ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 10, October 2014

MHD Flow, Heat and Mass Transfer about a Horizontal Cylinder in Porous Medium

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ABSTRACT: MHD flow, heat and mass transfer through porous media have seen a tremendous increase in research attention. This rapidly increasing research activity has been due to the increasing number of practical applications on porous media in chemical reactors, the underground spread of pollutant, many modern industries ranging from micro to macro and many other heat transfer processes. The problem of flow, heat and mass transfer about a horizontal circular cylinder in porous medium is considered in this study. Governing boundary layer equations are first transformed into ordinary differential equations and are solved by using Matlab's built in solver bvp4c. Velocity, temperature and concentration profiles are shown graphically for different values of parameters involved in the dimensionless equations and discussed in detail.

KEYWORDS: Horizontal circular cylinder, MHD flow, heat and mass transfer, porous medium, bvp4c.

I. INTRODUCTION

In 1856 Darcy performed experiments on flow through a sand column and based on his findings he postulated a law for determining velocity in isothermal flow in porous medium. This law is known as Darcy's law. Since then the theory has been applied to a number of disciplines including ground water hydrology, petroleum reservoir engineering, soil mechanics, chemical process engineering. In recent years there have been broad and considerable published research papers in the field of convective heat and mass transfer in porous media. Nield and Bejan [1-2], Ingham and Pop [3], Vafai [4], Pop and Ingham [5], Neild and Bejan [6] reviewed a good number of articles in their books. These indicate the level of understanding of momentum, heat and mass transport phenomena in porous media. However, much of the preceding works have been done either convection in plane walls or in channels bounded by porous medium. Till date there are relatively very limited published works on convective heat and mass transfer from heated bodies of higher complexity, such as circular cylinder embedded in porous media.

MHD Flow, heat and mass transfer from cylinders immersed in a fluid saturated porous media have practical importance in many engineering applications such as compact heat exchangers, solar power collectors and nuclear reactors. Cheng.P [7] studied the mixed convection for both horizontal cylinder and sphere in a fluid-saturated porous medium and Zhou and Lai [8] carried out studies in aiding and opposing mixed convection from a cylinder in a saturated porous medium. They discussed how the Rayleigh number and mixed convection parameter number Gr/Re affected the flow and heat transfer characteristics. Sparrow and Lee [9], looked at the problem of vertical stream over a heated horizontal circular cylinder. They obtain a solution by expanding velocity and temperature profiles in powers of x, the co-ordinate measuring distance from the lowest point on the cylinder. But the exact solution could not be reached out because of the non-linearity of the Navier-Stokes equations. Ingham and Pop [10] investigated the natural convection from a heated circular cylinder in an unbounded region of porous medium for the full range of Rayleigh numbers. They obtained a qualitative solution for small Rayleigh numbers and the second-order boundary-layer solution was obtained that takes into account the first-order plume solution for large Rayleigh numbers. They found that the plume solution which developed with increasing Rayleigh number agreed with that predicted by the theory presented using the boundary-layer approximation. No separation of the flow at the top of the cylinder was found and there were no indications that it would appear at higher values of the Rayleigh number. They also found a reasonable agreement with the existing experimental results for Rayleigh numbers of order unity. However, the Rayleigh number

DOI: 10.15680/IJIRSET.2014.0310008

ISSN: 2319-8753

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when increased to order 10^2 they experienced a large discrepancy between the theoretical and experimental results. Badr and Pop [11] investigated numerically mixed convection heat transfer from a horizontal rod of circular cross-section that was embedded in a porous medium. The rod temperature was first assumed to be the same as that of the medium and then suddenly increased to a higher constant value. The steady-state problem was solved by the method of series truncation in combination with a finite-difference scheme for the two flow configurations of parallel and counter-flow regimes. The flow and thermal fields as well as the variations of the average and local heat transfer rates with a wide range of Reynolds number, Grashof number and buoyancy parameter were examined in detail for a Prandtl number of 0.7. One of the interesting features found was the occurrence of a re-circulating flow zone near the upper half surface of the rod in the case of the counter-flow regime. Saeid [12] studied a non-equilibrium model to analyze the effect of the governing parameters, which were the heat transfer coefficient between the solid and fluid phases H and the porosity scaled thermal conductivity ratio Kr. The results showed that increasing H or Kr lead to increase in the total average Nusselt number. The value of the average Nusselt number for both fluid and solid phases as well as the total average Nusselt number approached the corresponding values of the thermally equilibrium model at high value of H×Kr. The forced convection regime used the simple Darcy model to relate the flow velocity to the applied pressure gradient. Cheng.P [13], Sano [14], Pop and Yan [15] used Darcy's model and presented analytic solutions for the energy equation in the boundary layer region. Kimura [16] analytically and numerically examined transient forced convection from a cylinder in a porous layer with cross flow. The Nusselt number variation for the transient stage and at the steady state was obtained analytically. It was found that the length of the transient period to reach the convective steady state was inversely proportional to Peclet number. Chamkha and Quadri[17] studied the heat and mass transfer from a permeable cylinder in a porous medium with magnetic field and heat generation/absorption effects and a parametric study of the physical parameters was conducted numerically.

A study of the flow of electrically conducting fluid in presence of magnetic field is important from the technical point of view and such types of problems have received much attention by many researchers. Merkin [18-19] was the first person to find the complete solution of MHD flow problem by using series expansion together with finite difference scheme. He also investigated the problem of free convection in the boundary layer flow on cylinder of elliptic cross section. Vajravelu and Hadjinicolaou [20] studied the convective heat transfer in an electrically conducting fluid at a stretching surface and found that the rate of cooling and hence the desired properties of the end product can be controlled by the use of electrically conducting fluids with the application of magnetic field. They also found that the velocity profiles are similar in the absence of free stream and differential system gave rise to non-similar velocity profiles in the boundary layer. Raptis and Kafousian [21] have investigated the problem of magneto-hydrodynamic free convection flow and mass transfer through a porous medium bounded by an infinite vertical porous plate with constant heat flux. Postelnicu [22] discussed magnetic field effect on heat and mass transfer by natural convection from vertical surfaces in porous media and found that local Nusselt number and local Sherwood number increases with the increasing values of magnetic field parameter.

Despite the large number of previous work done by different researchers dealing with MHD fluid flow, heat and mass transfer in porous media, there is still a considerable need for more comprehensive and reliable methods of accurately predicting the fluid flow, heat and mass transfer characteristics in many problems. In this paper we have investigated numerically the solution for MHD flow, heat and mass transfer problem about a horizontal circular cylinder in porous medium by using Matlab's built in solver bvp4c.

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II. MATHEMATICAL MODELLING

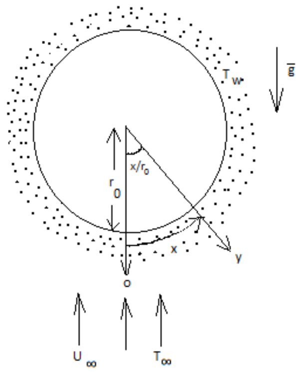

Figure1: The coordinate system about a horizontal cylinder in porous medium

We consider two dimensional laminar boundary flow of an incompressible viscous, thermally and electrically conducting fluid past a horizontal circular cylinder embedded in a saturated porous medium where x is the coordinate in the stream wise direction along the surface of the cylinder from the lowest point and y is the coordinate perpendicular to the surface; r_0 is the radius of the cylinder and x/r_0 is the angle of the y direction with respect to the vertical; A uniform weak magnetic field B_0 is applied in the axial direction. It is assumed that there is no applied voltage which implies the absence of an electrical field. Applied magnetic field is assumed to be very small so that the induced magnetic field and the Hall effects are negligible. T_w is the temperature of the heated surface and T_∞ is the ambient temperature of the fluid. It is assumed that $T_w > T_\infty$. If the thickness of the boundary layer δ is thin such that $\delta \ll r_0$, the boundary layer approximation is applicable.

Under the assumptions made above and Boussinesq approximations, the basic boundary layer equations describing the conservation of mass, momentum, energy and concentration in Cartesian frame of reference can be written as follows:

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

$$\frac{\mu u}{k_\rho}+\sigma\mu_e^{\,2}B_0^{\,2}u=\rho_\infty \bar{g}[\beta_T(T-T_\infty)+\beta_C(C-C_\infty)]\sin(x/r_0)\,, \qquad (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \qquad (3)$$

and

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D_m\frac{\partial^2 C}{\partial y^2}+\frac{D_m k_T}{T_m}\frac{\partial^2 T}{\partial y^2} \qquad (4)$$

with the boundary conditions

$$\frac{\partial\psi}{\partial x}=0,\quad T=T_w,\quad C=C_w \qquad \text{when } y=0 \qquad (5)$$

$$\text{and } \frac{\partial\psi}{\partial y}\to U(x),\quad T\to T_\infty,\quad C\to C_\infty \qquad \text{when } y\to\infty \qquad (6)$$

where (u, v) are Darcian velocity components in x and y directions, μ is the fluid viscosity, σ is the electrical conductivity, U(x) is the Darcian velocity in the tangential direction outside of the boundary layer, k_ρ is the intrinsic

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permeability of the saturated porous medium, μ_e is the magnetic permeability, B_0 is the magnetic induction, ρ is the fluid density, $\bar{g}$ is the acceleration due to gravity, β_T and β_C are volumetric thermal expansion coefficient and volumetric concentration expansion coefficient, α is the thermal diffusivity, D_m is the mass diffusivity, k_T is the thermal diffusivity ratio, C_s is the concentration susceptibility, C_p are specific heat at constant pressure, T_m is the mean fluid temperature, T, T_w, T_∞ and C, C_w, C_∞ are temperatures and concentrations of the fluid inside the boundary layer respectively. From potential theory explicit expression for U(x) on the surface of the cylinder is $2U_\infty \sin(x/r_0)$

III. METHOD OF SOLUTION

We introduce the stream function $\psi(x, y)$ such that

$$u = \frac{\partial\psi}{\partial y} \text{ and } v = -\frac{\partial\psi}{\partial x} \tag{7}$$

where

$$\psi = \sqrt{2U_\infty \alpha r_0}\, G_0(X) f(\eta) \text{ where } G_0(X) = \sqrt{1-\cos(X)}, \tag{8}$$

$$\eta = y\sqrt{\frac{2U_\infty}{\alpha r_0}} H_0(X) \text{ where } H_0(X) = \sin(X)/G_0(X) \text{ and } X = x/r_0, \tag{9}$$

$$T = T_\infty + (T_w - T_\infty)\theta(\eta) \tag{10}$$

and

$$C = C_\infty + (C_w - C_\infty)\phi(\eta). \tag{11}$$

The equation (1) of continuity is satisfied identically when u and v are expressed in terms of ψ as given by (7). Substituting the transformations (7) - (11) into the equations (2) to (6) we get the following non-linear ordinary differential equations:

$$(1+M^2)f''(\eta) - \frac{Gr_T}{Re}\theta' - \frac{Gr_C}{Re}\phi' = 0, \tag{12}$$

$$\theta'' + Du\phi'' + \frac{1}{2}f\theta' = 0, \tag{13}$$

$$\phi'' + LeSr\theta'' + \frac{1}{2}Lef\phi' = 0, \tag{14}$$

together with the boundary conditions

$$f = 0,\ \theta = 1,\ \phi = 1 \quad \text{when } \eta = 0 \text{ and} \tag{15}$$

$$f' \to 1,\ \theta \to 0,\ \phi \to 0 \quad \text{when } \eta \to \infty. \tag{16}$$

Here the primes denote differentiation with respect to η, and non-dimensionless parameters

$Gr_T = \frac{k_\rho \rho_\infty \beta_T \bar{g}(T_W - T_\infty)x}{2\nu^2}$, $Re = \frac{U_\infty x}{\nu}$, $Gr_C = \frac{k_\rho \rho_\infty \beta_T \bar{g}(C_W - C_\infty)x}{2\nu^2}$, $Du = \frac{D_m k_T (C_W - C_\infty)}{c_s c_p \nu (T_W - T_\infty)}$, $M^2 = \frac{k_\rho \sigma \mu_e^2 B_0^2}{\mu}$

$Sr = \frac{D_m k_T (T_w - T_\infty)}{T_m \alpha (C_w - C_\infty)}$ and $Le = \frac{\alpha}{D_m}$ are thermal Grashof number, Reynolds number, mass Grashof number, Dufour number, Hartmann number, Soret number and Lewis number respectively.

IV. RESULTS AND DISCUSSION

Solutions of non-linear coupled ordinary differential equations (12) to (14) under boundary conditions (15) and (16) cannot be obtained in closed form, hence these equations are solved numerically by using Matlab's built in solver bvp4c. Graphical representations of these solutions are shown below for various values of Reynolds number (Re),

ISSN: 2319-8753

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thermal Grashof number (Gr_T), mass Grashof number (Gr_C), Dufour number (Du), Soret number (Sr), Lewis number (Le) and Hartmann number (M).

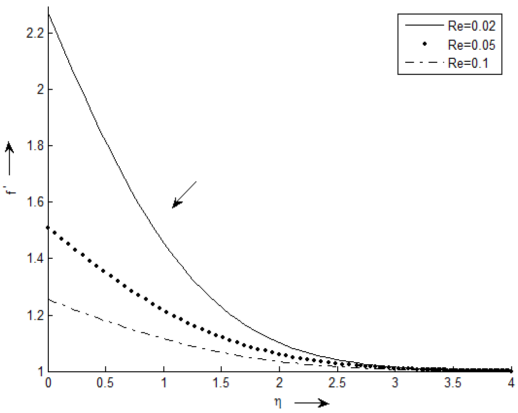

Figure 2

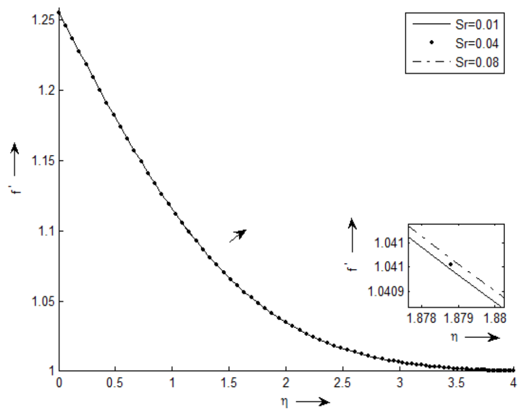

Figure 3

Velocity profile for different values of Reynolds number (Re) is shown in Figure 2. It is noticed that x-component of the velocity of the fluid near the surface of the cylinder is more than its value far away from the surface of the cylinder. It also depicts that this component of the velocity of the fluid decreases sharply with increase in the values of Reynolds number.

Figure 3 shows velocity profile for different values of Soret number (Sr). It reveals that velocity of the fluid increases with the increase in the value of Soret number but a least effect is noticed in fluid velocity due to this parameter.

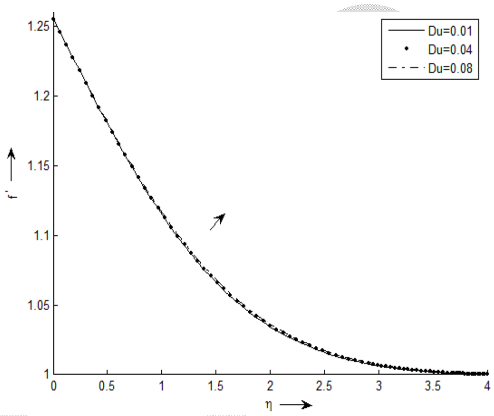

Figure 4

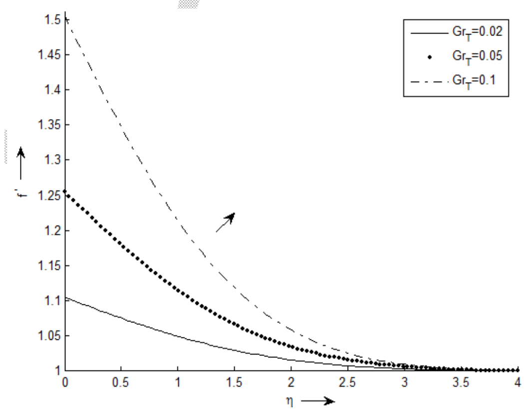

Figure 5

Figure 4 and Figure 5 exhibit velocity profile for various values of Dufour number (Du) and thermal Grashof number (Gr_T) respectively. These figures depict that velocity of the fluid increases slightly with the increase in the values of Dufour number and thermal Grashof number. It is noticed that x-component of the velocity of the fluid near the surface of the cylinder is more than its value far away from the surface of the cylinder due to the increasing values of thermal Grashof number. The effect of thermal Grashof number (Gr_T) on velocity is found to be significant while the effect of Dufour number (Du) is negligible.

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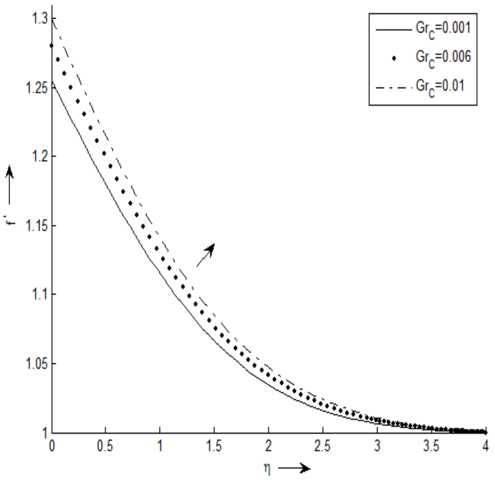

Figure 6

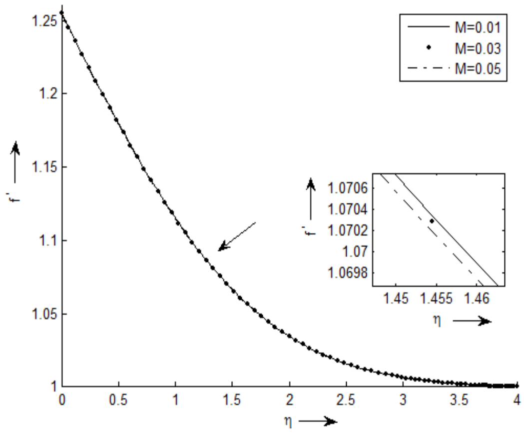

Figure 7

Figure 6 represents velocity profile for different values of mass Grashof number (Gr_C) and It exhibits that velocity of the fluid increases slightly with the increase in the values of mass Grashof number. The effect of mass Grashof number (Gr_C) on velocity variation is found to be more near the surface of the cylinder than far away from the surface of the cylinder. Figure 7 shows velocity profile for different values of Hartmann number (M). It displays that velocity of the fluid decreases with the increase in the value of Hartmann number. But a negligible effect is noticed in fluid velocity due to this parameter.

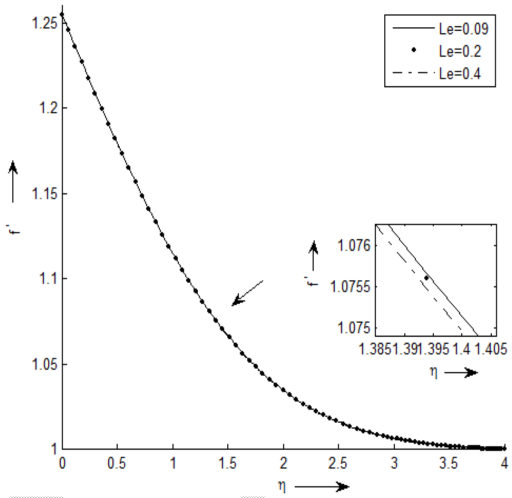

Figure 8

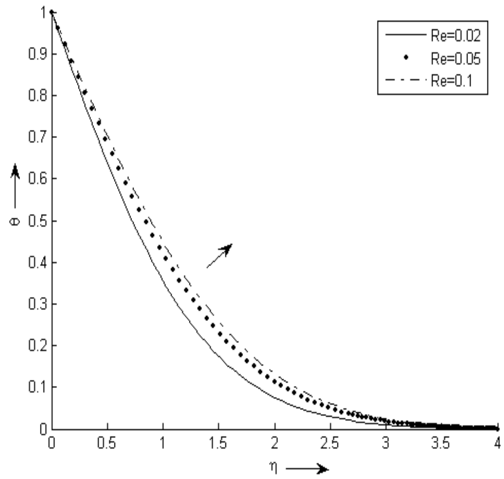

Figure 9

Velocity distribution for different values of Lewis number (Le) has been shown in Figure 8. It is observed that as the value of Lewis number increases the velocity of the fluid in the boundary layer region decreases but the effect is not of much significant. Figure 9 represents temperature profile for different values of Reynolds number (Re). It is clear that as the value of Reynolds number increases temperature of the fluid increases. It shows that the temperature of the fluid is more near the surface of the cylinder.

DOI: 10.15680/IJIRSET.2014.0310008

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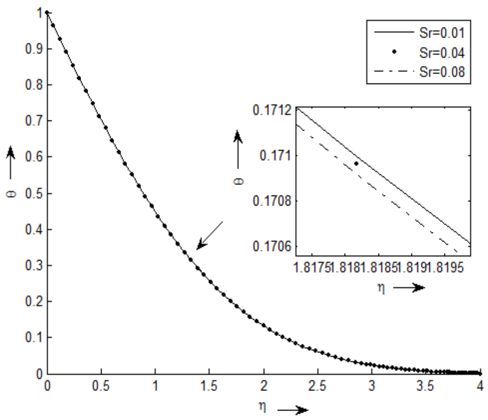

Figure 10

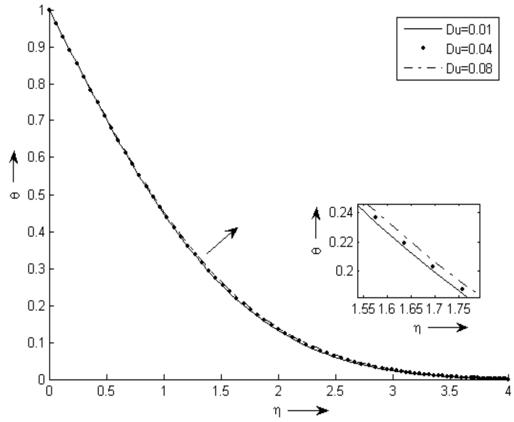

Figure11

Figure 10 represents temperature profile for different values of Soret number (Sr). It reveals that temperature of the fluid decreases with the increase in the value of Soret number but this effect is found to be very small. Temperature profile for various values of Dufour number (Du) is shown in Figure 11. It is observed that temperature of the fluid increases as the value of Dufour number increases.

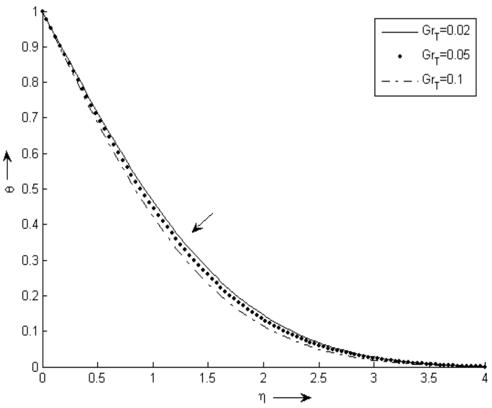

Figure12

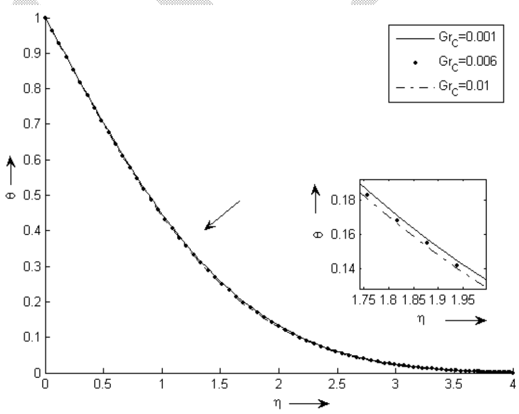

Figure13

Figure 12 shows the temperature profile for various values of thermal Grashof number (Gr_T). It has been noticed that temperature of the fluid decreases sharply with increasing value of the thermal Grashof number. Figure 13 represents temperature profile for various values of mass Grashof number (Gr_C). It displays that temperature of the fluid decreases with the increase in the value of mass Grashof number.

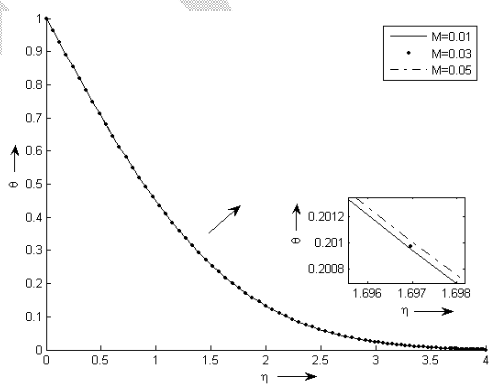

Figure14

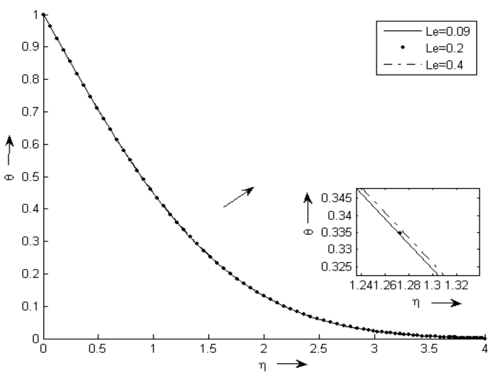

Figure15

ISSN: 2319-8753

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Figure 14 represents temperature profile for different values of Hartmann number (M). It displays that there is a small growth in temperature of the fluid with increasing values of Hartmann number. Both the effects (Gr_C and M) are of less significant. Figure 15 exhibits temperature profile for various values of Lewis number (Le). It is observed that temperature of the fluid increases with the increasing values of Lewis number. But the effect is not of much significant.

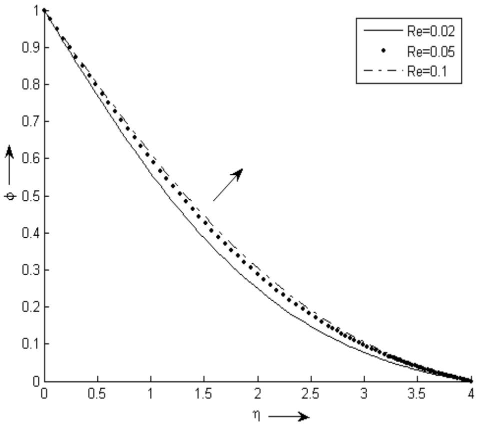

Figure16

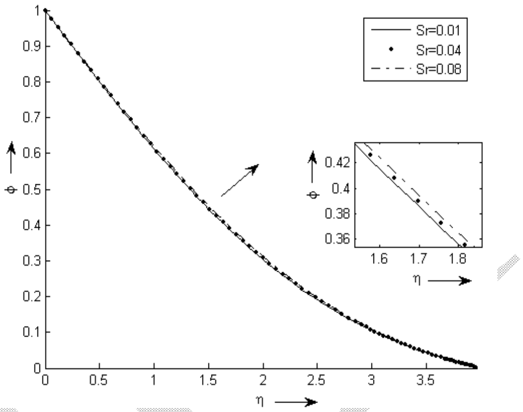

Figure17

Concentration profile for different values of Reynolds number (Re) and Soret number (Sr) have been shown in Figure 16 and Figure 17 respectively. It is observed that as the values of Reynolds number and Soret number increase concentration of the fluid increases.

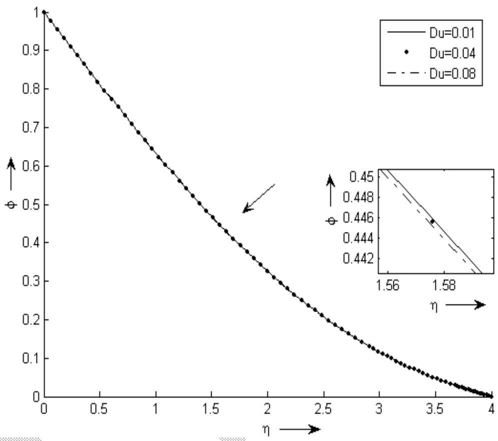

Figure18

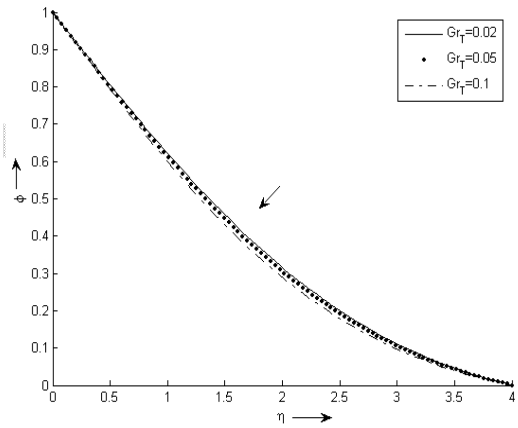

Figure19

Figure 18 and Figure 19 exhibit concentration profile for different values of Dufour number (Du) and thermal Grashof number (Gr_T). These figures depict that concentration of the fluid attains the maximum value near the surface of the cylinder. It is also observed that concentration decreases with the increase in the values of Dufour number and thermal Grashof number.

DOI: 10.15680/IJIRSET.2014.0310008

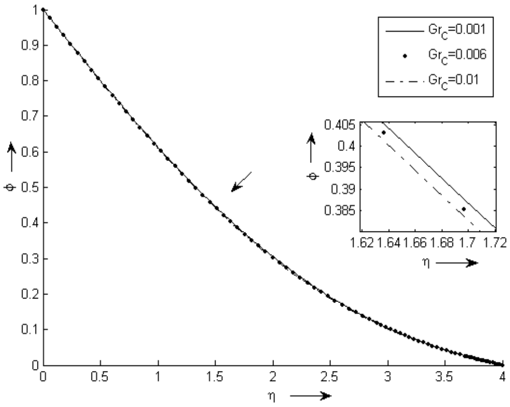

Figure20

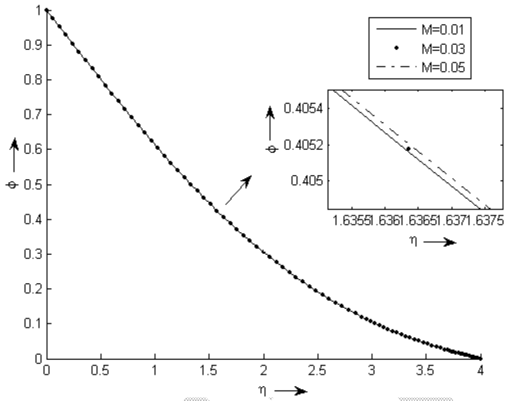

Figure21

Figure 20 represents concentration profile for different values of mass Grashof number (Gr_C). It shows that concentration of the fluid decreases with the increase in the value of mass Grashof number. Figure 21 represents concentration profile for different values of Hartmann number (M). It reflects that concentration of the fluid increases with increasing values of Hartmann number.

But these effects (Gr_C and M) on concentration of the fluid are of less significant.

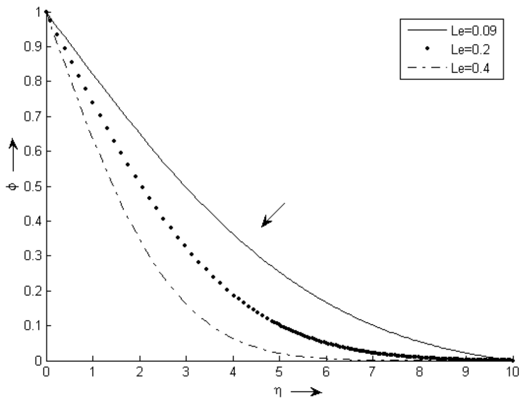

Figure 22

Figure 22 represents concentration profile for different values of Lewis number (Le). It is observed that as the value of Lewis number increases there is a significant decrease in concentration of the fluid.

We have assumed following parameter values.

Figure 2, Figure 9 and Figure 16: Re = (0.02, 0.05, 0.1), Gr_T = 0.05; Gr_C= 0.001; M = 0.02; Le = 0.4; Sr = 0.02; Du=0.02,

Figure 3, Figure 10 and Figure 17: Re = 0.1; Gr_T = 0.05; Gr_C = 0.001; M = 0.02; Le = 0.4; Sr = (0.01, 0.04, 0.08), Du=0.02,

Figure 4, Figure 11 and Figure 18: Re = 0.1; Gr_T = 0.05; Gr_C = 0.001; M = 0.02; Le = 0.4; Sr = 0.02; Du = (0.01, 0.04, 0.08),

Figure 5, Figure 12 and Figure 19: Re=0.1; Gr_T = (0.02, 0.05, 0.1); Gr_C = 0.001; M = 0.02; Le = 0.4; Sr = 0.02; Du = 0.02,

Figure 6, Figure 13 and Figure 20: Re = 0.1; Gr_T = 0.05; Gr_C = (0.001, 0.006, 0.01); M = 0.02; Le = 0.4; Sr = 0.02; Du=0.02,

Figure 7, Figure 14 and Figure 21: Re=0.1; Gr_T = 0.05; Gr_c= 0.001; M = (0.01, 0.03.0.05); Le = 0.4; Sr = 0.02; Du = 0.02,

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IJIRSET

ISSN: 2319-8753

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Figure 8, Figure 15 and Figure 22: Re = 0.1; Gr_T = 0.05; Gr_C = 0.001; M = 0.02; Le = (0.09, 0.2, 0.4); Sr = 0.02; Du = 0.02

Finally the effects of the rate of heat transfer and mass transfer which have practical importance are shown in the Table:1. The behaviour of these numbers is self evident and hence further discussion about them seems to be redundant.

Table:1

Re	Sr	Gr_T	Gr_C	Du	M	Le	$-\theta'(0)$	$-\phi'(0)$
0.02	0.02	0.05	0.001	0.02	0.02	0.4	0.7554	0.4681
0.05	0.02	0.05	0.001	0.02	0.02	0.4	0.6476	0.4194
0.1	0.02	0.05	0.001	0.02	0.02	0.4	0.6075	0.4016
0.1	0.01	0.05	0.001	0.02	0.02	0.4	0.6074	0.4030
0.1	0.04	0.05	0.001	0.02	0.02	0.4	0.6075	0.3989
0.1	0.08	0.05	0.001	0.02	0.02	0.4	0.6076	0.3935
0.1	0.2	0.05	0.001	0.01	0.02	0.4	0.6090	0.3770
0.1	0.2	0.05	0.001	0.04	0.02	0.4	0.6056	0.3773
0.1	0.2	0.05	0.001	0.08	0.02	0.4	0.6012	0.3777
0.1	0.02	0.02	0.001	0.02	0.02	0.4	0.5826	0.3907
0.1	0.02	0.07	0.001	0.02	0.02	0.4	0.6235	0.4087
0.1	0.02	0.1	0.001	0.02	0.02	0.4	0.6468	0.4190
0.1	0.02	0.05	0.003	0.02	0.02	0.4	0.6093	0.4025
0.1	0.02	0.05	0.007	0.02	0.02	0.4	0.6131	0.4042
0.1	0.02	0.05	0.010	0.02	0.02	0.4	0.6159	0.4055
0.03	0.02	0.05	0.001	0.02	0.01	0.4	0.6977	0.4419
0.03	0.02	0.05	0.001	0.02	0.05	0.4	0.6974	0.4417
0.03	0.02	0.05	0.001	0.02	0.07	0.4	0.6971	0.4416
0.1	0.02	0.05	0.001	0.02	0.02	0.1	0.6095	0.2876
0.1	0.02	0.05	0.001	0.02	0.02	0.2	0.6088	0.3258
0.1	0.02	0.05	0.001	0.02	0.02	0.3	0.6081	0.3640

V. CONCLUSION

From the above study we conclude that

- The effects of increase in the values of Soret number, Dufour number, thermal Grashof number and mass Grashof number, and decrease in the values of Reynolds number, Hartmann number and Lewis number are to increase the velocity of the fluid.
- The effects of increase in the values of Reynolds number, Dufour number, Hartmann number and Lewis number, and decrease in the values of Soret number, thermal Grashof number and mass Grashof number are to increase the temperature of the fluid.
- The effects of increase in the values of Reynolds number, Soret number and Hartmann number, and decrease in the values of Dufour number, thermal Grashof number, mass Grashof number and Lewis number are to increase the concentration of the fluid mixture.
- Effects of Soret number, Dufour number, Hartmann number and Lewis number on velocity distribution are less significant than that of the effects of Reynolds number, thermal Grashof number and mass Grashof number.
- Effects of Soret number, Dufour number, Hartmann number, mass Grashof number and Lewis number on temperature distribution are less significant than that of the effects of Reynolds number and thermal Grashof number.
- Effects of Soret number, Dufour number, Hartmann number, mass Grashof number on mass distribution are less significant than that of the effects of Reynolds number, thermal Grashof number and Lewis number.

ACKNOWLEDEMENTS

The second author is thankful to Nagaland Government for providing financial support and to Dibrugarh University for providing all academic facilities during the preparation of this research paper.

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