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Unsteady Free Convection MHD Flow over a Vertical Cone in Porous Media with Variable Heat and Mass Flux in Presence of Chemical Reaction

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ABSTRACT

This paper investigated unsteady free convection MHD flow over a vertical cone in porous media with variable heat and mass flux in presence of chemical reaction. Appropriate non-dimensional variables are used to reduce the dimensional governing equations that consists of continuity, momentum, energy, and concentration equations along with imposed initial and boundary conditions. The purpose of the study is to investigate this unsteady MHD flow problem using Crank-Nicolson method. The discretization equations were computed, and numerical results were plotted using MATLAB software. Numerical Results for the velocity, temperature and concentration profiles are presented graphically and discussed for different values of the physical parameters to show interesting features of the solutions. The result showed that the velocity profile increases when porosity and buoyancy ratio parameters are escalated, while an opposite behavior is notice against magnetic parameter and chemical reaction parameter.

1. Introduction

The heat transfer fluid flow over a cone has received much attention due to the various applications involving heat transfer. It plays a vital role in the field of technology and engineering but at the same time, it is very challenging to analyze the flow characteristics. It is encountered in many industrial applications, as well as in various natural circumstances. Natural convection flow over a vertical cone is one of the most interesting topics discussed by researchers under fluid flow area. The angle parameter of cone placed vertically gives challenges to researchers in formulation of the problem.

Owing to the fact, convectional flow over a vertical cone has been discussed in the literature by many authors since 1953. The pioneering work of flow over a cone was studied by Merk & Prins [1] and [2] that showed the general relations for similar solutions on a process taking place at fixed temperature axi-symmetric forms and showed that the vertical cone has such a solution. Furthermore, similarity solutions for steady convection flow over a vertical cone with variable surface

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temperature exist and it varies as a power function of distance along a cone ray as stated by Hering & Grosh [3]. Bapuji *et al.,* [4] studied free convection flow past a non-isothermal vertical cone using finite difference method. A numerical solution for laminar convective heat and mass transfer in a Walters-B viscoelastic fluid flow along a vertical cone was presented by Mohiddin *et al.,* [5]. Pullepu *et al.,* [6] investigated a non-linear, unsteady, laminar, natural convection flow over an incompressible viscous fluid past a vertical permeable cone with combined effects of chemical reaction and heat generation or absorption. This study used uniform wall temperature and uniform wall concentration as a boundary condition.

The study of convection heat and mass transfer phenomenon in fluid flows has gained considerable attention from researchers as it occurs frequently in nature. It can occur due to the variation of temperature, concentration or combination of these two. The transport of substance or mass caused by concentration gradient is called mass transfer. Coupled heat and mass transfer plays a crucial role in absorption, evaporation, condensation, extraction and drying. In nature, the present of pure water or air is not achievable since the reaction between foreign substance and fluid cannot be refuted as stated by Kandasamy *et al.,* [7]. In Thirupathi *et al.,* [8], effect of thermal radiation, viscous dissipation, heat source and chemical reaction for heat and mass transfer has been incorporated. The study was extended from previous study by considering an additional effect such as Soret effect, Dufour effect and inclined magnetic field.

The heat transfer due to free convection on a vertical cone with MHD and chemical reaction effects has a broad range of applications in the field of technology and science. A lot of practical processes involve molecular diffusion of a species in the presence of a chemical reaction either at the boundary or within the flow. A steady MHD boundary layer flow, heat and mass transfer of viscous fluid over a permeable truncated cone with variable temperature and concentration was explored by Chamkha *et al.,* [9]. The effects of thermal radiation and chemical reaction were also taken into account. Chambre & Young [10] analyzed the problem of the first-order destructive and generative chemical reactions in the neighborhood of a horizontal plate. Moreover, Kabeir *et al.,* [11] studied the heat and mass transfer over a vertical isothermal cone surface in micro polar fluids with MHD, chemical reaction and heat generation or absorption effects. Rashad and Chamkha [12] studied heat and mass transfer by natural convection flow over a cone embedded in a porous medium. The flow was induced by Soret and Dufour effects in presence of thermal radiation and chemical reaction. The numerical solutions are obtained by using implicit finite difference method. Thermal radiation and chemical reaction had been found to have major effects on the characteristics of heat and mass transfer due to Soret and Dufour effects.

In addition, a numerical investigation of Casson fluid flow over a vertical cone and flat plate saturated with non-Darcy porous medium in the presence of heat generating or absorbing, chemical reaction and cross-diffusion effects were discussed in Durairaj [13]. Nabajyoti & Sharma [14] examined effects of chemical reaction and thermal radiation on unsteady free convective flow past a vertical cone. The considered mathematical model was solved numerically using implicit Crank-Nicolson method. Fluid velocity, temperature, and species concentration profiles have been observed for different flow parameters and the velocity, temperature, and concentration increased with the increased in time. Moreover, the velocity and concentration increased, but temperature decreased with increased of the thermal radiation parameter and the chemical reaction parameter increased when the velocity and concentration decreased.

The numerical solution past a MHD vertical cone in the occurrence of mass flux and heat generation was solved by Crank-Nicholson method in Sambath *et al.,* [15]. It was observed that the velocity increased with increased of the thermal radiation parameter and the concentration decreased when the chemical reaction parameter increased. Moreover, Kajura and Kumar [16] investigated the impact of nonuniformly heated lateral side on the transient natural convection of Casson fluid past a vertical cone in the appearance of a constant magnetic field. The main findings were that the temperature and velocity profiles have a maximum magnitude at the middle of the lateral side of the cone. For ramped concentration case, the concentration profile has a maximum magnitude at t = 3.

Ghoneim *et al.,* [17] explored the interaction of thermal radiation, variable diffusivity and wall heat and mass fluxes through a vertical cone induced by Soret and Dufour effects. It was found that the higher value of viscosity parameter leads to a decrease in both the dimensionless temperature and dimensionless concentration. Moreover, an increase in the thermal conduc- tivity parameter tends to increase the dimensionless temperature that was away from the cone surface.

In the present study, effects of magnetic field, chemical reaction, porous media, thermal radiation and heat generation for the unsteady free convective flow are taken into consideration in the vertical cone. Dimensionless, nonlinear, coupled partial differential equations and solved numerically by Crank-Nicolson method [4] combined with Thomas algorithm [18]. An algorithm is developed in MATLAB software in order to obtain numerical results and discussed graphically in detail.

2. Mathematical Formulation

An axi-symmetric unsteady, laminar free convection flow of a viscous incompressible fluid past a vertical cone with half angle α and radius $r(r = xsin\alpha)$in porous medium under the influence of MHD and chemical reaction are considered. The surface of the cone is referring to x-axis and the normal to the cone is considered as y-axis. It is assumed that the cone surface and the surrounding fluid which is at rest are at the same temperature T_∞ and concentration C_∞ . Then at time $t > 0$, wall temperature subjected to power-law surface heat flu $q_w(x) = ax^n$ and wall concentration subjected to the power-law surface mass flux $m_w(x) = bx^m$, is considered. A uniform magnetic field is considered parallel to y-axis as illustrated in Figure 1 as follows:

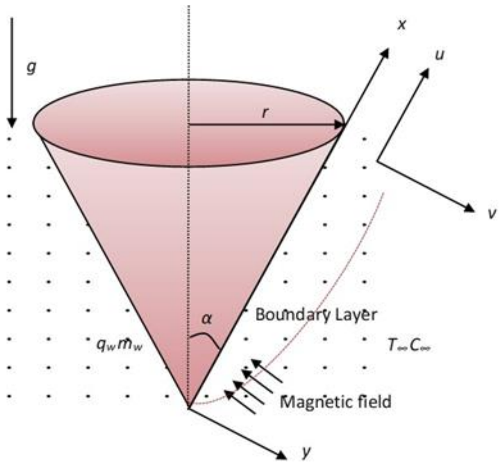


Fig. 1. Flow model and physical coordinate system

It is assumed that the effect of viscous dissipation is negligible. The above assumptions along with boundary layer approximations, the basic governing equations of the problem which consists of continuity, momentum, energy, and concentration equations can be written as follows, Continuity:

$$\frac{\partial}{\partial x}(ur) + \frac{\partial}{\partial y}(vr) = 0 \tag{1}$$

Momentum:

$$\rho\left(\frac{\partial u}{\partial t^*} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} + g(\rho\beta_T)\cos\alpha\,(T^* - T_\infty^*) + g(\rho\beta_C)\cos\alpha\,(C^* - C_\infty^*) - \sigma B^2 u - \frac{\mu}{k_0}u \tag{2}$$

Energy:

$$(\rho C_p)\left(\frac{\partial T^*}{\partial t^*} + u\frac{\partial T^*}{\partial x} + v\frac{\partial T^*}{\partial y}\right) = k\frac{\partial^2 T^*}{\partial y^2} \tag{3}$$

Concentration:

$$\frac{\partial C^*}{\partial t^*} + u\frac{\partial C^*}{\partial x} + v\frac{\partial C^*}{\partial y} = D\frac{\partial^2 C^*}{\partial y^2} - k_1(C^* - C_\infty^*) \tag{4}$$

subject to the initial boundary conditions,

$t^* \leq 0$: $\mathrm{u} = 0, \mathrm{v} = 0, T^* = T_\infty^*, C^* = C_\infty^*$ for all x and y

$t^* > 0$: $u = 0, v = 0, \frac{\partial T^*}{\partial y} = -\frac{q_w}{k}, \frac{\partial C^*}{\partial y} = -\frac{m_w}{D}$ at $y = 0$

,
$u = 0, T^* = T_\infty^*, C^* = C_\infty^*$ at $x = 0$

$u \to 0, T^* \to T_\infty^*, C^* \to C_\infty^*$ as $y \to \infty$ (5)

where, $u =$ velocity component in x direction, $v =$ velocity component in y direction, $r =$ local radius of the cone, $t^* =$ time, $T^* =$ temperature, $C^* =$ concentration, $x =$ spatial coordinate along the cone generator, $y =$ spatial coordinate along the normal to the cone generator, g =gravitational force, $\rho =$ density, $\beta_T =$ volumetric thermal expansion coefficient with temperature, $\beta_C =$ volumetric coefficient of expansion with concentration, $\alpha =$ half angle of the cone, $\sigma =$ electrical conductivity, $B =$ magnetic field, $\mu =$ dynamic viscosity, $k_0 =$ permiability of porous medium, $C_p =$ specific heat at constant pressure, $k =$ thermal conductivity, $D =$ mass diffusivity and $k_1 =$ dimensional chemical reaction parameter. Using dimensionless parameters:

$$X = \frac{x}{L}, Y = \frac{y}{L}(Gr_L)^{\frac{1}{4}}, R = \frac{r}{L}, V = \frac{\nu L}{v_f}(Gr_L)^{-\frac{1}{4}},$$

$$U = \frac{uL}{v_f}(Gr_L)^{-\frac{1}{2}}, t = \frac{v_f t^*}{L^2}(Gr_L)^{\frac{1}{2}}, T = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},$$

$$Gr_L = \frac{g\beta_f(T_w^* - T_\infty^*)L^3}{v_f^2}, C = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*},$$

$$Gr_c = \frac{g\beta_c(C_w^* - C_\infty^*)L^3}{v_f^2}, \frac{1}{k} = \frac{L^2}{k_0}(Gr_L)^{-\frac{1}{2}} \tag{6}$$

Eq. (1) - (4) are then reduced to the following non-dimensional form:

Equation on continuity:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} + \frac{U}{X} = 0 \tag{7}$$

Equation on momentum:

$$\frac{\partial \mathrm{U}}{\partial \mathrm{t}} + \mathrm{U}\frac{\partial \mathrm{U}}{\partial \mathrm{X}} + \mathrm{V}\frac{\partial \mathrm{U}}{\partial \mathrm{Y}} = \frac{\partial^2 \mathrm{U}}{\partial \mathrm{Y}^2} + \mathrm{T}\cos\alpha + \mathrm{NC}\cos\alpha - \mathrm{MU} - \frac{1}{\mathrm{K}}\mathrm{U} \tag{8}$$

Equation on energy:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \mathrm{U}\frac{\partial \mathrm{T}}{\partial \mathrm{X}} + \mathrm{V}\frac{\partial \mathrm{T}}{\partial \mathrm{Y}} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 \mathrm{T}}{\partial \mathrm{Y}^2} \tag{9}$$

Equation on concentration:

$$\frac{\partial \mathrm{C}}{\partial \mathrm{t}} + \mathrm{U}\frac{\partial \mathrm{C}}{\partial \mathrm{X}} + \mathrm{V}\frac{\partial \mathrm{C}}{\partial \mathrm{Y}} = \frac{1}{\mathrm{Sc}}\frac{\partial^2 \mathrm{C}}{\partial \mathrm{Y}^2} - \lambda\mathrm{C} \tag{10}$$

where, $Pr = \frac{v}{\alpha}$ is Prandtl number, $Sc = \frac{V}{D}$ is Schmidt number, $N = \frac{Gr_c}{Gr_L}$ is buoyancy ratio parameter, $\lambda = \frac{k_1 L^2}{v}(Gr_L)^{-\frac{1}{2}}$ is chemical reaction parameter, $M = \frac{\sigma B_0^2 L^2}{\mu}(Gr_L)^{-\frac{1}{2}}$ is magnetic field parameter and $K = \frac{L^2}{k_0}$ is porous permeability parameter. The corresponding non-dimensional initial and boundary conditions are:

$$t \leq 0: U = 0, V = 0, T = 0, C = 0 \; for \; all \; X \; and \; Y$$

$$t > 0: U = 0, V = 0, \frac{\partial T}{\partial Y} = -X^m, \frac{\partial C}{\partial Y} = -X^n \; at \; Y = 0$$

$$U = 0, T = 0, C = 0 \; at \; X = 0$$

$$U \to 0, T \to 0, C \to 0 \; as \; Y \to \infty \tag{11}$$

2.1 Numerical Procedure of Crank-Nicolson

All non-dimensional equations are discretized for numerical evaluation and implementation on digital computers. In order to formulate the problems in programming, the equations need to have a process of transferring continuous functions, variables, models, and equations into discrete. After the non-dimensional equations is discretized and iteration i and j is applied, it is then converted to the system of tri-diagonal equations. The finite difference equation equivalent to the Equations (7) - (9) are specified as follows:

Equation on continuity:

$$\frac{U_{i,j}^{k+1} - U_{i-1,j}^{k+1} + U_{i,j}^{k} - U_{i-1,j}^{k}}{2\Delta X} + \frac{V_{i,j}^{k+1} - V_{i,j-1}^{k+1} + V_{i,j}^{k} - V_{i,j-1}^{k}}{2\Delta Y} + \frac{1}{X_i}\frac{U_{i,j}^{k+1} + U_{i,j}^{k}}{2} = 0 \quad (12)$$

Equation on momentum:

$$\left(\frac{U_{i,j}^{k+1} - U_{i,j}^{k}}{\Delta t}\right) + U_{i,j}^{k}\left(\frac{U_{i,j}^{k+1} - U_{i-1,j}^{k+1} + U_{i,j}^{k} - U_{i-1,j}^{k}}{2\Delta X}\right) + V_{i,j}^{k}\left(\frac{U_{i,j+1}^{k+1} - U_{i,j-1}^{k+1} + U_{i,j+1}^{k} - U_{i,j-1}^{k}}{4\Delta Y}\right)$$
$$= \left(\frac{U_{i,j+1}^{k+1} - 2U_{i,j}^{k+1} + U_{i,j-1}^{k+1} + U_{i,j+1}^{k} - 2U_{i,j}^{k} + U_{i,j-1}^{k}}{2(\Delta Y)^2}\right) + T_{i,j}^{k}\cos\alpha - \left(M + \frac{1}{K}\right)U_{i,j}^{k}$$
$$+ NC_{i,j}^{k}\cos\alpha \quad (13)$$

Equation on energy:

$$\left(\frac{T_{i,j}^{k+1} - T_{i,j}^{k}}{\Delta t}\right) + U_{i,j}^{k}\left(\frac{T_{i,j}^{k+1} - T_{i-1,j}^{k+1} + T_{i,j}^{k} - T_{i-1,j}^{k}}{2\Delta X}\right) + V_{i,j}^{k}\left(\frac{T_{i,j+1}^{k+1} - T_{i,j-1}^{k+1} + T_{i,j+1}^{k} - T_{i,j-1}^{k}}{4\Delta Y}\right)$$
$$= \frac{1}{Pr}\left(\frac{T_{i,j+1}^{k+1} - 2T_{i,j}^{k+1} + T_{i,j-1}^{k+1} + T_{i,j+1}^{k} - 2T_{i,j}^{k} + T_{i,j-1}^{k}}{2(\Delta Y)^2}\right) \quad (14)$$

Equation on concentration:

$$\left(\frac{C_{i,j}^{k+1} - C_{i,j}^{k}}{\Delta t}\right) + U_{i,j}^{k}\left(\frac{C_{i,j}^{k+1} - C_{i-1,j}^{k+1} + C_{i,j}^{k} - C_{i-1,j}^{k}}{2\Delta X}\right) + V_{i,j}^{k}\left(\frac{C_{i,j+1}^{k+1} - C_{i,j-1}^{k+1} + C_{i,j+1}^{k} - C_{i,j-1}^{k}}{4\Delta Y}\right)$$
$$= \frac{1}{Sc}\left(\frac{C_{i,j+1}^{k+1} - 2C_{i,j}^{k+1} + C_{i,j-1}^{k+1} + C_{i,j+1}^{k} - 2C_{i,j}^{k} + C_{i,j-1}^{k}}{2(\Delta Y)^2}\right) - \lambda C_{i,j}^{k} \quad (15)$$

3. Results

This transient, non-linear non-dimensional coupled PDE is solved by using Crank-Nicholson method. The system of equations was then solved by using well known tri-diagonal matrix algorithm, which is Thomas algorithm in the period of time, t. The integral area is treated as a square or with $X_{max} = 1$ and $Y_{\{max\}} = 22$. The value of Y_{max} is compatible to Y_∞ and it is located outside both the velocity and temperature boundary layers. The value for Y is taken to be 10 by analyzing in detailed consideration in order to satisfy the ultimate and penultimate conditions of Eq. (11) with accuracy up to 10^{-4}. The meshing size has been mended $\Delta X = 0.05, \Delta Y = 0.05$ and the step size is $\Delta t =$

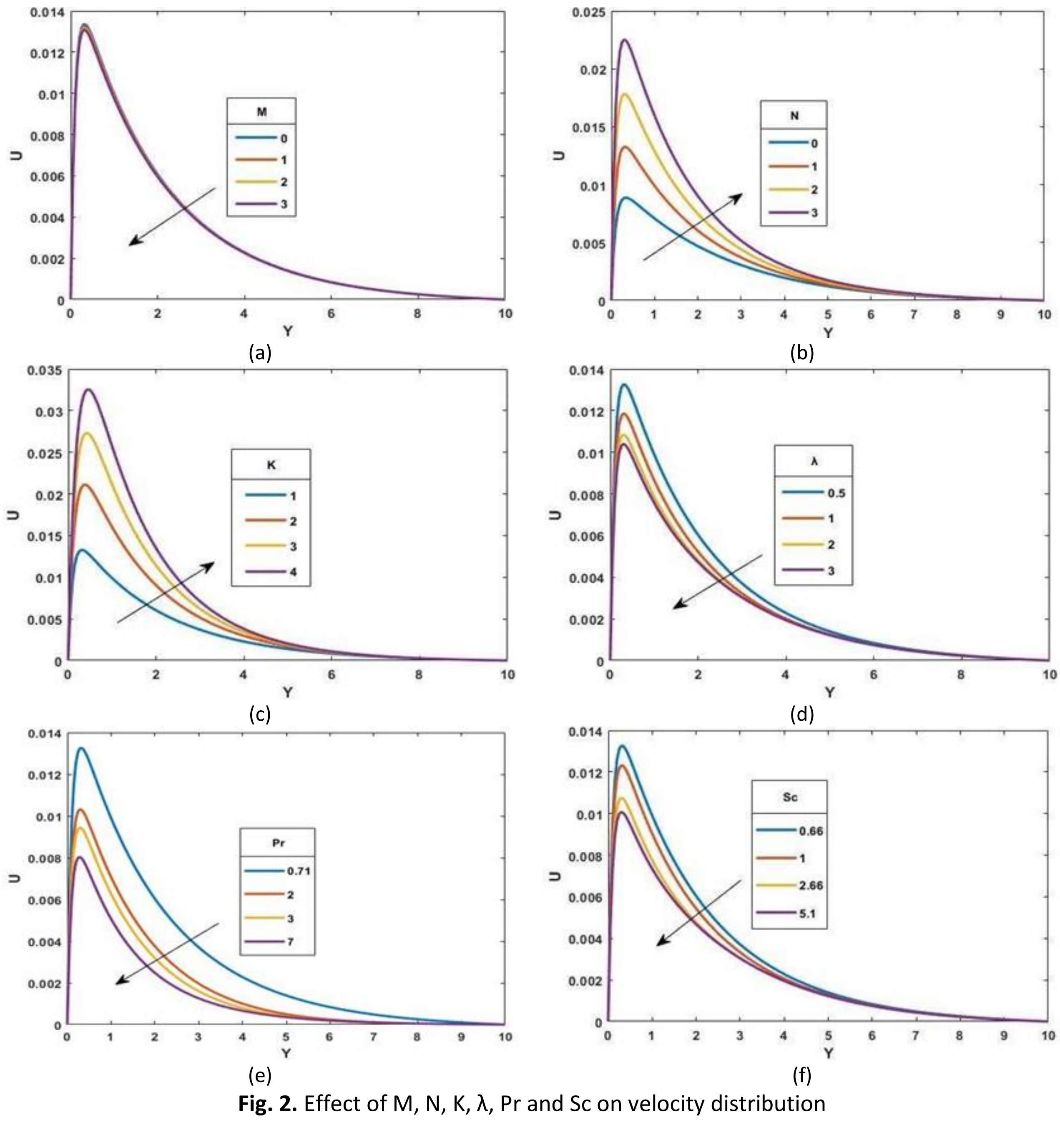
0.01. The shortness ignorance is $O(\Delta t^2 + \Delta Y^2 + \Delta X)$ approaches to null value as $\Delta t, \Delta Y$ and ΔX approaching the quantity of null. Based on the above calculations, approximations and computations, it can be concluded that an elaborate and systematic plan of action shows a solution can be able to exist and perform in harmonious as explained by Bapuji *et al.,* [19, 20] and Thandapani *et al.,* [21].

The variation effects of governing parameters on velocity, temperature and concentration profiles are examined. Numerical evaluation for M , N, K, λ, Pr and Sc are performed, and the results are illustrated graphically. The numerical computations are taken at fixed parameters $t = 10, n = 0.25, m = 0.25, \alpha = 20^o, K = 0.5, M = 1, N = 1, \lambda = 0.5, Pr = 0.71$ and $Sc = 0.66,$ except where specified. The numerical ranges of parameter considered in the figures are $K = 1, 2, 3, 4,$ $M = 0, 1, 2, 3,$ $N = 0, 1, 2, 3,$ $\lambda = 0.5, 1, 2, 3,$ $Pr = 0.71, 2, 3, 7,$ and $Sc = 0.66, 1, 2.66, 5.1.$

Figure 2 represents the effect of M , N, K, λ, Pr and Sc on velocity distribution, respectively. Through this plot (Figure 2(a)), it is examined that when magnetic effect is elevated, the velocity of the fluid decrease. This is due to strong Lorentz force which is resistant to the motion of fluid and gradually reduces the velocity of the fluid. In addition, the velocity profile decreases for increasing λ and Sc (Figure 2(d) and 2(f)). When the values of λ increase, the effect of the mass buoyancy force drop the concentration of fluid particles near the cone surface and thus decreases the fluid velocity. The computations also show that the velocity reduces as Pr rises since the fluid is increasingly viscous as Pr (Figure 2(e)) rises. On the other hand, the velocity profiles increase as N and K increases (Figure 2(b) and 2(c)). This is due to a cause that as N increases, β_T diminishes and simultaneously in the hydrodynamical boundary layer, the liquid flow velocity boosts. Moreover, the variation change in the area of fluid flow due to K is theoretically expected as an improved porosity effect reduce the obstacles in the flow, and result in an increase in velocity.

Figure 3 demonstrates the effect of M , N, K, λ, Pr and Sc on temperature distribution, respectively. Through this plot, it is evident from the figure that the temperature decreases gradually for higher values of N, K and Pr (Figure 3(b), 3(c) and 3(e)). Increasing the buoyancy ratio tends to increase the buoyancy force and values of Pr, accelerating the flow and thus increasing the heat transfer rate. On the contrary, the temperature dropped for increasing M, λ and Sc (Figure 3(a), 3(d) and 3(f)). It is obvious that an increase in the value of M encourages the temperature distribution. Normally, a high value of M generates a resistive force opposite to fluid flow. Owing to this fact, the thermal boundary layer raised up.

Figure 4 elucidates the influence of M, N, K, λ, Pr and Sc on the concentration distribution. It is observed that the concentration increases for increasing the values of M, N and Pr (Figure 4(a), 4(b) and 4(e)). Meanwhile, the concentration drops as K, λ and Sc increases (Figure 4(c), 4(d) and 4(f)). Due to the increase in λ, the constituents of the higher concentration zone (adherent to the surface) move to the species in the lower concentration zone (free stream), which lessen the thickness of the boundary layer of concentration, thus lower the concentration values.



(a) (b) (c) (d) (e) (f)

Fig. 2. Effect of M, N, K, λ, Pr and Sc on velocity distribution

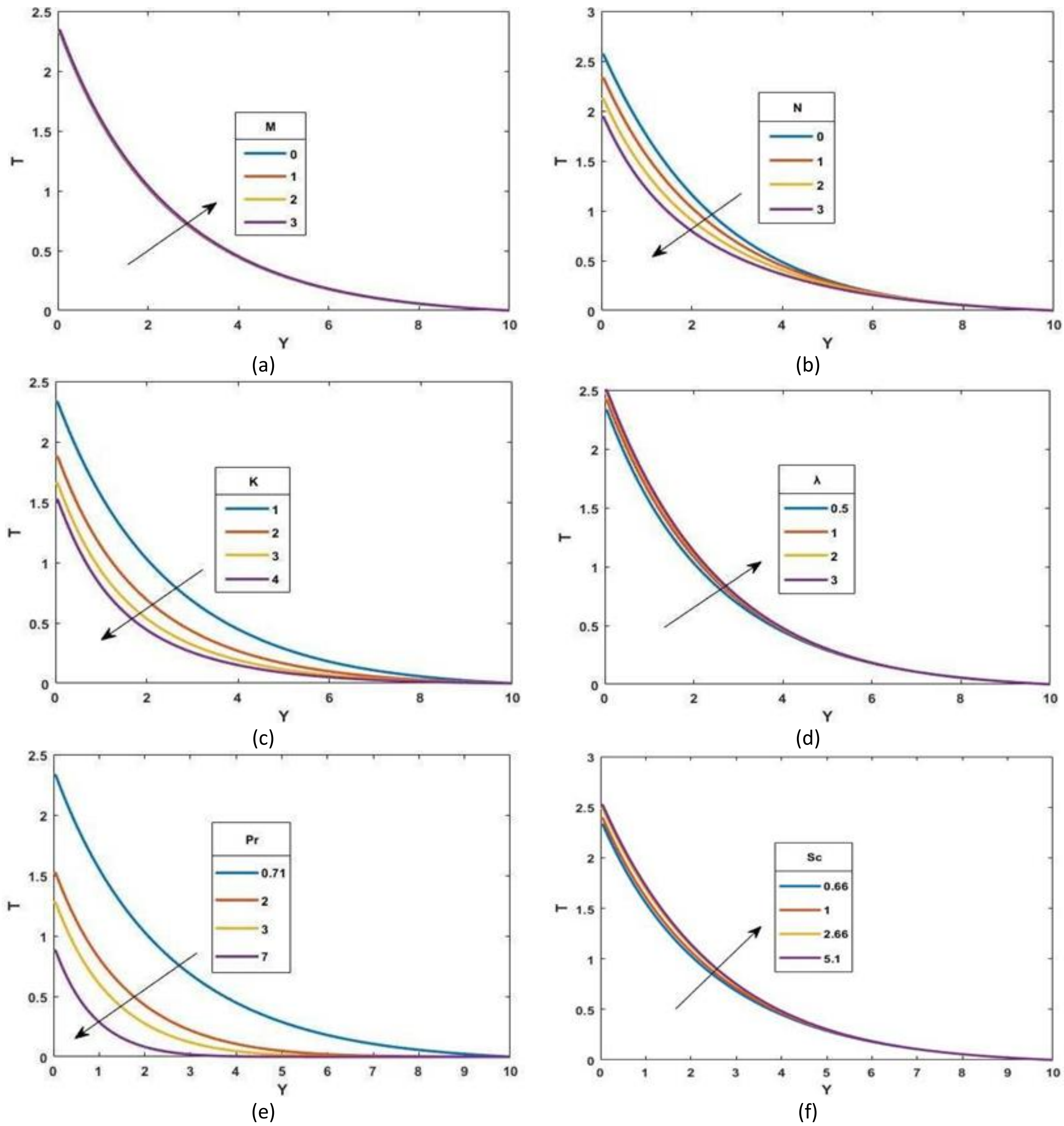
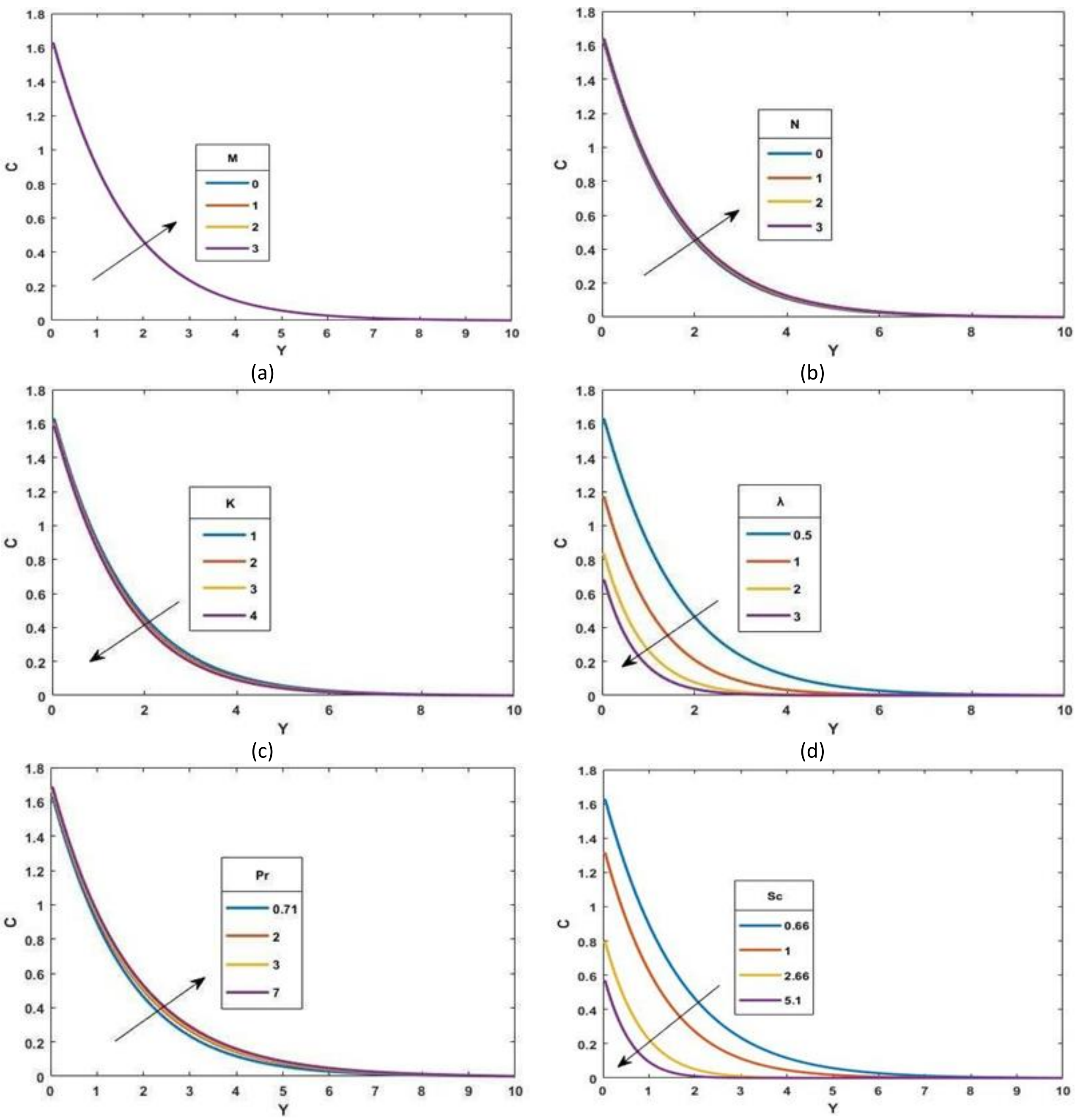


Fig. 3. Effect of M, N, K, λ, Pr and Sc on temperature distribution



(a) (b) (c) (d) (e) (f)

Fig. 4. Effect of M, N, K, λ, Pr and Sc on concentration distribution

4. Conclusion

The problem of magnetic field, chemical reaction and porous media effects with free convection flow over a non-isothermal vertical cone has been studied and considered. The formulation and the solutions of the problem has been presented by using MATLAB programming software. The result showed that the velocity profile increases when porosity parameters and buoyancy ratio parameter are escalated, while an opposite behavior is notice against magnetic parameter and chemical reaction parameter. The temperature profile increases when magnetic parameter and chemical reaction parameter rises, and opposite trend is observed against porosity parameter and buoyancy ratio parameter. In addition, the porosity parameter and chemical reaction parameter decreases, while magnetic parameter and buoyancy ratio parameter increases as the concentration profile increases.

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