	$-\phi'(0)$	$f'(0)$	$-\theta'(0)$
0.71	0.507185477218282	6.47127400108620	0.781821521565587
1.0	0.507185477218282	6.17020913252471	0.901898369547135
7.0	0.507185477218282	5.13597563847971	1.114170129007970

Table 4. Impact of several amounts of suction parameter (v_0) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$.

v_0	$-\phi'(0)$	$f'(0)$	$-\theta'(0)$
0.5	0.507185477218282	6.47127400108620	0.781821521565587
1.0	0.586804301507710	6.17756967523534	0.986187050917178
2.0	0.755419696725784	5.30784027051569	1.426736300865220
3.0	0.934224084317004	4.17686615134974	1.896646813952310

Table 5. Effect of different amounts of Schmidt number (Sc) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$.

Sc	$-\phi'(0)$	$f'(0)$	$-\theta'(0)$
0.22	0.507185477218282	6.47127400108620	0.781821521565587
0.33	0.642713920752462	6.07378759374058	0.781821521565587
0.50	0.824880790844464	5.66874223807153	0.781821521565587
0.67	0.988063441117625	5.39028801968476	0.781821521565587

Table 6. Comparison of $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$ when $Ec = 0.0$.

Q	$f'(0)$ Hasanuzzaman, Sharin et al. (2022)	$f'(0)$ Present Study	$-\theta'(0)$ Hasanuzzaman, Sharin et al. (2022)	$-\theta'(0)$ Present Study
$Q = 1.0$	6.364211	6.364512	0.705806	0.706702
$\Pr = 1.0$	6.004290	6.005139	0.878070	0.878627
$M = 0.5$	6.364211	6.364321	0.705806	0.705913

$-\theta'(0)$ improves for mounting amounts of heat absorption and decreases for growing values of heat production. The $f'(0)$ increases around by 8% for mounting amounts of the heat production parameter Q (1.0 - 2.0). Rising quantities of heat absorption from −0.5 to −1.0 lessens the $f'(0)$ by around 2%. The $-\theta'(0)$ advances by around 12% and lessens by around 63% for increased amounts of Q (−0.5 to −1.0) and Q (1.0 to 2.0), respectively. The mass transmission rate remains unchanged for Q.

The role of Prandtl number (Pr) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$ are shown in Table 3. The transmission rate enhances for growing quantities of Pr. Also, the $f'(0)$ declines for rising quantities of Pr. Besides, the $-\phi'(0)$ remains unchanged owing to advanced amounts of Pr. The $-\theta'(0)$ upsurges by around 43% but the $f'(0)$ diminishes by around 21% for upward quantities of Pr (0.71–7.0).

Table 4 illustrates the role of the suction parameter (v_0) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$. From Table 4, it is noticed that $-\phi'(0)$ and $-\theta'(0)$ improve and the $f'(0)$ reduces for rising quantities of v_0. The $-\phi'(0)$ and $-\theta'(0)$ advance by around 82% and 49% for upward quantities of v_0 (0.5 - 2.0). Besides, the $f'(0)$ lowers by around 18% for rising amounts of v_0(0.5 - 2.0).

The role of Schmidt number (Sc) on $f'(0)$, $-\phi'(0)$, and $-\theta'(0)$ is plotted in Table 5. Table 5 noticed that the $-\phi'(0)$ advances and the $f'(0)$ decays for upward amounts of Sc. But the $-\theta'(0)$ remained constant for Sc. The $-\phi'(0)$ quickens by around 63% but the $f'(0)$ declines by around 12% for increaing quantities of Sc (0.22 - 0.50).

4.4. *Comparison*

The outcomes of this present paper are compared with Hasanuzzaman, Sharin et al. (2022). The comparison of $f'(0)$, and $-\theta'(0)$ are plotted in Table 6. Our numerical findings and Hasanuzzaman, Sharin et al. (2022) are found to have the best agreement.

5. Conclusions

The time-dependent hydromagnetic free convective transmission upon a vertical permeable sheet is investigated numerically with the impacts of heat production and viscous dissipation. The subsequent observations can be made:

- The $\theta(\eta)$ and $f(\eta)$ go up for upward amounts of Ec and Q.
- The $f'(0)$, increases by around 12%, and the $-\theta'(0)$ retards by around 52% for uprising amounts of the Eckert number from 0.5 to 2.5.
- The $-\theta'(0)$ advances by around 12% and lessens by around 63% for increased amounts of Q (−0.5 to −1.0) and Q (1.0 to 2.0), respectively.
- The $-\phi'(0)$ quickens by around 63% but the $f'(0)$ declines by around 12% for increaing quantities of Sc (0.22–0.50).
- The findings of this study more closely align with an article that has been published.

The outcome of this paper may be supportive for industry, geosciences, and engineering such as petrology, hydrology, turbine blades,gas-particle trajectories, foam combustion, etc.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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