

UNSTEADY MAGNETOHYDRODYNAMIC MIXED CONVECTION FLOW WITH HEAT AND MASS TRANSFER OVER A HORIZONTAL CIRCULAR CYLINDER EMBEDDED IN A POROUS MEDIUM

by

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Original scientific paper
DOI: 10.2298/TSC16S5381B

The objective of the present study is to investigate the effect of flow parameters on the mixed convection heat and mass transfer of an unsteady magnetohydrodynamic flow of an electrically conducting, viscous, and incompressible fluid over a horizontal circular cylinder embedded in porous medium, considering effects of chemical reaction and heat source/sink, by taking into account viscous dissipation. The present magnetic field is homogenous and perpendicular to the body surface. Magnetic Reynolds number is significantly lower than one i. e. considered the problem is in approximation without induction. The governing non-linear partial differential equations and associated boundary conditions are made dimensionless using a suitable similarity transformation and similarity parameters. System of non-dimensionless equations are solved numerically by implicit finite difference three-diagonal and iteration method. Numerical results obtained for different values of porous medium, magnetic, diffusion and temperature parameters, buoyancy diffusion parameter and thermal parameter and for different values Prandtl, Eckart, and Schmidt numbers. Variation of velocity, temperature and concentration and many integral and differential characteristics boundary layer are discussed and shown graphically.

Key words: magnetohydrodynamic boundary layer, mixed convection, porous medium, chemical reaction, heat source or sink

Introduction

Many engineering applications comfort with magnetohydrodynamic (MHD) flow and heat and mass transfer such as the geometric principle, the heat exchanger, and the nuclear reactor cooling. On the other hand, the analysis of flow around and inside porous media has achieved signification attention lately owing to importance in various application such as pipe flows, geothermal engineering, filtration processes in chemical engineering, and electronic cooling. In the last time, many researchers have studied magnetic effects in various geometries embedded in a porous medium, Interest in effect of outer magnetic filed on heat-physical processes appear sixty years ago [1]. Many researchers investigated the effects of MHD free and forced convection flow both experimentally and theoretically [2-4]. A number of different physical models of MHD boundary layer are investigated using different methods giving exact or approximated solutions [5-8]. Special interest shown by the analysis of MHD flow

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around a horizontal circular cylinder [9-13] and flow around cylinder embedded in porous medium, without [14, 15] and with influence of a magnetic field [16, 17].

The subject of the present study is given an analytic investigation on the effects of heat and mass transfer in 2-D unsteady laminar, dynamic, thermal, and diffusion MHD laminar boundary layer flow over a horizontal circular cylinder embedded in porous medium of electrical conductivity fluid, in the presence of diffusion buoyancy-force, heat source or sink, and chemical reactions. The external magnetic field is homogeneous and perpendicular to the body. Magnetic Reynolds number is significantly lower then. Considered problem is in approximation without induction. System of dimensionless equations is solved using the finite difference method and iteration method. Numerical results are obtained and presented for different parameters such Prandtl number, Eckart number, Schmidt number, magnetic number, temperature, thermal, diffusion, and chemical reaction parameters. The solutions for the flow, temperature and diffusion transfer and other integral characteristics, boundary layer, are evaluated numerical for different values the magnetic field. Transient effects of velocity, temperature, and diffusion are analysed.

Formulation of the problem

A mathematical model, unsteady MHD laminar, dynamics, thermal, and diffusion laminar boundary layer, on horizontal circular cylinder, with the uniform external magnetic field $B(x, t)$ perpendicular to the surface of the body, when the magnetic Reynolds number is significantly lower – approximation without induction, and the free stream velocity $U(x, t)$, ambient temperature, T_∞ , and concentrations, c_∞ , defined with system of for simultaneous equations.

In the following system of equations and boundary conditions the parameter labelling used is common for the MHD boundary layer theory, x, y is the longitudinal and transversal co-ordinate, u, v – the longitudinal and transversal velocity components, on outer edge of boundary layer, ν – the kinematic viscosity of fluid, K – the permeability of the porous medium, σ – the fluid electrical conductivity, ρ – the fluid density, β_c – the coefficient of diffusion expansion, λ – the thermal conductivity, c_p – the the specific heat at constant pressure, D – the effective diffusion coefficient, k_h – the chemical reaction parameter, T – the temperature, and c – the concentration of ionic species in solution

Continuity, momentum, energy, and mass diffusion equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} + g\beta_c(c - c_\infty) + \frac{\sigma B^2}{\rho}(U - u) + \frac{\nu}{K}(U - u) \quad (2)$$

$$\begin{aligned} \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = & \frac{\lambda}{\rho c_p} \frac{\partial^2 T}{\partial y^2} + \frac{1}{c_p} \left(\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} \right) + \\ & + (U - u) + \frac{\nu}{c_p} \left(\frac{\partial u}{\partial y} \right)^2 + \frac{\sigma B^2}{\rho c_p} u(u - U) + Q(T - T_\infty) \end{aligned} \quad (3)$$

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D \frac{\partial^2 c}{\partial y^2} + k_h(c - c_\infty) \quad (4)$$

and corresponding boundary and initial conditions:

$$\begin{aligned}
 u = 0, \quad v = 0, \quad T = T_w(x), \quad c = c_w(x) \quad \text{for } y = 0 \\
 u \rightarrow U(x, t), \quad T \rightarrow T_\infty, \quad c = c_\infty \quad \text{for } y \rightarrow \infty \\
 u = u_0(x, y), \quad T = T_0(x, y), \quad c = c_0(x, t) \quad \text{for } t = t_0 \\
 u = u_1(t, y), \quad T = T_1(t, y), \quad c = c_1(x, t) \quad \text{for } x = x_0
 \end{aligned} \tag{5}$$

The term $Q(T - T_\infty)$ is assumed to be the amount of heat generated or absorbed per unit volume, when Q is a heat generation/absorption constant.

The introduction of the system of equations and associated boundary conditions (1)-(5), stream function $\psi(x, y, t)$, new general similarities variables [6, 8, 12]:

$$\begin{aligned}
 x = x, \quad t = t, \quad y = \frac{h(x, t)}{D_0} \eta(x, y, t), \quad \psi(x, y, t) = \frac{U(x, t)h(x, t)}{D_0} \varphi(x, t, \eta), \\
 C(x, t, \eta) = \frac{c_w - c}{c_w - c_\infty}, \quad \theta(x, t, \eta) = \frac{T_w - T}{T_w - T_\infty}
 \end{aligned}$$

and Eckart, Prandtl, and Schmidt numbers:

$$\text{Ec} = \frac{U^2}{c_p(T_w - T_\infty)}, \quad \text{Sc} = \frac{\nu}{D}, \quad \text{Pr} = \frac{\nu \rho c_p}{\lambda}$$

the system of eqs. (1)-(4) is transformed into non-dimensional form:

– momentum equation

$$\begin{aligned}
 D_0^2 \varphi_{\eta\eta\eta} + \frac{f(x, t) + 2f_1(x, t)}{2} \varphi \varphi_{\eta\eta} + \frac{\eta Z(\dot{x}, t)}{2} \varphi_{\eta\eta} + f_1(x, t)(1 - \varphi_\eta^2) + \alpha_1^c(x, t)(1 - C) + \\
 + [f_0(x, t) + g(x, t) + p(x, t)](1 - \varphi_\eta) = Z \varphi_{\eta t} + Z(x, t)U(x, t)(\varphi_\eta \varphi_{\eta x} - \varphi_x \varphi_{\eta\eta})
 \end{aligned} \tag{6}$$

– energy-equation

$$\begin{aligned}
 \frac{D_0^2}{\text{Pr}} \theta_{\eta\eta} + \frac{f(x, t) + 2f_1(x, t)}{2} \varphi \theta_\eta + \frac{\eta Z(\dot{x}, t)}{2} \theta_\eta - g(x, t)(1 - \varphi_\eta) \varphi_\eta - \\
 - \text{Ec}[f_1(x, t) + f_0(x, t)](1 - \varphi_\eta) + [l_1(x, t) - q(x, t)](1 - \theta) + \\
 + D_0^2 \text{Ec}(\varphi_{\eta\eta})^2 = Z \theta_t + Z(x, t)U(x, t)(\varphi_\eta \theta_x - \varphi_x \theta_\eta)
 \end{aligned} \tag{7}$$

– mass diffusion equation

$$\begin{aligned}
 \frac{D_0^2}{\text{Sc}} C_{\eta\eta} + \frac{f(x, t) + 2f_1(x, t)}{2} \varphi C_\eta + \frac{\eta Z(\dot{x}, t)}{2} C_\eta + [c_1(x, t) - s(x, t)](1 - C) = Z C_t + \\
 + Z(x, t)U(x, t)(\varphi_\eta C_x - \varphi_x C_\eta)
 \end{aligned} \tag{8}$$

with boundary conditions:

$$\begin{aligned}
 \varphi = \frac{\partial \varphi}{\partial \eta} = \varphi_\eta = 0, \quad \theta = 0, \quad C = 0 \quad \text{for } \eta = 0 \\
 \varphi_\eta \rightarrow 1, \quad \theta \rightarrow 1, \quad C \rightarrow 1 \quad \text{for } \eta \rightarrow \infty
 \end{aligned}$$

where dimensionless parameters similarity are introduced in the following form:

– dynamical-parameters

$$f(x, t) = U(x, t)Z'(x, t), \quad f_1(x, t) = U'(x)Z(x, t), \quad f_0(x, t) = \frac{U(\dot{x}, t)}{U(x, t)} Z(x, t)$$

– magnetic-parameter

$$g(x, t) = N(x, t)Z(x, t), \quad N(x, t) = \frac{\sigma B(x, t)^2}{\rho}$$

– parameter of the porous medium

$$p(x, t) = \frac{v}{K} Z(x, t)$$

– temperature-parameter

$$l_1(x, t) = \frac{T'(x)}{T_w(x) - T_\infty} Z(x, t)$$

– thermal-parameter

$$q(x, t) = QZ(x, t)$$

– chemical-reaction parameter

$$s(x, t) = k_h Z(x, t)$$

– diffusion-parameter

$$c_1(x, t) = \frac{c'_w(t)}{c_w(t) - c_\infty} U(x, t)Z(x, t)$$

(8) diffusion buoyancy-parameter $\alpha_1^c = UZ\alpha^c$:

$$\alpha^c(x, t) = \frac{g\beta_c \sin \alpha(x)}{c_p E_c^c} = \alpha^{cc} \sin \alpha(x) \quad (9)$$

where $Z(x, t) = \delta^{**2}/v$.

Sets of these independent parameters represents the impact of free stream velocity change $U = U(x, t)$, influence of magnetic field $N(x, t)$, porosity media K , temperature $T_w(x)$, and diffusion $c_w(x)$ in the body, the influence of chemical reactions k_h or heat source or sink Q , $\alpha^c(x, t)$, buoyancy force. The integral form $Z(x, t)$, also present and pre-history of flow in boundary layer.

The D_0 is the normalizing constant, which is determined from the condition that the first, dynamics equation, is reduced to the case of flow past a flat plate:

$$\varphi_{0\eta\eta\eta} + \varphi_0\varphi_{0\eta\eta} = 0$$

from which value $D_0 = (\xi_0)^{1/2} = 0.469$.

To determine the four unknown functions, $\varphi(x, t, \eta)$, $Q(x, t, \eta)$, $C(x, t, \eta)$, and the new unknown function $Z(x, t)$, it is necessary to introduce one more, fourth equation. It may be an integral equation of dynamical, thermal, or diffusion boundary layer. In this paper, the impulse equation is used as an integral equation:

$$\frac{H^*}{2} \frac{\partial Z(x, t)}{\partial t} + \frac{U(x, t)H^{**}}{2} \frac{\partial Z(x, t)}{\partial x} = \zeta - \left\{ \begin{array}{l} \left[\frac{U(\dot{x}, t)}{U(x, t)} + U'(x, t) + N(x, t) \right] H^* \\ + 2U'(x, t)H^{**} + U\alpha^c H_c \end{array} \right\} Z(x, t) \quad (10)$$

with initial and boundary conditions:

- (1) $\partial Z/\partial t = 0$, for $t = 0$, this initial condition, means the pre-history of the boundary layer or stationary boundary,
- (2) $\partial Z/\partial x = 0$, for $x = 0$, this boundary condition means, that all the boundary layer thickness, in front of the stagnation point has a tangent parallel to the x-axis.

In the integral eq. (10) are introduced characteristic functions of the boundary layer in the following form: shear stress on the body:

$$\zeta = \left[\frac{\partial \left(\frac{u}{U} \right)}{\partial \left(\frac{y}{h} \right)} \right]_{y=0}$$

$$H^* = \frac{\delta^*}{h}, \quad H^{**} = \frac{\delta^{**}}{h}, \quad H_c = \frac{\delta_c}{\delta^{**}}$$

where

$$\delta^* = \int_0^\infty (1 - \varphi_y) dy - \text{displacement thickness,}$$

$$\delta^{**} = \int_0^\infty \varphi_y (1 - \varphi_y) dy - \text{momentum thickness,}$$

$$\delta_c = \int_0^\infty \left(1 - C \frac{u}{U} \right) dy - \text{temperature thickness,}$$

$$\delta_c = \int_0^\infty \left(1 - C \frac{u}{U} \right) dy - \text{mass diffusion thickness.}$$

The system of eqs. (6)-(8), (10), obtained in the paper, is a universal-generalized system. With equalization to zero certain parameters similarities, this system reduced to simple physical models

In this papper, as a concrete example MHD boundary layer, considers the unsteady flow around a horizontal circular cylinder. When the strength $B(x, t)$, of externally uniform magnetic field, is constant, the analysis will be carried in non-dimensional form, where longitudinal co-ordinate and velocity will be scaled in relation to velocity of outer flow $U(x, t)$ and the radius of the cylinder a , and the co-ordinate and velocity, perpendicular to the boundary

layer, will be divided with $\text{Re}^{1/2}$ ($\text{Re} = U_\infty a/\nu$). The boundary conditions for velocity of outer flow, temperature and concentration and friction on the body, determined with:

$$\begin{aligned} \hat{U}(\hat{x}, \hat{t}) &= (1 + a_1 \hat{t}^2) \sin \hat{x} T_w(\hat{x}) = T_\infty + T_0(1 + a_2 \hat{x}) c_w(\hat{x}, \hat{t}) = c_\infty + c_0(1 + a_3 \hat{t}) \\ \tau_w &= \mu \left(\frac{\partial u}{\partial y} \right)_0 \end{aligned} \quad (11)$$

where \hat{x} is the angular co-ordinate of arbitrary points on the cylinder measured from the stagnation point in radians, and \hat{t} – the dimensionless size of the time.

Size in terms a_1 , a_2 , and a_3 are arbitrary positive or negative dimensionless constants. Positive constant value a_1 corresponding to rapid fluid flow, a negative, slow fluid flow. Positive or negative value constants a_2 , and a_3 indicate increase or decrease the temperature and concentration, with angular co-ordinate \hat{x} .

For this case introduced similarity parameters (9) are transformed into the form:

$$\begin{aligned} f(x, t) &= (1 + a_1 t^2) \sin x Z'(x, t), & f_1(x, t) &= (1 + a_1 t^2) \cos x Z(x, t), \\ f_0(x, t) &= \frac{2t}{1 + a_1 t^2} Z(x, t), & g(x, t) &= N Z(x, t), & l(x, t) &= \frac{a_2}{1 + a_2 t} Z(x, t), \\ c_1(x, t) &= \frac{a_3}{1 + a_3 t} Z(x, t), & p(x, t) &= \frac{\nu}{K} Z(x, t), \\ q(x, t) &= Q Z(x, t), & s(x, t) &= k_h Z(x, t) \end{aligned} \quad (12)$$

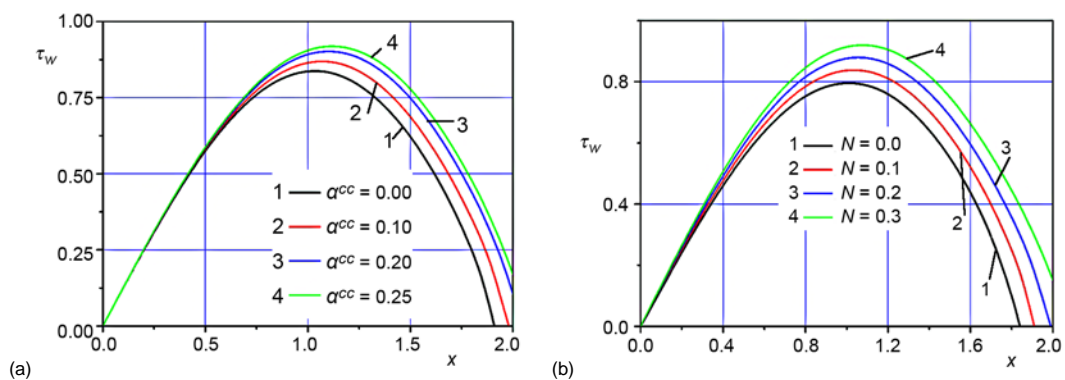
Method of solution, results, and discussion

In this paper the non-dimensional system of parabolic differential eqs. (6)-(8) and integral momentum eq. (10), with introduced boundary conditions (11), is solved numerically with most efficient and accurate method known as finite difference method with an adequate block scheme. Approximation of non-linear differential equations is performed by a system of algebraic equations, defined on a discrete set of points of integration network as defined in the 3-D co-ordinate system x/m , t/n , η/k . For linearization the non-linear members of equations is solved using iteration method. In this paper, the obtained system of algebraic equations, that is suitable for further computations, is solved using three-diagonal method.

The solutions for the dimensionless velocity, temperature and concentration and integral characteristics boundary layer, are evaluated numerical for difference values of numbers Prandtl, Eckart, and Schmidt, and also for different values dynamic and magnetic parameters, parameter of the porous medium, temperature and diffusion parameters, thermal and chemical reaction parameters. Transient effects of velocity, temperature and diffusion, is also analysed.

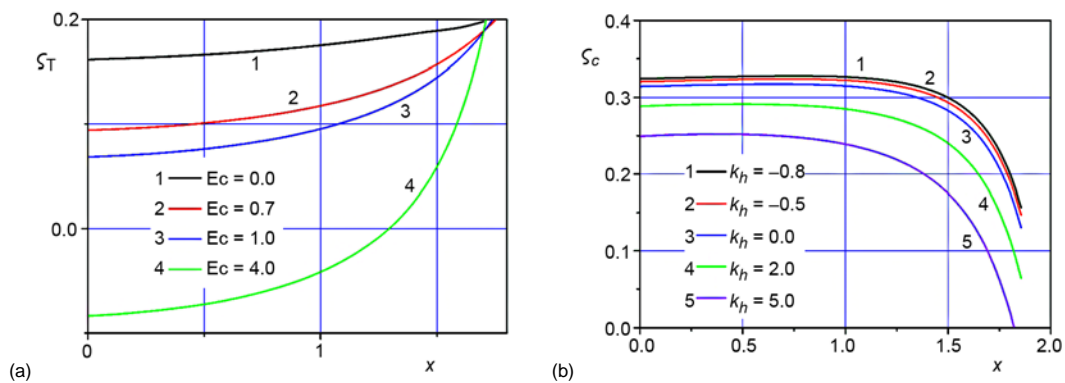
A part of the numerical obtained results is presented in the figs. 1-10. Figures 1-4 show the variations of the variables τ_w , $\zeta_T = \theta_0$, and $\zeta_c = C_{\eta 0}$, in function of the co-ordinate x , figs. 5-7 show displacement thickness, temperature thickness, and mass diffusion thickness. Figures 8-10 show the variations dimensionless velocity, temperature, and concentration, in a certain section of the boundary layer, for several values of the magnetic parameter N , Prandtl number, Eckart number, and Schmidt number and for several values of the $p \rightarrow K$ – permeability parameter, $q \rightarrow Q$ – heat source/sink parameter, and $s \rightarrow k_h$ chemical reaction parameter.

From diagrams in fig. 1(a), it can be noticed that the diffusion buoyancy-parameter, α^{cc} , influences considerably to the position of the boundary layer separation point. The increase in the buoyancy-parameter move the point of boundary layer separation downstream and in that sense its influence can be considered positive. These conclusions are valid also for values of the magnetic parameter, N , and porous parameter, p , fig. 1(b). The increase values of the magnetic parameter, and porous parameter, move the point of boundary layer separation downstream and in that sense its influence can be considered positive.



Figures 1. stream function τ_w

Figures 2(a) and 2(b), show the graphs of characteristic functions: dimensionless temperature gradient ζ_T and dimensionless concentration gradient ζ_c , in function of co-ordinate x , for different values of Eckart number, respectively, for different values chemical reaction parameter $s-k_h$.

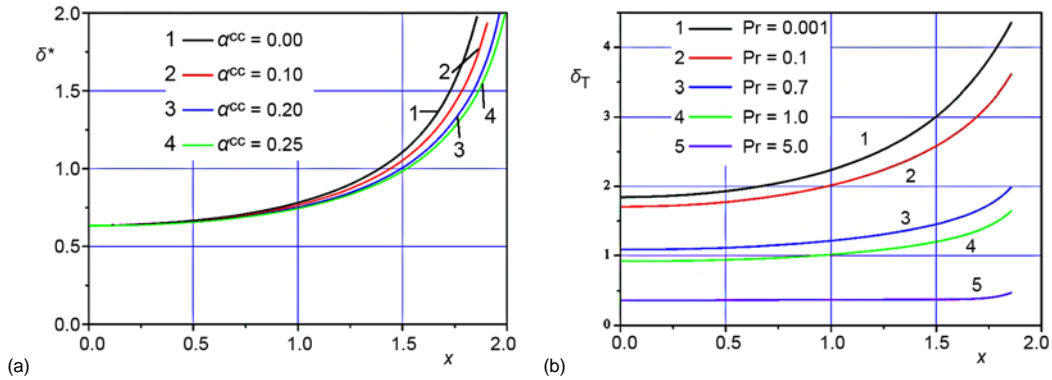


Figures 2. Dimensionless temperature ζ_T and concentration gradient ζ_c

Figures 3(a), 3(b), and 4 show the graphs of integral characteristic functions: thickness of dynamic boundary layer, δ^* , thickness of temperature boundary layer, δ_T , and thickness concentration boundary layer, δ_c , in function of co-ordinate x , for different values of Prandtl number, respectively, for different values diffusion buoyancy-parameter α^{cc} .

Figures 5, 6, and 7, show the influence of diffusion buoyancy-parameter, α^{cc} , thermal parameter $q \rightarrow Q$, magnetic field, N , and porous parameter, p , on profiles the develop-

ment of dimensionless velocity, temperature, θ , and concentration, C , as a function of the transverse dimensionless co-ordinates η .



Figures 3. Thickness of dynamic δ^* and of temperature boundary layer δ_T

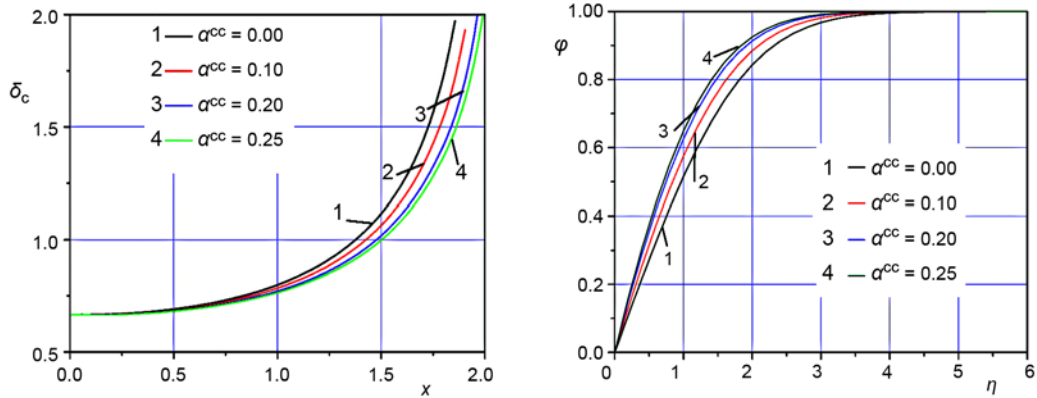


Figure 4. Thickness of diffusion boundary layer δ_c

Figure 5. Dimensionless velocity ϕ

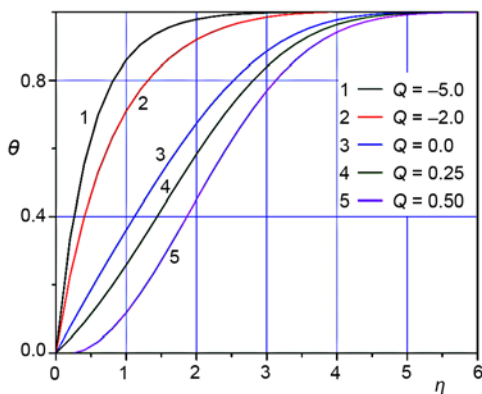


Figure 6. Dimensionless temperature θ

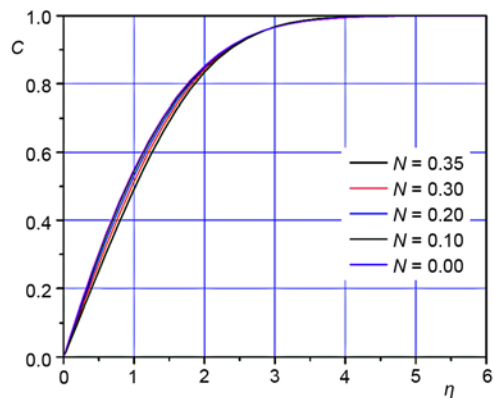


Figure 7. Dimensionless concentration C

Conclusion

This study presents the research of the laminar unsteady 2-D dynamic, thermal, and diffusion MHD laminar boundary layer flow over a horizontal circular cylinder. Fluid is incompressible and electrical conductivity. Analyzed the effects of the presence of diffusion buoyancy force, permeability of porous medium, heat source or sink and chemical reactions. The system non-linear partial differential governing boundary layer equations and associated boundary conditions are converted into a dimensionless form using a suitable similarity transformation and similarity parameters. Numerical solution of dynamic, temperature and diffusion boundary layer equations, with integral impulse equation are obtained by using the finite difference method, combined with the method of iteration. Obtained results show the solutions for the velocity, temperature, and concentration, and integral characteristics boundary layer, are obtained and presented for different values introduced similarity parameters. In this paper, the results of integral and differential characteristics of the boundary layer, show the effects of magnetic field, diffusion buoyancy force, permeability of porous medium, heat source or sink, and chemical reactions on the development of fluid flow around the horizontal circular cylinder surface.

Nomenclature

a, b – constants, [-]
 B – induction uniform magnetic field, [T]
 C – dimensionless concentration function
 c – concentration of the fluid
 D – effective diffusion coefficient [m^2s^{-1}]
 H – characteristic function, [-]
 K – permeability of the porous medium, [m^2]
 k_h – chemical reaction parameter [s^{-1}]
 N – characteristic function, [s^{-1}]
 Q – heat generation/absorption constant, [s^{-1}]
 T – fluid temperature, [K]
 t – time, [s]
 U – free stream velocity, [ms^{-1}]
 u, v – velocities in boundary layer, [ms^{-1}]
 x, y – longitudinal and transversal co-ordinates, [m]
 Z – characteristic function, [s]

Greek symbols

δ – boundary layer thickness, [m]
 ζ – characteristic function, [-]
 η – dimensionless transversal co-ordinate, [-]
 θ – dimensionless temperature function, [-]
 σ – the fluid electrical conductivity, [$\text{Nm}^3\text{V}^{-2}\text{s}^{-1}$]
 τ – shear stress, [Pa]
 φ – dimensionless stream function, [-]
 ψ – stream function, [m^2s^{-1}]

Subscripts

η, x, t – differentiation with respect to η, x, t
 w – surface conductions
 0 – initial time moment $t = t_0$
 1 – boundary layer cross-section $x = x_0$
 ∞ – conductions far away from the surface

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