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Unsteady MHD Flow Past A Vertical Porous Plate : A FEM and FDM Correlative Approach

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ABSTRACT

In the present paper FEM and FDM analysis is made to analyze the effect of Dufour number variation on unsteady free convection flow of an electrically conducting, viscous fluid past an infinite vertical porous plate embedded in porous medium. Magnetic field is applied normal to the flow. The governing non-linear coupled partial differential equations with boundary conditions are solved using Galerkin finite element and Crank-Nicholson methods. Graphical results for velocity, temperature and concentration fields and tabular values of Skin-friction and Nusselt numbers are presented and discussed. It is observed that the velocity and Temperature, Skin–friction and Nusselt number increase in the presence of viscous dissipation and for the increasing values of Dufour number.

Keywords : MHD Flow, Vertical Plate, Dufour, Viscous Dissipation, Galerkin Finite Element Method , Crank-Nicholson Method.

I. INTRODUCTION

In industries, many transport processes exist in which, heat and mass transfer takes place, simultaneously, as a result of combined buoyancy effect of thermal diffusion of chemical species. The phenomenon of heat and mass transfer has been the object of wide research due to its applications in science and technology. Such phenomenon is observed in buoyancy-induced motions in the atmosphere, in bodies of water, quasi- solid bodies such as earth so on. Unsteady oscillatory free connective flows play a significant role in chemical engineering, turbo machinery and aerospace technology. Such flows arise owing to unsteady motion of a boundary or boundary temperature. Besides, unsteadiness may also be owing to oscillatory free stream velocity and temperature. In the past decades an intensive research effort has been devoted to problems on heat and mass transfer in consideration of their application to astrophysics, geophysics and engineering.

II. LITERATURE REVIEW

Eckert *et al* [1] have done establish work on heat and mass transfer. The equations governing the mass transfer phenomenon are complicated. However, Gebhart [2] simplified these equations by assuming the presence of species concentration at very low levels and made wide studies on combined heat and mass transfer flow, to highlight the insight of the phenomenon. Due to importance of these flows, several authors [3-11] have studied the problems on free convection and mass transfer flow of a viscous fluid through porous medium. In these studies, the permeability of the porous medium is imagined to be constant. However, a porous material containing the fluid is a non-homogeneous medium and the porosity of the medium may not essentially be constant. Shreekanth *et al*[13] studied the effect of permeability variation on free convective flow past a vertical porous wall in a porous medium when the permeability varies with time. Singh *et al* [14] considered hydro magnetic free convection and mass transfer flow of a viscous stratified fluid considering variation in permeability with direction. Acharya *et al* [12] conferred magnetic field effects on the free-convection flow through porous medium with constant suction and constant heat flux.

Singh *et al* [15] considered the effects of permeability variation and oscillatory suction velocity on free convection and mass transfer flow of a viscous fluid past an infinite vertical porous plate to a porous medium when the plate is subjected to a time dependent suction velocity perpendicular to the plate in the presence of magnetic field. The permeability of the porous medium is considered to be $K(t')=K_0(1+\varepsilon e^{in't'})$ and the suction velocity is supposed to be $V(t')=V_0(1+\varepsilon e^{in't'})$ where $V_o>0$ and $\varepsilon<<1$ is a positive constant.

In all the above stated problems, the effect of Soret and Dufour on the flow field has not been considered. Such effect is important when density differences exist in the flow regime. For example when species are initiated at a surface in fluid domain, with different (lower) density than the surrounding fluid, both Soret and Dufour effects can be considerable. Also, when heat and mass transfer arise simultaneously in a moving fluid, the relations between the fluxes and the driving potentials are of more complicated nature. It has been found that an energy flux can be created not only by temperature gradients but also by composition gradients. The mass fluxes can be created by temperature gradients is called the Soret effect. The thermal-diffusion (Soret) effect, for instance, has been utilized for isotope separation and in mixture between gases with very light molecular weight (H2, He) and of medium molecular weight (N2, air). The thermal-diffusion effect was found to be of a significant magnitude such that it cannot be ignored (Eckert and Drake [1]). In view of the significance of this effect, Jha and Singh [18] studied the free-convection and mass transfer flow about an infinite vertical flat plate moving impulsively in its own plane, taking into account the Soret effects. Kafoussias [19] studied the same problem in the case of MHD flow. Srihari et al[20] analyzed the Soret number variation on free convection hydro-magnetic flow of a viscous, electrically conducting fluid, past an infinite vertical porous plate with oscillatory suction velocity with heat sink.Anand Rao et al. [21] analyzed the effect of Soret number on an unsteady two-dimensional laminar mixed convective boundary layer flow of a chemically reactingfluid, along a semi-infinite vertical permeable moving plate with viscous dissipation. Srihari and Kesavareddy [22] have made the investigation to study the effects of Soret and Magnetic field on unsteady laminar boundary layer flow of a radiating and chemically reacting incompressible viscous fluid along a semi-infinite vertical plate.

In most of the previous studies analytical or perturbation methods were applied to obtain the solution of the non linear problem. However, in the present paper Galerkin finite element and Finite difference analysis is made to study the effect of

Dufour in the presence of viscous dissipation on free convection flow of an incompressible fluid past an infinite vertical porous pate. A magnetic field is applied normal to the fluid flow. To obtain the solution and to explain the physics of the problem, the present non-linear boundary value problem is solved numerically using Galerkin finite element and Crank-Nicholson methods.

III. MATHEMATICAL FORMULATION OF THE PROBLEM

Unsteady free-convection flow of an incompressible, electrically conducting viscous fluid, past an infinite vertical plate embedded with porous medium is considered. In Cartesian coordinate system, let x'-axis be along the plate in the direction of the flow and y'-axis normal to it. A uniform magnetic field is introduced normal to the direction of the flow. In addition, the analysis is based on the assumptions. (i) the plate temperature and species concentration are instantly raised to $T' = T'_w(1+\varepsilon e^{in't'})$ and $C' = C'_w(1+\varepsilon e^{in't'})$ are maintained as such; (ii) the fluid properties are not affected by the temperature differences except that of the density in the body force term; (iii) the influence of density variations in other terms of the momentum, energy and concentration equations and the variation of the expansion coefficient with temperature is negligible;(iv) the magnetic Reynolds number is much less than unity so that, the induced magnetic field is neglected; (v) the plate is electrically non conducting so that, the equation of conservation of electric charge $\vec{\nabla}.\vec{J} = 0$ given by $J_{y'}$ =constant = 0, everywhere in the flow; (vi) the joule heating effect and viscous dissipation terms have been neglected.

Within the abovementioned framework, under usual Boussinesq's approximation, the equations relevant to the problem are:

$$\frac{1}{4}\frac{\partial u}{\partial t} - (1+\varepsilon e^{int})\frac{\partial u}{\partial y} = Gr\,T + Gm\,C + \frac{\partial^2 u}{\partial y^2} - \frac{u}{K_0(1+\varepsilon e^{int})} - M^2 u \quad (1)$$

$$\frac{1}{4}\frac{\partial \theta}{\partial t} - (1+\varepsilon e^{int})\frac{\partial \theta}{\partial y} = \frac{1}{\Pr}\frac{\partial^2 \theta}{\partial y^2} + Du\frac{\partial^2 \phi}{\partial y^2} + Ec\left(\frac{\partial u}{\partial y}\right)^2 \quad (2)$$

$$\frac{1}{4}\frac{\partial \phi}{\partial t} - (1+\varepsilon e^{int})\frac{\partial \varphi}{\partial y} = \frac{1}{Sc}\frac{\partial^2 \phi}{\partial y^2} \quad (3)$$

The relevant boundary conditions in dimensionless form are:

$$u = 0,\ \theta = 1 + \varepsilon e^{int},\ \Phi = 1 + \varepsilon e^{int} \text{ at } y = 0 \quad (4)$$

$$u \to 0,\ \theta \to 0,\ \Phi \to 0 \text{ as } y \to \infty.$$

The non-dimensional quantities introduced in the above equations are defined as:

$$y = \frac{v_0 y'}{4v},\quad t = \frac{v_0^2 t'}{4v},\quad n = \frac{4\upsilon n'}{v_0^2},\quad u = \frac{u'}{v_0},$$

$$\theta = \frac{T' - T_\infty}{T_w - T_\infty},\quad \phi = \frac{C' - C_\infty}{C_w - C_\infty}.$$

$S = \frac{S'\upsilon}{v_o^2}$ (heatsource parameter),

$Gr = \frac{\upsilon g \beta^*(T_w - T_\infty)}{v_0^3}$ (Grashof number),

$Sc = \frac{\vartheta}{D}$ (Schmidt number), $\Pr = \frac{\mu C_p}{K_T}$ (Prandtl number),

$M = \frac{B_0}{v_0}\sqrt{\frac{\sigma\upsilon}{\rho}}$ (Magnetic parameter),

$Du = \frac{D_m k_T (C_w - C_\infty)}{\upsilon Cs\, Cp(T_w - T_\infty)}$ (Dufour number)

$Gm = \frac{\upsilon g \beta (C_w - C_\infty)}{v_0^3}$ (Modified Grashof number),

$K_0 = \frac{K'_0 v_0^2}{\upsilon^2}$ (Constant Permeability of the medium)

$Ec = \frac{U_0^2}{C_p(T_w - T_\infty)}$ (Eckert number)

IV. METHOD OF SOLUTION

The finite element method has been implemented to obtain numerical solutions of equationss. (1–3) under boundary conditions (4). The fundamental steps comprising the method are now summarized.

Step 1: Discretization of the domain into elements

Step 2: Derivation of the element equations

The derivation of finite element equations i.e., algebraic equations among the unknown parameters of the finiteelement approximation, involves the following three steps.

- Construct the variational formulation of the differential equation.
- Assume the form of the approximate solution over a typical finite element.
- Derive the finite element equations by substituting the approximate solution into the variational formulation.

Step 3: Assembly of element equations.

Step 4: Impositions of Boundary Conditions.

Step 5: Solution of the assembled equations.

By implementing the step (1-3) to the nonlinear differential equation(1), the assembled element equations for two consecutive elements $y_{i-1} < y < y_i$ and $y_i < y < y_i + 1$put row corresponding to the node 'i' to zero, with the difference schemes by taking $l^{(e)} = h$ the following is obtained

$$\frac{1}{24}\left[\dot{u}_{i-1} + 4\dot{u}_i + \dot{u}_{i+1}\right] + \frac{1}{h^2}\left[-u_{i-1} + 2u_i + u_{i+1}\right] - \frac{B}{2h}\left[-u_{i-1} + u_{i+1}\right] + \frac{m}{6}\left[u_{i-1} + 4u_i + u_{i+1}\right] = P \tag{5}$$

Applying the trapezoidal rule, following the system of equations in Crank-Nicholson method are obtained

$$A_1 u_{i-1}^{j+1} + A_2 u_i^{j+1} + A_3 u_{i+1}^{j+1} = A_4 u_{i-1}^{j} + A_5 u_i^{j} + A_6 u_{i+1}^{j} + P^* \tag{6}$$

$$A_1 = h + 2mr - 12rh + 6Bk, A_2 = 4h + 24rh + 8mkh, A_3 = h + 2mr - 12rh - 6Bk,$$

$$A_4 = h - 2mr + 12rh - 6Bk, A_5 = 4h - 24rh - 8mkh, A_6 = h - 2mr + 12rh + 6Bk,,$$

$$P^* = 12kP = 12kGr\theta_i^j + 12kGm\theta_i^j, \; m = \frac{1}{K_0 B} + M^2, B = 1 + \varepsilon A e^{nt}$$

Apply the same strategy, the following is obtained

$$B_1\theta_{i-1}^{j+1} + B_2\theta_i^{j+1} + B_3\theta_{i+1}^{j+1} = B_4\theta_{i-1}^{j} + B_5\theta_i^{j} + B_6\theta_{i+1}^{j} + P^{**} \tag{7}$$

$$C_1\phi_{i-1}^{j+1} + C_2\phi_i^{j+1} + C_3\phi_{i+1}^{j+1} = C_4\phi_{i-1}^{j} + C_5\phi_i^{j} + C_6\phi_{i+1}^{j}$$

$B_1 = h\Pr + 6Bk\Pr - 12rh, B_2 = 4h\Pr + 24rh, \ B_3 = h\Pr - 6Bk\Pr - 12rh$

where $B_4 = h\Pr - 6Bk\Pr + 12rh, \quad B_5 = 4h\Pr - 24rh, B_6 = h\Pr + 6Bk\Pr + 12rh$

$$P^{**} = 24k\left(Du\frac{\partial^2 \phi_i}{\partial y_i^2} + Ec\left(\frac{\partial u_i}{\partial y_i}\right)^2 \right)$$

$C_1 = hSc + 6kBSc - 12rh, C_2 = 4hSc + 24rh, \ C_3 = hSc - 6kBSc - 12rh$

$C_4 = hSc - 6kBSc + 12rh, \quad C_5 = 4hSc - 24rh, \ ,C_6 = hSc + 6kBSc + 12rh$

Here, $r = k/h^2$ and h, k are mesh size along the y direction and the time direction respectively. Index i refers to space and j refers to the time. In the Equations (5) – (7), taking $i = 1..., n$ and using boundary conditions (4), the following system of equations are obtained:

$$A_i X_i = B_i \ i = 1(1)3 \tag{8}$$

Where A_i's are the matrix of order n and X_i, B_i's column matrices having n components. The solutions of the above systems of equations are obtained by using the Thomas algorithm for velocity, temperature, and concentration. Also, the numerical solutions are obtained by executing the MATLAB program with the smaller values of h and k. No significant change was observed in u, and θ then the Galerkin finite element method is stable and convergent.

Finite difference Method

Using Finite difference formulae in equations (1) to (4) and simplifying implicitly according to the Crank-Nicholson method, the following system of equations are obtained

$$A_1 u_{i-1}^{j+1} + B_1 u_i^{j+1} + A_1 u_{i+1}^{j+1} = C_{1i}^j \tag{9}$$

$$A_2 \theta_{i-1}^{j+1} + B_2 \theta_i^{j+1} + A_2 \theta_{i+1}^{j+1} = C_{2i}^j \tag{10}$$

$$A_3 \phi_{i-1}^{j+1} + B_3 \phi_i^{j+1} + A_3 \phi_{i+1}^{j+1} = C_{3i}^j \tag{11}$$

Where $C_{1i}^j = (r/2)u_{i-1}^j + (-r - r\Delta yp - \Delta t/k_0 p - \Delta tM^2 + 1/4)u_i^j + (r\Delta yp + r/2)u_{i+1}^j + \Delta tG_r\theta_i^j + \Delta tG_m\phi_i^j$

$$C_{2i}^j = (r/2)\theta_{i-1}^j + (\Pr/4 - \Pr r\Delta y\ p - r)\theta_i^j + (\Pr r\ \Delta y\ p + r/2)\theta_{i+1}^j + Du\Pr r\big(\phi(i-1) - 2\phi(i) + \phi(i+1)\big) + Ec\ r\ \big(u(i+1) - u(i)\big)^2$$

$$C_{3i}^j = (r/2)\phi_{i-1}^j + (Sc/4 - Sc\ r\Delta yp - r - Ch\ Sc\ \Delta t)\phi_i^j + (Sc\ r\Delta yp + r/2)\phi_{i+1}^j$$

$A_1 = \text{r}/2, \ B_1 = \text{r} + 1/4, \ A_2 = -(\text{r})/2, B_2 = (\text{r}) + \Pr/4, \ A_3 = \text{r}/2, B_3 = \text{r} + /4.$

And $r = \Delta t/(\Delta y)^2, \ p = 1 + \varepsilon e^{int}$, Δy and Δt are mesh sizes along space and time direction respectively.

To obtain the difference equations, the region of the flow is divided into a grid or mesh of lines parallel to y and t axes. Solutions of difference equations are obtained at the intersection of these mesh lines called nodes. The finite-difference equations at every internal nodal point on a particular n-level constitute a tri-diagonal system of equations. These equations are solved by using the Thomas algorithm [17]. To prove the convergence of finite difference scheme, the computation is carried out for slightly changed values of $\Delta\eta$ and Δt, running same program. Negligible change is observed.

V. RESULTS AND DISCUSSION

Inherent physics of the problem of investigation is analyzed with suitable CFD tools namely, Finite difference and Finite element techniques. Impact of different physical parameters of the flow involved is investigated by taking the consideration of their graphical representations

The effect of Dufour number variation on velocity and temperature field is shown in figures (1) and (5) respectively. Dufour number signifies the contribution of the concentration gradients to the thermal energy flux in the flow. From these figures, it is observed that velocity and temperature of the fluid increase for the increasing values of Dufour number as raising of Dufuor affects on concentration gradients to thermal energy fluxes.

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The analysis of figure (2) and (6) reveal that velocity and temperature of the fluid rise for increasing values of Eckert number (Ec). This is physically true owing to the fact that rising value of Ec produces the viscous dissipation heating within in the system in such way that temperature of the fluid increases with increase in Ec. Consequently, the velocity of the fluid increases for the increasing values of Ec. Fig(3) shows the effect of magnetic parameter M on velocity field u. It is observed from figure that velocity of the flow reduces in the presence magnetic parameter as Lorentz resistive type body force suppress the flow thus reduces the velocity of the fluid flow. Figure (4) show that an increase in Gr and Gm leads to increase in the velocity of the flow. This is due to the fact that with the increasing values of thermal Grashof number and mass Grashof number has the tendency to increase the thermal and mass buoyancy effect. This gives rise to an increase in the induced flow.

Skin-friction coefficient (τ) values are shown in table (1) for different values of Du, Ec, M, Sc, Pr, and K_0, in the case of cooling of the plate. From this table it is observed that an increase in Du, Ec, and K_0 leads to enhance in the Skin-friction but an increase in M, Pr, and Sc leads to decrease in the Skin-friction. Table (2) shows the Nusselt number (N_u). From this table it is noted that an increase in source parameter Ec and Du, leads to increase in the the Nusselt number. But an enhance in Pr reduces the Nusselt number (N_u).

VI.CONCLUSION

(1) Temperature and Nusselt number increase as the value of Eckert number increases due to the frictional heating between fluid and plate. Therefore Velocity, Skin–friction and Nusselt number increase in the presence viscous dissipation.

(2) for increasing values of Dufour parameter, there is a considerable enhancement in the velocity of the fluid is observed.

Nomenclature

u	velocity along the x-axis
K_T	Thermal conductivity
υ	kinematic coefficient of viscosity
β	coefficient of volume expansion for the heat transfer
β^*	volumetric coefficient of expansion with species concentration
T_∞	fluid temperature at infinity
C_∞	species concentration at infinity,

D	chemical molecular diffusivity
K_0	constant permeability of the medium
μ	coefficient of viscosity
C_p	specific heat at constant pressure
n	frequency of oscillation
ρ	density of the fluid

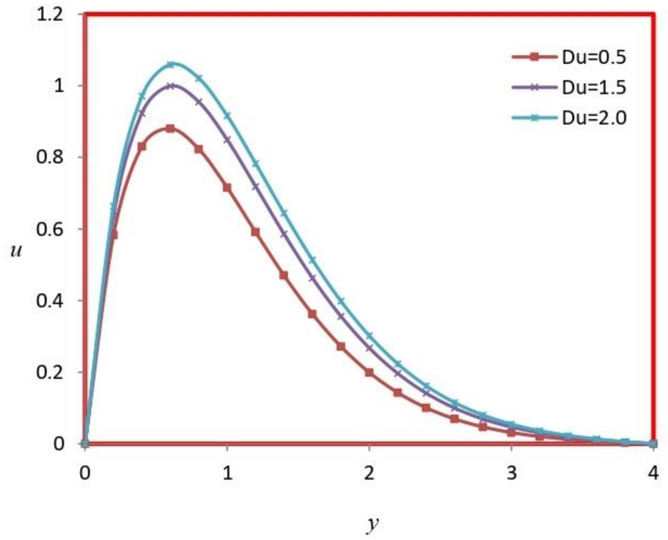

Fig1: Effect of Dufour Du on velocity field u
(G_r=5.0,Gm=5.0, M=0.5,Sc=0.22,Pr=0.71,K_o=1.0,Ec=0.5, ε =0.005 and nt=π/2)

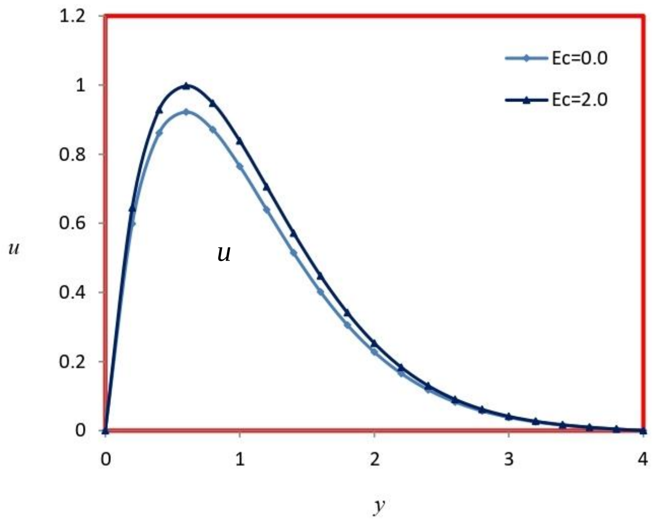

Fig 2: Effect of viscous dissipation on velocity field u
(G_r=5.0,Gm=5.0, M=0.5,Sc=0.22,Pr=0.71,K_o=1.0,Du=1.0, ε =0.005 and nt=π/2)

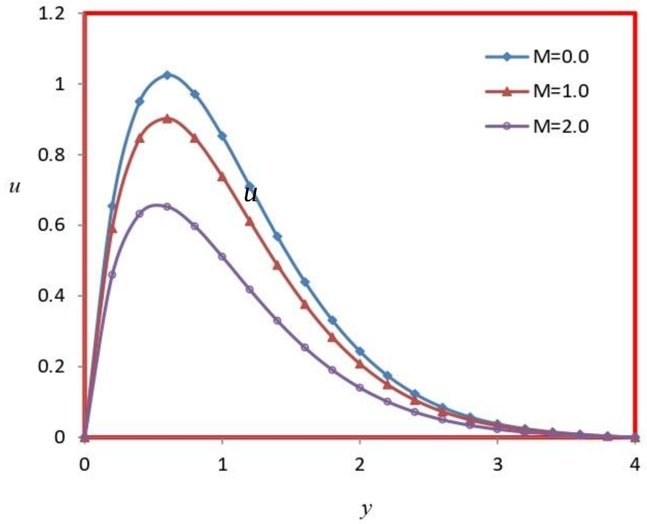

Fig 3: Effect of Magnetic parameter M on velocity field u
(G_r=5.0,Gm=5.0, Sc=0.22,Pr=0.71, Du=1.0, K_o=1.0, Ec=0.5, ε =0.005 and nt=π/2)

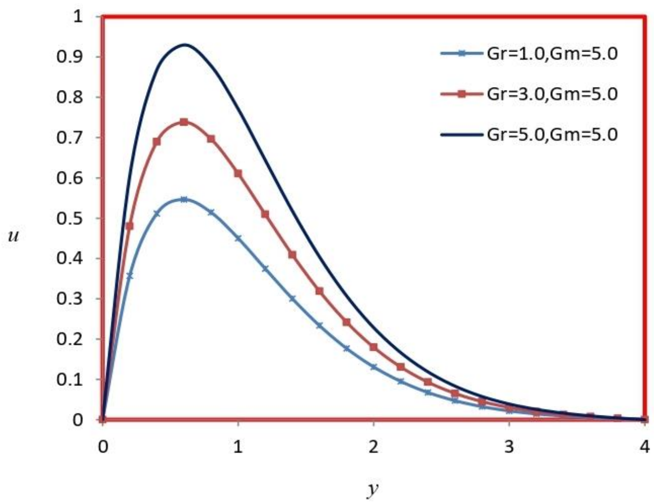

Fig 4: Effect of Gr and Gm on velocity field u
(M=1.0, Du=1.0,Sc=0.22,Pr=0.71,K_o=1.0,Ec=0.5, ε =0.005 and nt=π/2)

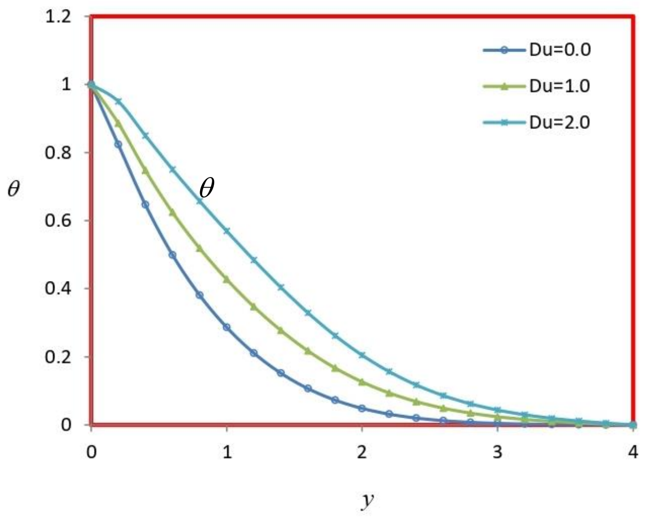

Fig 5: Effect Dufour Du on temperature field θ

(Gr=5.0, Gm=5.0, Pr=0.71, M=1.0, Ec=0.5, K_o=1.0,ε=0.005 and nt =π/2)

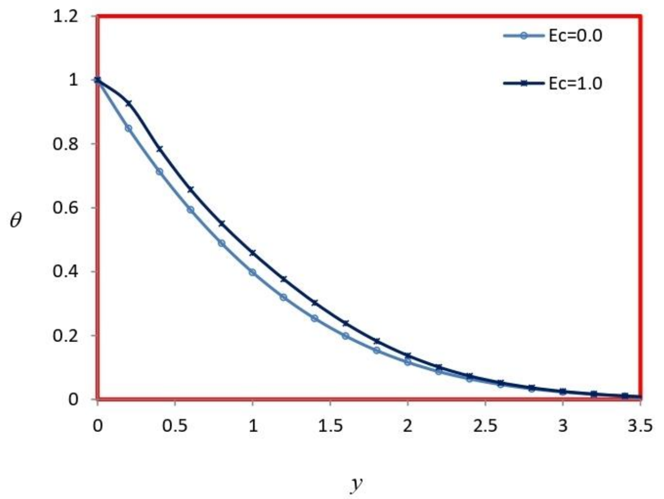

Fig 6: Effect of viscous dissipation Ec on temperature field θ

(Gr=5.0, Gm=5.0, Pr=0.71, M=1.0, Du=1.0, K_o=1.0,ε=0.005 and nt =π/2)

Table 1 : Skin-friction coefficient (τ)

Gr	Gm	M	Du	Pr	Sc	K_0	Ec	τ (FDM)	τ (FEM)
5.0	5.0	1.0	0.0	0.71	0.22	0.5	0.5	3.301038	3.311098
5.0	5.0	1.0	0.5	0.71	0.22	0.5	0.5	3.442620	3.452584
5.0	5.0	2.0	0.5	0.71	0.22	0.5	0.5	2.726658	2.736234
5.0	5.0	1.0	0.5	0.71	0.22	0.5	1.0	3.499813	3.509223
5.0	5.0	1.0	0.5	7.0	0.22	0.5	0.5	2.797158	2.807154
5.0	5.0	1.0	0.5	0.71	0.66	0.5	0.5	3.222829	3.222456

Table 2: Nusselt number Nufor Gr=5.0,Gm=5.0,M=1.0, K_0=1.0

Pr	Du	Ec	Nu (FDM)	Nu (FEM)
0.71	0.0	0.5	-0.831495	-0.841234
0.71	1.0	0.5	-0.491660	-0.501134
0.71	1.0	1..0	-0.173085	-0.183654
7.0	1.0	0.5	-0.637034	-0.647876

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