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Combined effects of free convection and chemical reaction with heat–mass flux conditions: A semianalytical technique

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Abstract. This paper discusses the effect of heat and mass flux on the natural convective laminar flow of a viscous incompressible fluid under the influence of radiation, magnetic field and Joule heating. The partial differential equations related to the problem have been changed as a set of ordinary differential equations employing non-dimensional quantities. Semianalytical approach such as the Adomian decomposition method (ADM) is employed to solve the system of ordinary differential equations. The behaviour of characterising parameters on the velocity, heat and mass transfer profiles, and the engineering quantities of interest, i.e. skin friction, heat and mass transfer rates and other indices are presented through graphs.

Keywords. Magnetohydrodynamics; heat and mass flux; viscous dissipation; Joule heating; Adomian decomposition method.

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1. Introduction

In many engineering and real-life problems, some motions are stimulated as a result of temperature and concentration variations. Combined effects of thermal and mass diffusion affect the rate of heat and mass transfer variations. In some industries, a lot of transportation processes exist in which heat and mass transfer take place. In many chemical procedures involved in industries, the application of energy and concentration transport normally exists, namely food processing, polymer procedure, etc. Free convection also plays a vital role in various industrial applications, such as in fibre manufacture and granular insulation, in geothermal systems etc.

Magnetohydrodynamics (MHD) is the science which deals with the flow of electrically conducting fluids with magnetic fields. The study of MHD under the influence of the transfer of heat and mass under the influence of radiation has stimulated several researchers due to its diverse significance in science and technology. Henkes and Hoogendoorn [1] have investigated natural convective laminar flow over a vertical surface. Seddek [2] has analysed the impact on a laminar boundary layer hydromagnetic motion for heat and mass transfer past a flat surface with heat generation/absorption and chemical reaction. Takhar *et al* [3] have analysed the impact of buoyancy, transverse magnetic field and radiation on MHD natural convective heat transfer flow of a gas past a vertical sheet. Lin and Wu [4] have analysed parallel transfer of energy and mass in free convective laminar motion with a vertical sheet. Bestman and Adjepong [5] have studied the unsteady MHD free convective flow with radiation in a rotating fluid. Ganesan and Loganathan [6] have studied the natural convection laminar motion of a viscous incompressible fluid over a vertical cylinder under constant heat and mass fluxes and chemical reaction. Muthucumaraswamy and Kulandaivel [7] have studied a perturbation solution to the flow issue over a vertical surface by taking into account the chemical reaction and heat flux boundary condition. They observed that velocity and concentration reduce by enhancing chemical reaction parameters. Transient natural convective motion of a viscous fluid over a vertical surface by incorporating the first-order chemical reaction and constant heat and mass flux has been analysed by Muthucumaraswamy and Ganesan [8]. They demonstrated that by enhancing the chemical

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reaction descriptor, the velocity reduces. Chamkha [9] has considered an unsteady hydromagnetic convective flow with heat and mass transfer in the presence of a uniform magnetic field. Mohammed Ibrahim and Suneetha [10] have investigated the unsteady natural convective flow having variable permeability past a vertical sheet in a porous medium by considering the first-order chemical reaction, radiation and Soret effect. Gurivi Reddy *et al* [11] have studied the flow of an electrically conducting fluid over an infinite moving porous sheet. They examined the impact of thermodiffusion by incorporating thermal radiation, chemical reaction and magnetic field.

Flows of fluids along porous media have attracted the attention of many researchers and practitioners due to their presence in many real-world scenarios. These types of flows have drawn the attention of researchers and scientists due to their great importance in several streams of science and technology. Chambré and Young [12] have explored the impact of chemical reaction on the flow past a parallel sheet. Chen and Yuh [13] have made an analytical study on the heat and mass transfer properties of free convection flow through a vertical cylinder under the influence of heat and mass fluxes. Babu and Satyanarayana [14] have analysed the impact of variable suction on natural convection motion through permeable medium with radiation. The unsteady MHD natural convection flow through a porous vertical surface after considering the temperature gradient dependent heat transfer and radiation has been discussed by Rao *et al* [15]. The MHD laminar natural convective motion in a micropolar liquid in the presence of chemical reaction can be seen in [16]. The influence of transfer of energy and mass in Jeffrey liquid motion in permeable media with a transverse magnetic field in the case of a stretching sheet and having a heat source/sink was also discussed in [17]. In this work, the researchers have observed that the elasticity, porosity of the media and magnetic field counter the movement of the Jeffery fluid as a porous medium. Also it has been noted that the magnetic field enhances the temperature profile in the flow domain. Misra and Adhikary [18] have analysed the oscillatory MHD blood flow under the influence of a permeable arteriole with an external magnetic field. Tripathy *et al* [19] have proposed a study of the impact of MHD boundary layer motion of a viscoelastic fluid past a moving vertical surface in a permeable medium by considering the effect of heat and mass transfer on the chemical reaction. They found that the velocity reduces with an increase in the local magnetic variable, the heat and mass transfer boundary layer flow width enhances with an increase in the strength of the magnetic field, the energy description goes up linearly in the non-attendance of porous medium with source parameter. They also observed that the energy buoyancy variable lessens the heat boundary layer whereas the permeability increases the energy field at every point. It is observed that the appearance of source variable reduces the energy description and in the case of the occupancy of permeable matrix, the concentration boundary layer lessens. Ahmed *et al* [20] have studied the 3D flow in a fluid having chemical reaction across two vertical parallel plates with a transverse magnetic field. They noticed that the velocity close to the plate and motion is increased with enhanced permeability and magnetic parameter. They also found that higher Reynolds number escalates the skin friction on the plate in the x-direction and reduces it in the z-direction.

The impact of viscous dissipation on flows, particularly in industrial operations and geographical situations, plays an important role and can be characterised by the Eckert number (Ec). The impact of viscous dissipation and constant suction on the 2D unsteady natural convection flow over an infinite vertical permeable surface has been discussed by Soundalgekar [21]. The influence of viscous dissipation, thermal radiation and variable diffusion of heat and mass transfer on hydrodynamic motion of a viscous incompressible fluid over an oscillating surface saturated in a permeable medium have been discussed by Kishore *et al* [22]. The impact of thermal radiation on the MHD flow has become very significant in many industrial applications. Several engineering procedures arise at excessive energy and so the awareness of radiation and heat transfer is important for designing industrial apparatus. Eckert and Drake [23] in their book entitled *Heat and Mass Transfer* have given various examples for industrial applications e.g., gas turbines, missiles, several propulsion tools for aircraft, nuclear energy plants and satellites. The impact of radiative natural convective motion past a permeable vertical surface was examined by Hossain *et al* [24]. Makinde [25] has studied the boundary-layer motion over a moving vertical permeable sheet in the presence of thermal radiation. Babu *et al* [26] have reported the steady MHD laminar motion over an exponential stretching surface under the influence of radiation, mass transfer and heat source/sink. They found that the velocity profile speeds up with the enhancement of wall mass suction and magnetic field. The MHD flow of a steadily moving vertical sheet under the influence of chemical reaction, mass and heat flux conditions in a permeable medium has been discussed by Girish [27]. The MHD free convection motion past an inclined sheet through a permeable medium was explained by Mangathai *et al* [28]. In this study the mass diffusion and variable temperature were taken into consideration. They demonstrated that the impact of the magnetic and permeability parameters on velocity is contrasting. It is also observed that the velocity enhances on enhancing the permeability parameter, Grashof number (Gr) and Prandtl number (Pr). Also, the velocity reduces with enhancing values of magnetic parameter, Schmidt number (Sc), permeability and radiation parameter. The temperature increases with enhancing Pr but reduces if the radiation parameter enhances. Kayalvizhi *et al* [29] have studied the analytic and numerical solutions of the momentum slip effect on the energy and mass flux conditions of a viscous fluid flow past an extending surface. In this study, the effect of ohmic and viscous dissipations was considered. They found that the wall absorption enhances with the increase in the magnetic and slip parameters whereas it decreases with the increase in Sc. The non-dimensional wall temperature seems to be reducing for lower values of slip variable; it increases for larger values of slip variable with viscous dissipation. The impact of energy and mass transfer on MHD viscoelastic liquid past a vertical plate in a permeable medium has been studied by Mishra *et al* [30]. In this study, the impact of transverse magnetic field, chemical reaction, internal heat generation/absorption, Joule and viscous dissipations are also examined. The impact of heat and mass flux on the MHD steady flow of Jeffrey nanofluid with thermal radiation, Brownian motion and thermophoresis has been explored by Abbasi *et al* [31]. Geetha and Muthucumaraswamy [32] have illustrated the impact of natural convection flow on the transfer of energy and concentration generated by a steady concentration flux on a vertical surface with variable energy. They found that when the solutal Gr enhances, the values of skin friction decreases. They also observed that as time grows the values of shear stress decreases. Hayat *et al* [33] have proposed the 3D Powell–Eyring nanofluid flow under the influence of radiation, thermophoresis and Brownian motion.

Seth *et al* [34] have examined the influence of Hall current on MHD free convection flow of a heat absorbing fluid past an impulsively moving vertical plate with ramped temperature. Seth *et al* [35] have analysed the impact on hydromagnetic free convection flow with heat and mass transfer of a heat absorbing fluid past an impulsively moving vertical plate with ramped temperature. Seth *et al* [36] have reported the unsteady hydromagnetic natural convection flow with heat and mass transfer of a thermally radiating and chemically reactive fluid past a vertical plate with Newtonian heating and time-dependent free stream. Seth *et al* [37] have investigated the unsteady hydromagnetic natural convection flow past an impulsively moving vertical plate with Newtonian heating in a rotating system. Seth *et al* [38] have explored the unsteady MHD free convection flow with Hall effects of a radiating and heat absorbing fluid past a moving vertical plate with variable ramped temperature. Seth *et al* [39] have considered the hydromagnetic convective flow of viscoelastic nanofluid with convective boundary condition over an inclined stretching sheet. Sarkar and Seth [40] have studied the unsteady hydromagnetic natural convection flow past a vertical plate with time-dependent free stream through a porous medium in the presence of Hall current, rotation and heat absorption.

In this study, the parallel effects of transfer of heat and mass are examined by using the Adomian decomposition method (ADM) to study the transient free convective flow over an impulsively started semi-infinite vertical sheet which is subjected to uniform heat and mass flux with radiation, magnetic field and Joule heating. A homogeneous first-order chemical reaction arises among the diffusing species and the liquid.

2. Mathematical formulation and analysis

The main purpose of this work is to examine a steady MHD motion of an incompressible viscous fluid in a permeable medium over a semi-infinite vertical infinite plate. The x^*-axis is along the flow direction and y^*-axis is normal to it. A uniform magnetic field of strength B_0 is applied normal to the flow direction (see figure 1). Viscous dissipation and, due to the appearance of the magnetic field, Joule dissipation are also incorporated in the energy equation which cannot be neglected. Cogley radiative heat flux is also considered which affects the heat transfer phenomenon. The density in the body force term is supposed to be a variable and other fluid properties are constant.

The fluid flow determined by the momentum, energy and concentration profiles by considering the governing equations under the above assumptions are

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

$$v^*\frac{\partial u^*}{\partial y^*} = \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_1(T^* - T_\infty) + g\beta^*(C^* - C_\infty) - \frac{\nu}{K_p^*}u^* - \frac{\sigma B_0^2 u^*}{\rho}, \tag{2}$$

$$v^*\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\nu}{C_p}\left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y^*} - \frac{\sigma B_0^2}{\rho C_p}u^{*2}, \tag{3}$$

$$v^*\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - k_c C^*. \tag{4}$$

Here, β_1 is the volumetric coefficient expansion due to temperature, g is the acceleration due to gravity, T_∞ is

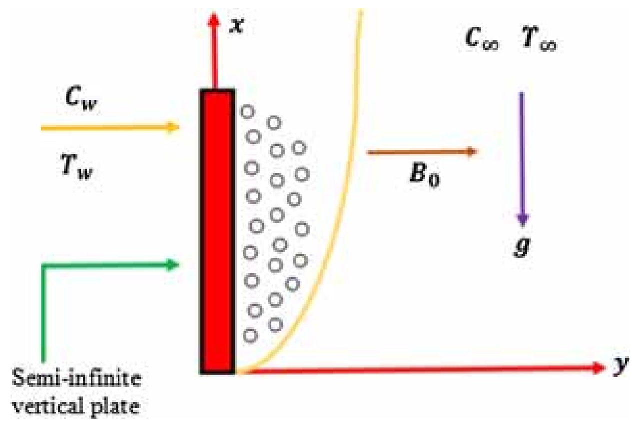

Figure 1. Flow configuration.

the fluid temperature at infinity, β^* is the coefficient of the volume, C_∞ is the species concentration at infinity, ρ is the density of the fluid, C_p is the specific heat at constant pressure, q_r is the radiative heat flux, D is the chemical molecular diffusivity.

The solution of eq. (1) is

$$v^* = \text{constant} = -v_0. \tag{5}$$

Here $v_0 > 0$ is the constant suction velocity normal to the sheet. Succeeding Cogley *et al* [41], we have the radiative heat flux as stated below:

$$\frac{\partial q_\mathrm{r}}{\partial y^*} = 4(T^* - T_\infty)I^*, \tag{6}$$

where $I^* = \int K_\lambda(\partial e_\lambda/\partial T^*)\,\mathrm{d}\lambda$, K_λ is the absorption coefficient of the plate and e_λ is the Plank's function.

In this case the relevant boundary conditions are:

$$\left.\begin{array}{l} u^* = 0, \quad \dfrac{\partial T^*}{\partial y^*} = -\dfrac{q}{\kappa}, \quad \dfrac{\partial C^*}{\partial y^*} = -\dfrac{m}{D} \quad \text{at} \quad y^* = 0 \\ u^* \to 0, \quad T^* \to T_\infty, \quad C^* \to C_\infty \quad \text{as} \quad y^* \to \infty \end{array}\right\}. \tag{7}$$

Using eqs (5) and (6), eqs (2)–(4) reduce to

$$-v_0\frac{\partial u^*}{\partial y^*} = \nu\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta_1(T^* - T_\infty) + g\beta^*(C^* - C_\infty) - \frac{\nu u^*}{K_\mathrm{p}^*} - \frac{\sigma B_0^2 u^*}{\rho}, \tag{8}$$

$$-v_0\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_\mathrm{p}}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{\nu}{C_\mathrm{p}}\left(\frac{\partial u^*}{\partial y^*}\right)^2 - \frac{1}{\rho C_\mathrm{p}}4(T^* - T_\infty)I^* - \frac{\sigma B_0^2}{\rho C_\mathrm{p}}u^{*2}, \tag{9}$$

$$-v_0\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}} - k_\mathrm{c}C^*. \tag{10}$$

Consider the following non-dimensional parameters:

$$\left.\begin{array}{l} f(\eta) = \frac{u^*}{v_0}, \quad \eta = \frac{v_0 y^*}{\nu}, \quad \mathrm{Pr} = \frac{\mu C_\mathrm{p}}{\kappa}, \quad F = \frac{4\nu^2 I^*}{v_0^2} \\ \alpha = \frac{v_0^2 K_p^*}{\nu^2}, \quad C = \frac{(C^* - C_\infty)}{((m\nu/Dv_0))}, \theta = \frac{(T^* - T_\infty)}{((q\nu/\kappa v_0))} \\ \mathrm{Gr} = \frac{g\beta_1 q\nu^2}{kv_0^4}, \quad \mathrm{Gm} = \frac{g\beta^* m\nu}{Dv_0^3}, \quad \mathrm{Sc} = \frac{\nu}{D} \\ Kr = \frac{k_c\nu}{v_0^2}, \quad M = \frac{\sigma\nu B_0^2}{\rho v_0^2}, \quad E = \frac{\kappa v_0^2}{qC_\mathrm{p}} \end{array}\right\}. \tag{11}$$

Here, η is the similarity variable, v_0 is the scale of suction velocity, Pr is the Prandtl number, F is the radiation parameter, θ is the dimensionless temperature, κ is the thermal conductivity, Gr is the Grashof number for heat transfer expansion with species concentration, ν is the kinematic viscosity, M is the magnetic parameter.

After introducing the non-dimensional parameters given in eq. (11), eqs (8)–(10) become

$$f'' + f' - \left(\frac{1}{\alpha} + M\right)f = -\mathrm{Gr}\,\theta - \mathrm{Gm}\,C, \tag{12}$$

$$\theta'' + \mathrm{Pr}\,\theta' - F\theta = -E\,\mathrm{Pr}\,f'^2 - \mathrm{Pr}\,EMf^2, \tag{13}$$

$$C'' + \mathrm{Sc}C' = \mathrm{Sc}KrC, \tag{14}$$

where all the primes represent derivatives with respect to η, Gm is the Gr for mass transfer.

Now, the corresponding boundary conditions (7) change to

$$\left.\begin{array}{l} \eta = 0, \; f = 0, \; \theta' = -1, \; C' = -1 \\ \eta \to \infty, \; f \to 0, \; \theta \to 0, \; C \to 0 \end{array}\right\}. \tag{15}$$

3. Method of solution: ADM

The semianalytical technique used for the coupled ordinary differential equations (ODEs) (12)–(14) with boundary conditions (15) is as follows:

$$f'' = -f' + \left(\frac{1}{\alpha} + M\right)f - \mathrm{Gr}\,\theta - \mathrm{Gm}\,C, \tag{16}$$

$$\theta'' = -\mathrm{Pr}\,\theta' + \mathrm{Pr}\,F\theta - E\,\mathrm{Pr}\,f'^2 - \mathrm{Pr}\,EMf^2, \tag{17}$$

$$C'' = -\mathrm{Sc}C' + \mathrm{Sc}KrC. \tag{18}$$

Let us introduce $L_1 = (\mathrm{d}^2/\mathrm{d}\eta^2)()$ with inverse operators $L_1^{-1}() = \int_0^\eta\int_0^\eta ()\,\mathrm{d}\eta\,\mathrm{d}\eta$. Thus eqs (16)–(18) become

$$f = L_1^{-1}\left(-f' + \left(\frac{1}{\alpha} + M\right)f - \mathrm{Gr}\,\theta - \mathrm{Gm}\,C\right), \tag{19}$$

$$\theta = L_1^{-1}\left(-\Pr\theta' + \Pr F\theta - E\Pr f'^2 - \Pr EMf^2\right), \tag{20}$$

$$C = L_1^{-1}\left(-\mathrm{Sc}C' + \mathrm{Sc}KrC\right). \tag{21}$$

The unknown functions $f(\eta)$, $g(\eta)$ and $\theta(\eta)$ can be expressed as infinite series of the form:

$$f(\eta) = \sum_{m=0}^{\infty} f_m(\eta), \quad \theta(\eta) = \sum_{m=0}^{\infty} \theta_m(\eta)$$

and

$$C(\eta) = \sum_{m=0}^{\infty} C_m(\eta). \tag{22}$$

The linear and nonlinear terms of (19)–(21) can now be decomposed by an infinite series of polynomials as

$$\left.\begin{array}{ll} \sum_{m=0}^{\infty} A_m = f', & \sum_{m=0}^{\infty} B_m = f \\ \sum_{m=0}^{\infty} C_m = \theta, & \sum_{m=0}^{\infty} D_m = C \\ \sum_{m=0}^{\infty} E_m = \theta', & \sum_{m=0}^{\infty} F_m = f'^2 \\ \sum_{m=0}^{\infty} G_m = f^2, & \sum_{m=0}^{\infty} H_m = C' \end{array}\right\}. \tag{23}$$

The exact solutions of (16)–(18) are as follows:

$$f(\eta) = \lim \sum_{m=0}^{\infty} f_m(\eta), \quad \theta(\eta) = \lim \sum_{m=0}^{\infty} \theta_m(\eta)$$

and

$$C(\eta) = \lim \sum_{m=0}^{\infty} C_m(\eta). \tag{24}$$

Therefore, the RHSs of eqs (19)–(21) can be written as

$$L_1^{-1}(L_1 f) = f(\eta) - f(0) - \eta f'(0), \tag{25}$$

$$L_1^{-1}(L_1\theta) = \theta(\eta) - \theta(0) - \eta\theta'(0), \tag{26}$$

$$L_1^{-1}(L_1 C) = C(\eta) - C(0) - \eta C'(0). \tag{27}$$

From (15), invoking the boundary conditions

$$f(0) = 0,\ f'(0) = p,\ \theta(0) = q,\ C(0) = r. \tag{28}$$

The solutions of eqs (16)–(18) may therefore be written as

$$f(\eta) = \eta p + L_1^{-1}\left(-f' + \left(\frac{1}{\alpha} + M\right)f - \mathrm{Gr}\,\theta - \mathrm{Gm}\,C\right), \tag{29}$$

$$\theta(\eta) = q - \eta + L_1^{-1}\left(-\Pr\theta' + \Pr F\theta - E\Pr f'^2 - \Pr EMf^2\right), \tag{30}$$

$$C(\eta) = r - \eta + L_1^{-1}\left(-\mathrm{Sc}C' + \mathrm{Sc}KrC\right). \tag{31}$$

Here the unknown values of p, q and r are to be determined. On utilising eqs (25)–(27) the initial guess solutions and the successive order solutions are expressed as follows:

$$f_0(\eta) = \eta p, \quad \theta_0(\eta) = q - \eta$$

and

$$C_0(\eta) = r - \eta, \tag{32}$$

$$f_{m+1}(\eta) = L_1^{-1}\left(-A_m + \left(\frac{1}{\alpha} + M\right)B_m - \mathrm{Gr}\,C_m - \mathrm{Gm}\,D_m\right), \tag{33}$$

$$\theta_{m+1}(\eta) = L_1^{-1}(-\Pr E_m + \Pr FC_m - E\Pr F_m - \Pr EMG_m), \tag{34}$$

$$C_{m+1}(\eta) = L_1^{-1}(-\mathrm{Sc}H_m + \mathrm{Sc}KrD_m). \tag{35}$$

By using $m = 0{-}2$ in eqs (33)–(35) the solutions of eqs (16)–(18) are expressed as follows:

$$\begin{aligned} f(\eta) &= \sum_{i=0}^{3} f_i(\eta) \\ &= f_0(\eta) + f_1(\eta) + f_2(\eta) + f_3(\eta) + O(f_4(\eta)) \\ &= p\eta + T_1\eta^2 + (T_2 + T_7)\eta^3 \\ &\quad + (T_8 + T_{17})\eta^4 + (T_9 + T_{18})\eta^5 + T_{19}\eta^6 \\ &\quad + T_{20}\eta^7 + T_{21}\eta^8, \end{aligned} \tag{36}$$

$$\begin{aligned} \theta(\eta) &= \sum_{i=0}^{3} \theta_i(\eta) \\ &= \theta_0(\eta) + \theta_1(\eta) + \theta_2(\eta) + \theta_3(\eta) + O(\theta_4(\eta)) \\ &= q - \eta + T_3\eta^2 + (T_4 + T_{10})\eta^3 \\ &\quad + (T_{11} + T_{22})\eta^4 + (T_{12} + T_{23})\eta^5 \\ &\quad + (T_{13} + T_{24})\eta^6 + T_{25}\eta^7 + T_{26}\eta^8, \end{aligned} \tag{37}$$

$$\begin{aligned} C(\eta) &= \sum_{i=0}^{3} C_i(\eta) \\ &= C_0(\eta) + C_1(\eta) + C_2(\eta) + C_3(\eta) + O(C_4(\eta)) \\ &= r - \eta + T_5\eta^2 \\ &\quad + (T_6 + T_{14})\eta^3 + (T_{15} + T_{27})\eta^4 \\ &\quad + (T_{16} + T_{28})\eta^5 + T_{29}\eta^6 + T_{30}\eta^7. \end{aligned} \tag{38}$$

4. Results and discussion

Comprehensive solutions have been obtained and are presented in figures 2–13. The numerical problem comprises one independent variable (η), three dependent fluid dynamic variables (f, θ, C) and nine thermophysical and body force control parameters, namely M, α, Gr, Gm, Ec, Sc, Pr, Kr, F. The following default parameter values, i.e. $M = 1$, $\alpha = 0.5$, Gr $=$ Gm $= 5$, Ec $= 0.001$, Sc $= 0.22$, Pr $= 0.71$, $Kr = 2.5$, $F = 1$

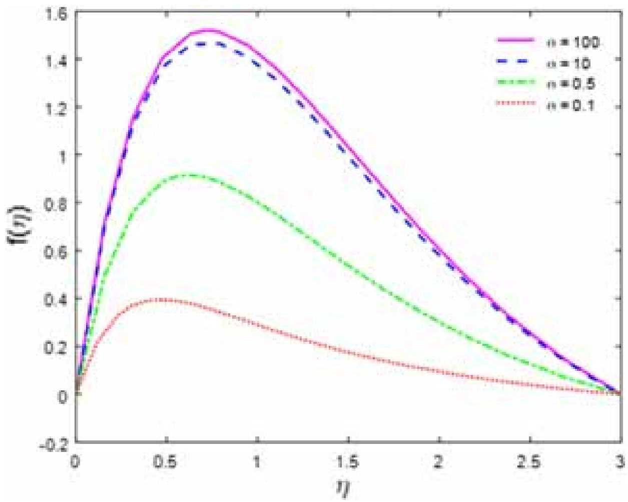

Figure 2. Velocity description for various values of α.

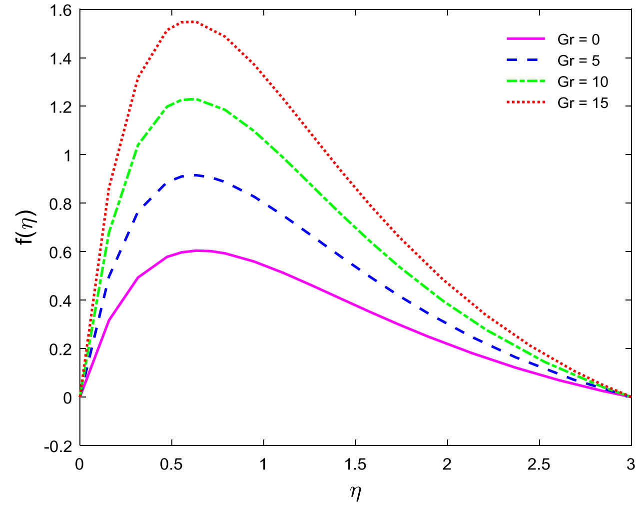

Figure 4. Velocity description for various values of Gr.

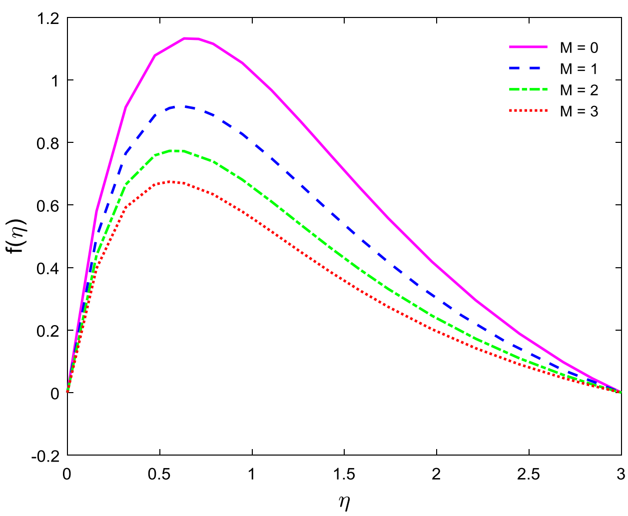

Figure 3. Velocity description for various values of M.

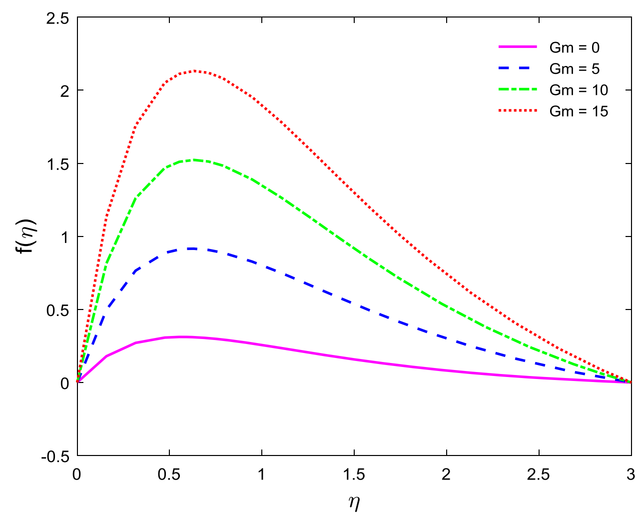

Figure 5. Velocity description for various values of Gm.

are prescribed (unless otherwise stated). At the time of computation, the values of characterising parameters $M = 1, \alpha = 0.5, \mathrm{Gr} = \mathrm{Gm} = 5, \mathrm{Ec} = 0.001, \mathrm{Sc} = 0.22, \mathrm{Pr} = 0.71, Kr = 2.5, F = 1$ are treated as fixed except for the variation of the parameters corresponding to different figures. We have obtained the computational outcome for various parameters, namely permeability parameter (α), magnetic parameter (M), Prandtl number (Pr), Eckert number (Ec), chemical reaction parameter (Kr), Schmidt number (Sc), Grashof number for heat transfer (Gr), Grashof number for mass transfer (Gm), etc.

The velocity descriptions are depicted in figures 2–5. Figure 2 displays the impact of porous media coefficient (α) on the description of the velocity. We have noticed an increase in the velocity with an increment in α. It has also been noted that the velocity of the fluid improves, gains the optimal limit past a small distance from the surface and afterwards it slowly decreases to zero for non-negative values of α. From figure 3 which displays the effects of M, it can be noticed that the velocity reduces with an enhancement in M. This implies that the magnetic field tends to retard fluid velocity in the boundary layer region. This is due to the fact that the application of a magnetic field always results in a resistive-type force (Lorentz force) which is similar to the drag force and upon increasing the values of M, the drag force increases and tends to resist the fluid flow and thus reduces the fluid motion significantly. The impact of Gr on the profile of the velocity is revealed in

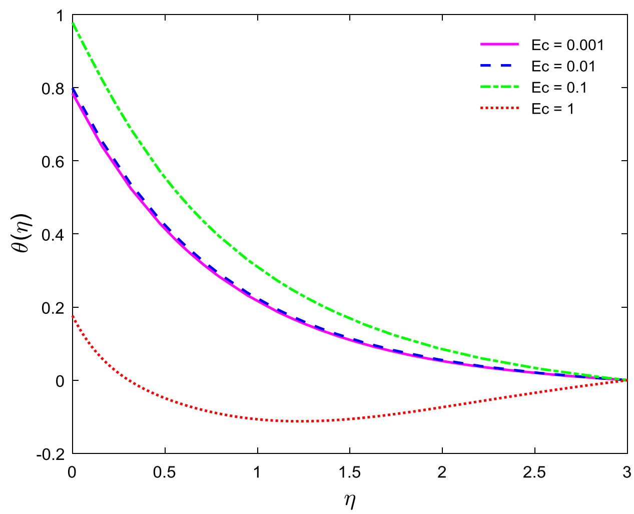

Figure 6. Temperature description for various values of Ec.

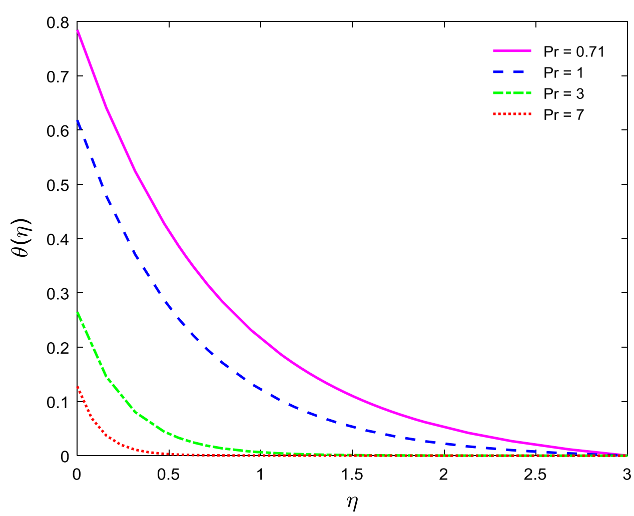

Figure 7. Temperature description for various values of Pr.

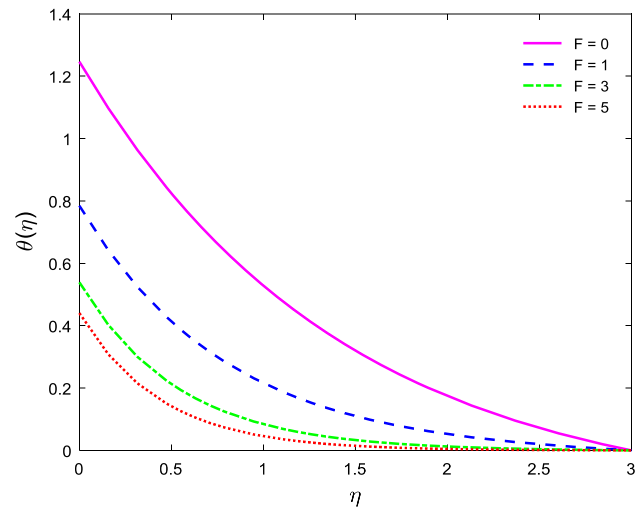

Figure 8. Temperature description for various values of F.

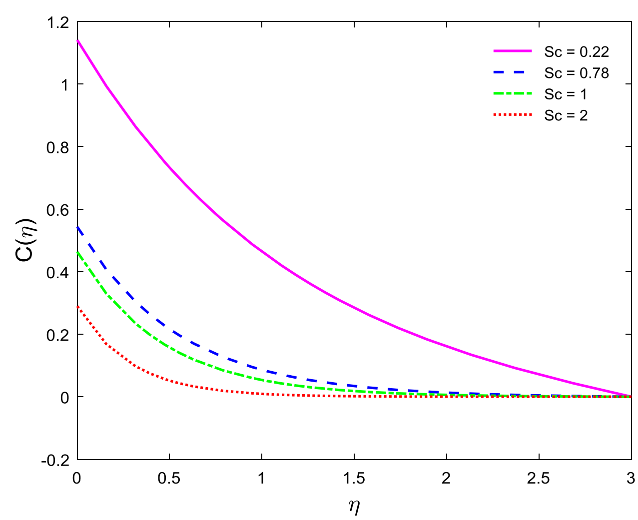

Figure 9. Concentration description for various values of Sc.

figure 4. We have noticed the enhancement in the velocity as there is an enhancement in Gr. The impact of Gm on the profile of momentum is depicted in figure 5. It is noted that the momentum increases with an increase in Gm. This implies that Gr signifies the relative measure of the thermal buoyancy force to viscous force. This means that the thermal buoyancy force becomes stronger when Gr increases. The solutal Gr is the ratio of the solutal buoyancy force to the viscous force. An increase in solutal Gr indicates smaller viscous effect than solutal buoyancy effects in the momentum equation, and consequently, causes an increase in fluid velocity. The temperature trends are depicted in figures 6–8. Figure 6 exhibits the impact of Ec on temperature the temperature reduces with an enhancement in Ec. The impact of Pr on temperature is presented in figure 7 and it has been noted that the temperature reduces with the increase in Pr. As Pr is the ratio of momentum diffusivity to thermal diffusivity, an increase in Pr implies a decrease in thermal diffusivity. This implies that thermal diffusion tends to enhance fluid temperature throughout the boundary layer region. In figure 8, the influence of F on the temperature description is depicted. It has been observed that the temperature reduces with an enhancement in F. The concentration descriptions are depicted in figures 9 and 10. Figure 9 exhibits the influence of Sc on concentration. It has been noticed that the concentration reduces when an enhancement in Sc occurs. Figure 10 shows the impact of Kr on concentration. It has been found that the concentration reduces with an increase in Kr.

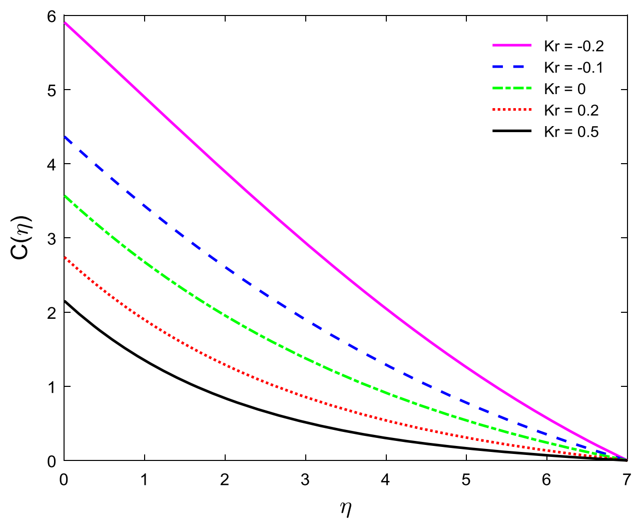

Figure 10. Concentration description for various values of *Kr*.

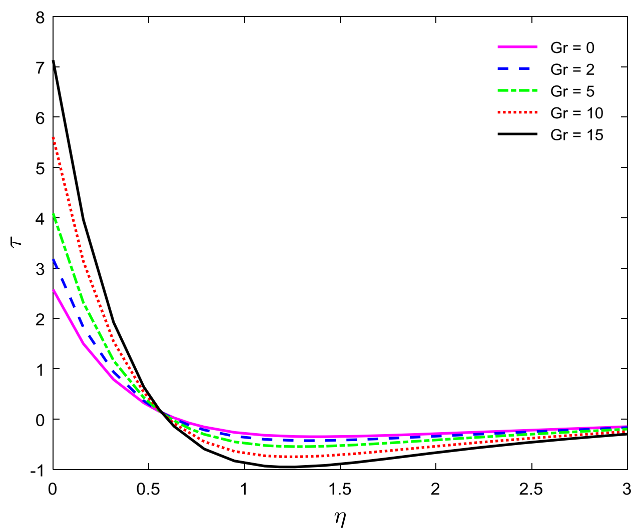

Figure 11. Skin friction description for various values of Gr.

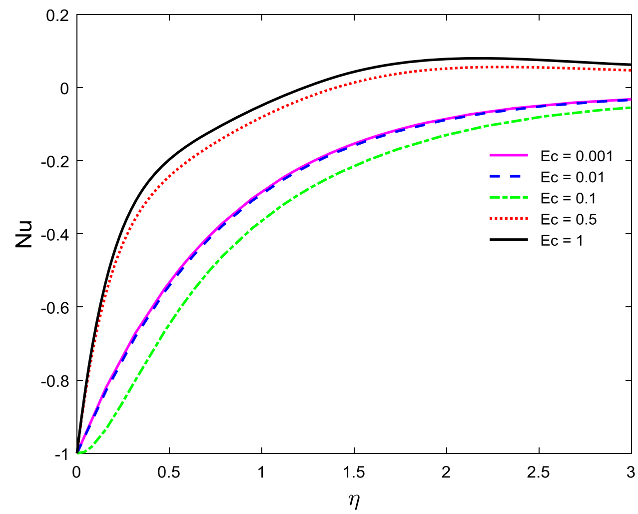

Figure 12. Nusselt number description for various values of Ec.

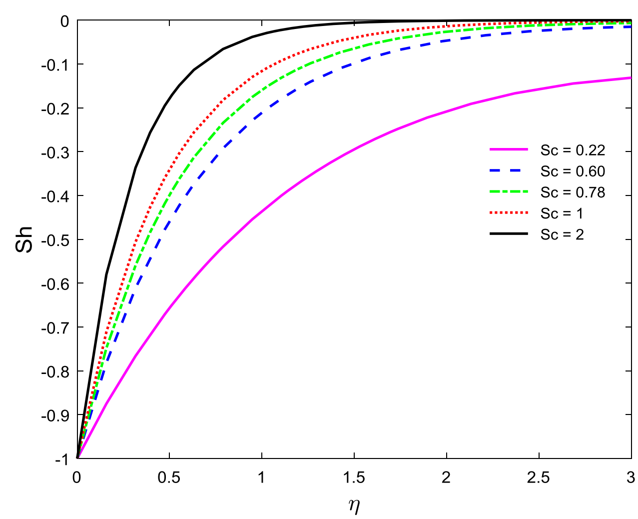

Figure 13. Sherwood number description for various values of Sc.

The fluid motion is retarded on account of the chemical reaction in the boundary layer region. This elucidates that the consumption of chemical species leads to a fall in the concentration field, which in turn diminishes the buoyancy effects due to concentration gradients. Consequently, the fluid flow is decelerated. Figure 11 exhibits the effects of Gr on skin friction. Interestingly, we notice that the skin friction reduces when there is an enhancement in Gr. A change in the transfer of the rate of heat is revealed in the form of Nu as depicted in figure 12. It is clear that Nu increases with an increase in the value of Ec. In the same way, the Sherwood number (Sh) shown in figure 13 seems to increase when an increase in Sc occurs. This implies that the concentration level of the fluid drops due to increasing Sc indicating that the mass diffusivity raises the concentration level steadily in the boundary-layer region.

5. Conclusion

Based on numerical experiments, the outcome of the investigation can be outlined in this way: The velocity of fluid flow enhances with the enhancement in α, Gr and Gm. It has been demonstrated that the velocity of fluid flow reduces with the increase in M but the temperature of the fluid decreases with an increase in Ec, F, Pr. It has been observed that the concentration of the fluid reduces with the increase in Sc and Kr. The value of skin friction reduces against Gr. The value of Nu increases with the increase in Ec and the value of Sh increases with the increase in Ec.

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