Dufour Effect on Three-Dimensional Heat and Mass Transfer Flow through a Porous Medium

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Abstract: *The present article deals with the effect of Dufour number variation on free-convection flow of a viscous incompressible fluid through a porous medium bounded by an infinite vertical porous plate with periodic permeability. Obtaining closed form solution for this type of 3-D flow problems is practically not feasible due to its high degree of non-linearity. So the problem is solved using finite difference and perturbation methods, for which numerical simulation is carried out by coding in C-Program. Graphical results for velocity, temperature, concentration, Skin-friction and Nusselt number are presented and discussed at various parametric conditions. It is observed that velocity, temperature and Nusselt number increase in the presence of Dufour. Dufour effect greatly influence the temperature profile in the thermal boundary layer.*

Key words: *Diffusion-thermo, Porous medium; Periodic permeability; Finite deference method.*

1. Introduction

The phenomenon of three dimensional free convective flows with simultaneous heat and mass transfer has been a subject of discussion in the research circles because of its various applications in natural sciences, engineering sciences and in industry. Such phenomenon is observed in buoyancy induced motions in the atmosphere, in bodies of water, quasi-solid bodies such as earth, etc. Free convective flows with periodic permeability through highly porous media play an significant role in chemical engineering, turbo-machinery and in aerospace technology. Such flow include numerous practical applications, for example, geothermal reservoirs, drying of porous solids, thermal insulation, enhanced oil recovery, packed-bed catalytic reactors, cooling of nuclear reactors and under-ground energy transport. Due to these applications, a majority of the investigators [1-6] have confined themselves to two-dimensional flows only by taking either constant or time dependent permeability of the porous medium. However, there situations may be encountered where the flow field is aessentially three dimensional, for example, when variation of the permeability distribution is transverse to the potential flow. The effect of such a transverse permeability distribution of the porous medium bounded by horizontal flat plate has been studied by Sing and Verma [7] and Singh *et al* [8]. The effect of magnetic field on three dimensional flow of a viscous, incompressible and electrically conducting fluid past an infinite porous plate with transverse sinusoidal suction was discussed by Singh [9]. Singh, [10] studied hydro magnetic effects on the three dimensional oscillatory flow of an electrically conducting viscous incompressible fluid past an infinite porous plate subjected to a transverse sinusoidal sections. Singh and Sharma [11] studied the effect of transverse periodic variation of the permeability on the heat transfer and the free-convective of a viscous incompressible fluid through a highly porous medium bounded by a vertical porous plate. Later this same study with mass transfer was extended by Varshney and Singh [12]. Jain et al. [14] analyzed the effects of periodic temperature and periodic permeability on three-dimensional free convective flow through porous medium in slip flow regime. Srihari and Anand Rao [15] analyzed the effect of magnetic field on three-dimensional free-convective heat and mass transfer flow through a porous medium with periodic permeability. Ahmed [16] obtained an analytical solution for three-dimensional mixed convective flow with mass transfer along an infinite vertical porous plate in the presence of a magnetic field effect. Ravinder Reddy et al [17] analyzed the effect of heat sink in the presence of magnetic field on three-dimensional free convective heat and mass transfer flow through a porous medium with periodic permeability. Hayat et al. [18] investigated the three-dimensional flow of viscous fluid with convective boundary conditions and heat generation/absorption. Many transport processes are found in different ways in which the combined heat and mass transfer takes place due to buoyancy forces caused by difference in temperature and concentrations. The relations between the fluxes and the driving potentials may be of a more complicated nature when heat and mass transfer occurs simultaneously in a moving fluid. An energy flux can be generated not only by temperature gradients but also by concentration gradients. The energy flux caused by a composition gradient is termed the diffusion-thermo or Dufour effect. On the other hand, mass fluxes can also be created by temperature a gradient is known as thermal-diffusion or Soret effect. Such effects are significant when density differences exist in the flow regime.

In the above three-dimensional investigations, the effect of Dufour number has not been studied. So, the objective of the present investigation is to analyze the effect of Dufour number variation on three-dimensional free-convection flow of a viscous incompressible fluid through a porous medium bounded by an infinite vertical porous plate. In order to obtain the solution and to describe the physics of the problem, first the governing non-linear equations with boundary conditions are transformed to ordinary and partial differential equations of zeroth and first order respectively, using perturbation method. Subsequently, the partial differential equations of first order are reduced to coupled non-linear differential equations using appropriate substitutions. Then, these coupled equations are solved using finite difference formulae.

2. Mathematical analysis:

The flow of a viscous fluid through a highly porous medium bounded by an infinite vertical porous plate with constant suction is considered. The plate is lying vertically on the x^*-z^* plane with x^*-axis taken along the plate in the upward direction. The y^*-axis is taken perpendicular to the plane of plate and directed into the fluid flowing laminarly with a uniform free stream velocity U. Since the plate consider infinite in x* -direction, so all physical quantities will be independent of x*.

The permeability of the porous medium is assumed to be of the form

$$K^*(z^*) = \frac{K_0^*}{(1+\varepsilon\cos\pi z^*/L)} \tag{1}$$

Where K_0^* is the mean permeability of the medium. L is the wavelength of the permeability distribution and ε (<<1) is the amplitude of the permeability variation. The problem becomes three-dimensional due to such a permeability variation.

Thus, denoting velocity components by u^*, v^*, w^* in the directions of x^*, y^*, z^* respectively and the temperature by the T^* and concentration by C^*, the flow through a highly porous medium is governed by following non-dimensional equations:

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

$$v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = Gr\,\mathrm{Re}\,\theta + Gm\,\mathrm{Re}\,\phi + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{(u-1)\,(1+\varepsilon\cos\pi z)}{\mathrm{Re}\,K_0} \tag{3}$$

$$v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{(1+\varepsilon\cos\pi z)\,v}{\mathrm{Re}\,K_0} \tag{4}$$

$$v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{(1+\varepsilon\cos\pi z)w}{\mathrm{Re}\,K_0} \tag{5}$$

$$v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2}\right) + \frac{Du}{\mathrm{Re}}\left(\frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2}\right) \tag{6}$$

$$v\frac{\partial \phi}{\partial y} + w\frac{\partial \phi}{\partial z} = \frac{1}{\mathrm{Re}\,Sc}\left(\frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2}\right) \tag{7}$$

with boundary conditions in non-dimensional form :

$$y = 0;\ u = 0,\ v = -1,\ w = 0,\ \theta = 1,\ \phi = 1 \tag{8}$$

$$y \to \infty;\ u \to 1,\ w \to 1,\ p \to p_\infty,\ \theta \to 0,\ \phi \to 0$$

Where $y = \frac{y^*}{L},\quad z = \frac{z^*}{L},\quad u = \frac{u^*}{U},$

$$v = \frac{v^*}{V},\ w = \frac{w^*}{V},\ p = \frac{p^*}{\rho U^2},\ \theta = \frac{T^* - T_\infty^*}{T_w^* - T_\infty^*},$$

$$\phi = \frac{C^* - C_\infty^*}{C_w^* - C_\infty^*},\ Gr = \frac{\upsilon g\beta(T_w^* - T_\infty^*)}{UV^2},$$

$$Du = \frac{D_m(C_w - C_\infty)}{\upsilon(T_w - T_\infty)},\quad Gm = \frac{\upsilon g\beta^*(C_w^* - C_\infty^*)}{UV^2}$$

$$\mathrm{Re} = \frac{VL}{\upsilon},\quad \mathrm{Pr} = \frac{\mu C_p}{k},\ Sc = \frac{\upsilon}{D},\ K_0 = \frac{K_0^*}{L^2}$$

To solve the above equations, the solutions of the equations (2) to (7) are assumed to be of the form:

$$f(y,z) = f_0(y) + \varepsilon\, f_1(y,z) + \varepsilon^2 f_2(y,z) + \ldots \tag{9}$$

Where f stands for u, v, w, p, θ and ϕ.

Using (9) in the equations (2) to (7) and equating the co-efficient of like powers of ε, neglecting the higher powers of ε, the following sets of the differential equations are obtained:

Zeroth-order equations:

$$\frac{dv_0}{dy} = 0 \tag{10}$$

$$\frac{d^2u_0}{dy^2} - v_0\,\mathrm{Re}\frac{du_0}{dy} - \frac{1}{K_0}u_0 = -Gr\,\mathrm{Re}^2\,\theta_0 - Gm\,\mathrm{Re}^2\,\phi_0 - \frac{1}{K_0} \tag{11}$$

$$\frac{d^2\theta_0}{dy^2} - v_0\,\mathrm{Re}\,\mathrm{Pr}\frac{d\theta_0}{dy} = -Du\ \mathrm{Pr}\frac{d^2\phi_0}{dy^2} \tag{12}$$

$$\frac{d^2\phi_0}{dy^2} - v_0\ \mathrm{Re}\,Sc\frac{d\phi_0}{dy} = 0 \tag{13}$$

The corresponding boundary conditions are

$$y = 0;\ u_0 = 0,\ v_0 = -1,\ \theta_0 = 1,\ \phi_0 = 1 \quad (14)$$

$$y \to \infty;\ u_0 \to 1,\ p_0 \to p_\infty,\ \theta_0 \to 0,\ \phi_0 \to 0$$

First order equations:

$$\frac{\partial v_1}{\partial y} + \frac{\partial w_1}{\partial z} = 0 \quad (15)$$

$$v_1 \frac{\partial u_0}{\partial y} - \frac{\partial u_1}{\partial y} = Gr\operatorname{Re}\theta_1 + Gm\operatorname{Re}\phi_1 + \frac{1}{\operatorname{Re}}\left(\frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2}\right) - \frac{(u_0 - 1)\varepsilon\cos\pi z + u_1}{\operatorname{Re}K_0} \quad (16)$$

$$-\frac{\partial v_1}{\partial y} = -\frac{\partial p_1}{\partial y} + \frac{1}{\operatorname{Re}}\left(\frac{\partial^2 v_1}{\partial y^2} + \frac{\partial^2 v_1}{\partial z^2}\right) - \frac{(v_1 - \cos\pi z)}{\operatorname{Re}K_0} \quad (17)$$

$$-\frac{\partial w_1}{\partial y} = -\frac{\partial p_1}{\partial z} + \frac{1}{\operatorname{Re}}\left(\frac{\partial^2 w_1}{\partial y^2} + \frac{\partial^2 w_1}{\partial z^2}\right) - \frac{w_1}{\operatorname{Re}K_0} \quad (18)$$

$$v_1 \frac{\partial \theta_0}{\partial y} - \frac{\partial \theta_1}{\partial y} = \frac{1}{\operatorname{Re}\Pr}\left(\frac{\partial^2 \theta_1}{\partial y^2} + \frac{\partial^2 \theta_1}{\partial z^2}\right) + \frac{Du}{\operatorname{Re}}\left(\frac{\partial^2 \phi_1}{\partial y^2} + \frac{\partial^2 \phi_1}{\partial z^2}\right) \quad (19)$$

$$v_1 \frac{\partial \phi_0}{\partial y} - \frac{\partial \phi_1}{\partial y} = \frac{1}{\operatorname{Re}Sc}\left(\frac{\partial^2 \phi_1}{\partial y^2} + \frac{\partial^2 \phi_1}{\partial z^2}\right) \quad (20)$$

The corresponding boundary conditions are

$$y = 0;\ u_1 = 0,\ v_1 = 0,\ w_1 = 0,\ \theta_1 = 0,\ \phi_1 = 0 \quad (21)$$
$$u_1 \to 0,\ w_1 \to 0,\ p_1 \to 0,\ \theta_1 \to 0,\ \phi_1 \to 0$$

The Solutions of equations (10) to (13) under the boundary conditions (14) are given by

$$u_0 = 1 + (\lambda_0 - \lambda_1 + \lambda_2 - 1).\, e^{-r_3 y} + (\lambda_1 - \lambda_2)e^{-r_2 y} - \lambda_0 e^{-r_1 y}$$

$\theta_0 = (1 + A_1)e^{-r_1 y} - A_1 e^{-r_2 y}$ $\quad \phi_0 = e^{-r_2 y}$ with

$v_0 = -1,\ w_0 = 0$ and $p_0 = p_\infty$

Where $\lambda_0 = \dfrac{Gr(1 + A_1)\operatorname{Re}^2}{r_1^2 - \operatorname{Re} r_1 - \dfrac{1}{K_0}}$,

$$r_1 = \operatorname{Re}.\Pr, \quad r_2 = \operatorname{Re}.Sc$$

$$\lambda_2 = \frac{Gm.\operatorname{Re}^2}{r_2^2 - \operatorname{Re} r_2 - \dfrac{1}{K_0}}, \quad r_3 = \frac{\operatorname{Re}}{2} + \sqrt{\frac{\operatorname{Re}^2}{4} + \frac{1}{K_0}}$$

$$\lambda_1 = \frac{GrA_1\operatorname{Re}^2}{r_2^2 - \operatorname{Re} r_2 - \dfrac{1}{K_0}}, \quad A_1 = \frac{r_2^2\ Du.\Pr}{r_2^2 - \operatorname{Re}.\Pr r_2},$$

In order to solve equations (15) to (20), we separate the variables y and z in the following manner.

$$v_1(y, z) = -v_{11}(y)\cos\pi z \quad (22)$$

$$w_1(y, z) = \frac{1}{\pi}v'_{11}(y)\sin\pi z \quad (23)$$

$$p_1(y, z) = p_{11}(y)\cos\pi z \quad (24)$$

Making use of equations (22), (23) and (24) in equations (17) and (18) and eliminating the terms p'_{11}, p_{11}, we have

$$v_{11}^{iv} + \operatorname{Re}v'''_{11} - \left(M^2 + \frac{1}{K_0} + 2\pi^2\right)v''_{11} - \operatorname{Re}\pi^2 v'_{11} + \left(\pi^4 + \frac{\pi^2}{K_0}\right)v_{11} + \frac{\pi^2}{K_0} = 0 \quad (25)$$

The corresponding boundary conditions are

$$y = 0:\ v_{11} = 0,\ v'_{11} = 0 \quad (26)$$
$$y \to \infty:\ v_{11} = 0$$

In order to solve the equations (16), (19) and (20) for u_1, θ_1 and ϕ_1 the subsequent are supposed

$$u_1(y, z) = u_{11}(y)\cos\pi z \quad (27)$$
$$\theta_1(y, z) = \theta_{11}(y)\cos\pi z \quad (28)$$
$$\phi_1(y, z) = \phi_{11}(y)\cos\pi z\ . \quad (29)$$

Using the above expressions u_1, θ_1 and ϕ_1 in (16), (19) and (20), the following are obtained:

$$u''_{11} + \operatorname{Re}u'_{11} - \left(\frac{1}{K_0} + \pi^2\right)u_{11} = -\operatorname{Re}v_{11}u'_0 - Gr\operatorname{Re}^2\theta_{11} - Gm\operatorname{Re}^2\phi_{11} + \frac{u_0 - 1}{K_0} \quad (30)$$

$$\theta''_{11} + \operatorname{Re}\Pr\theta'_{11} - \pi^2\theta_{11} = -\operatorname{Re}\Pr v_{11}\theta'_0 - Du\Pr\left(\frac{d^2\phi_{11}}{dy^2} - \pi^2\phi_{11}\right) \quad (31)$$

$$\phi''_{11} + \operatorname{Re}Sc\phi'_{11} - \pi^2\phi_{11} = -\operatorname{Re}Sc\, v_{11}\phi'_0 \quad (32)$$

with boundary conditions

$$y = 0:\ u_{11} = 0,\ \theta_{11} = 0,\ \phi_{11} = 0 \quad (33)$$
$$y \to \infty:\ u_{11} \to 0,\ \theta_{11} \to 0,\ \phi_{11} \to 0.$$

Obtaining exact solution of the above coupled differential equations is difficult, so substituting the following finite difference formulae

$$f' = (f(i+1) - f(i-1))/2h$$

$$f'' = (f(i+1) - 2f(i) + f(i-1))/h^2,$$

$$f^{IV} = (f(i+2) - 4f(i+1) + 6f(i) - 4f(i-1) + f(i-2))/h^4$$

$$f''' = (f(i+2) - 2f(i+1) + 2f(i-1) - f(i-2))/2h^3,$$

Where f stands $u_{11}, \theta_{11}, \phi_{11}$ and v_{11}

in the equations (25), (30), (31) and (32),the following are obtained.

$$A_1 v_{11}(i+2) - A_2 v_{11}(i+1) + A_3 v_{11}(i) - A_4 v_{11}(i-1) + A_5 v_{11}(i-2) + 2\pi^2 h^4/K_0 = 0 \quad (34)$$

$$A_1 u_{11}(i+1) - B_1 u_{11}(i) + A_5 u_{11}(i-1) = B(i) \quad (35)$$

$$D_1\theta_{11}(i+1) - D_2\theta_{11}(i) + D_3\theta_{11}(i-1) = D(i) \quad (36)$$

$$E_1\phi(i+1) - D_2\phi(i) + E_3\phi(i-1) = E(i) \quad (37)$$

Where, $A_1 = 2 + \mathrm{Re}\, h$,

$$A_2 = 8 + 2\,\mathrm{Re}\, h + 2h^2\left((1/K_0) + 2\pi^2\right) + \mathrm{Re}\, h^3\pi^2$$

$$A_4 = 8 - 2\,\mathrm{Re}\, h + 2h^2\left((1/K_0) + 2\pi^2\right) - \mathrm{Re}\, h^3\pi^2,$$

$$A_5 = 2 - \mathrm{Re}\, h,$$

$$D_1 = 2 + \mathrm{Re}\,\mathrm{Pr}\, h,$$

$$D_2 = 4 + 2(\pi^2 - S)h^2,$$

$$D_3 = 2 - \mathrm{Re}\,\mathrm{Pr}\, h$$

$$D(i) = 2(h\,\mathrm{Re}\, P_r)v_{11}(i)\left\{-(1 + A_1)r_1 e^{r_1 y} + r_2 A_1 e^{-r_2 y}\right\} - 2\,Du\,\mathrm{Pr}\left(\phi_{11}(i+1) - (2 + \pi^2 h^2)\phi_{11}(i) + \phi_{11}(i-1)\right),$$

$$E_3 = 2 - \mathrm{Re}\, Sc\, h,\quad E(i) = 2(h\,\mathrm{Re}\, Sc)r_2 v_{11}(i)e^{-r_2 ih},$$

$$B_1 = 4 + 2h^2\left((1/K_0) + \pi^2\right)$$

$$B(i) = -R_e v_{11}(i)B_2(i) - 2(h\,\mathrm{Re})^2\left(Gr\theta_{11}(i) + Gm\phi_{11}(i)\right) + (2h^2/K_0)B_3(i)$$

$$B_2(i) = -r_3\left(\lambda_0 - \lambda_1 + \lambda_2 - 1\right).\,e^{-r_3 y} - r_2(\lambda_1 - \lambda_2)e^{-r_2 y} + r_1\,\lambda_0 e^{-r_1 y}$$

$$B_3(i) = u_0 = \left(\lambda_0 - \lambda_1 + \lambda_2 - 1\right).\,e^{-r_3 y} + (\lambda_1 - \lambda_2)e^{-r_2 y} - \lambda_0 e^{-r_1 y}$$

Equations (34), (35),(36) and (37) are solved by Gauss-seidel iteration method, for which numerical code is executed by using C-Program. In order to obtain the numerical solution with slight error and to verify the convergence of present numerical scheme, a grid independent test is applied by experimenting with various grid sizes i.e. the computation is carried out by a little varied values of h. This process is repeated until we get the results up to the desired degree of accuracy 10^{-8}. No significant change is observed in the values of velocity, temperature and concentration profiles.

Skin-Friction coefficient:

Skin friction components in the x^* -direction in the non-dimensional form is given by:

$$\tau = \frac{\tau^*}{\rho UV} = \frac{\upsilon}{VL}\left(\frac{\partial u}{\partial y}\right)_{y=0} = \frac{1}{\mathrm{Re}}\left(\frac{du_0}{dy} + \varepsilon\frac{du_{11}}{dy}\cos\pi z\right)_{y=0} \qquad (38)$$

Nusselt -number:

The rate of heat transfer coefficient in terms of Nusselt number Nu is given by

$$Nu = \frac{-q^*}{\rho VC_p\left(T_w^* - T_\infty^*\right)} = \frac{k}{\rho VC_p L}\left(\frac{\partial\theta}{\partial y}\right)_{y=0} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{d\theta_0}{dy} + \varepsilon\frac{d\theta_{11}}{dy}\cos\pi z\right)_{y=0} \qquad (39)$$

3. Results and discussion:

In order to know the physics of the problem, the problem of three-dimensional free-convection flow through a porous medium is solved approximately using finite difference and perturbation methods. The effects of main controlling parameters, which are appeared in the governing equations, are discussed graphically in the presence of Dufour.

The effect of Dufour (Du) on velocity and temperature field is shown in the figures (1), (5) respectively. The Dufour number describes the contribution of the concentration gradients to the thermal energy flux in the flow. It is noted that the velocity and temperature increase for the increasing values of Dufour number. Figures (7) and (8) show that Skin-friction τ versus Reynolds number Re and Nusselt number Nu versus Re respectively. The assessment of the curves in the figures shows that an increase in the Dufour number leads to increase in the Skin-friction and Nusselt number.

Figures (2) and (3) show the velocity field u for various values of Grashof number (Gr) and modified Grashof number (Gm), respectively. It is observed from the figures that the velocity of the flow increase with the increasing values of Gr and Gm. This is due to the physical fact that the growing values of thermal Grashof number and mass Grashof number has the inclination to increase the thermal and mass buoyancy effect. This gives rise to an enhancement in the induced flow. It is also observed that as the values of Gr (or) Gm increases, the peak value of the velocity increases rapidly near the wall of the plate and then decay to the free stream velocity. From fig (4), a significant observation noted that raise in permeability parameter leads to increase in the velocity of the flow as the degrees of moment of particles in the fluid becomes maximum. More over it is interesting to note that the velocity, temperature, Skin-friction and Nusselt number increase in the presence of Dufour.

Figure (6) depicts the temperature profile for various values of Pr. It is observed that a fluid with higher Prandtl number is to initiate to decelerate the temperature of the fluid at all points. This is owing to the physical reality that a fluid with high Prandtl number has a comparatively low thermal conductivity which consequences in the decline of the thermal boundary layer. The effect of Schmidt number (Sc) on the concentration field is shown in figure (9). It is seen that the concentration of the fluid decreases with the increasing values of Sc. Physically; the increase of Sc means decline of molecular diffusivity (D) those consequences in decrease of concentration boundary layer. Hence, the concentration of the species is higher for small values of Sc and lower for bigger values of Sc.

4. Conclusions:

The following conclusions have been drawn from the above results:

- The temperature, velocity, Skin–friction and Nusselt number increase in the presence of Dufour.
- Dufour effects greatly influence the temperature profile in the thermal boundary layer.
- For increasing values of Dufour parameters, there is a considerable enhancement in the velocity of the fluid is observed.

5. Nomenclature

g- Acceleration due to gravity, β - Coefficient of volumetric thermal expansion, β^* - Coefficient of mass expansion, p^* - Pressure, ρ -Density, υ - Kinematics viscosity, μ - Viscosity , k- Thermal conductivity, C_p -Specific heat at constant pressure,*D*-Concentration diffusivity C_w^* - Concentration of the plate, T_w^* -Temperature of the plate, T_∞^* - Temperature of the fluid far away from the plate C_∞^* - Concentration of the fluid far away from the plate , p_∞ -pressure in stream, Du-Dufour number, Pr- Prandtl number, Sc-Schmidth number, Gr-Grashof number, Gm- Modified Grashof number.

6. Figures

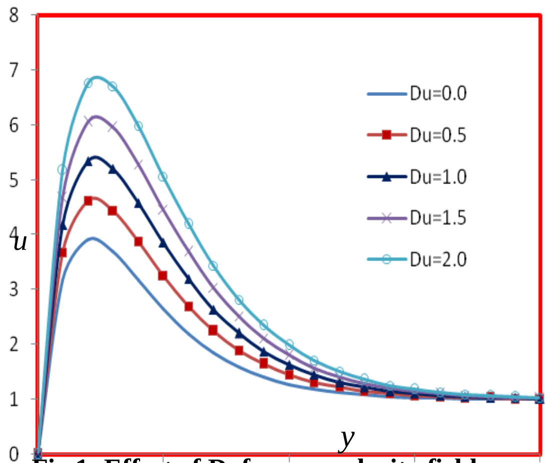

Fig.1: Effect of Dufour on velocity field u
(Gr=3.0, Gm=3.0, Re=3.0, K_0 =1.0, Pr=0.71, Sc=0.66, ε =0.1 and

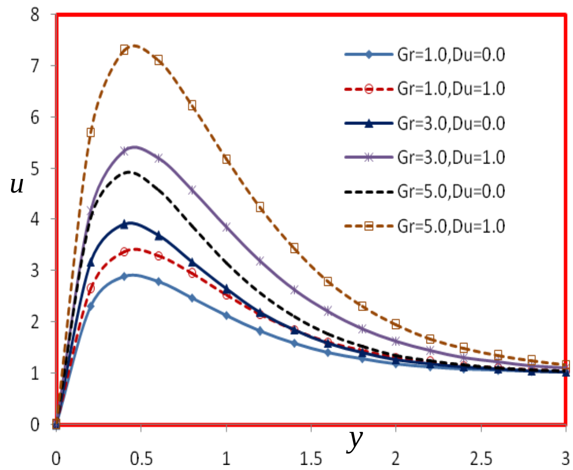

Fig.2: Effect of 'Gr' velocity field u in the presence of Dufour
(Gr=3.0, Gm=3.0, K_0 =1.0, Pr=0.71, Sc=0.66, ε =0.1 and Z=0.0)

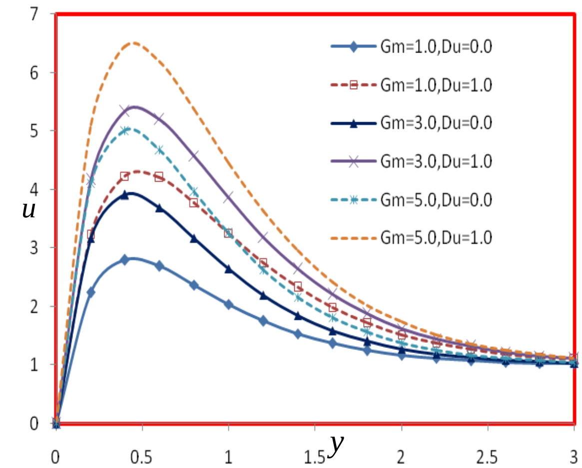

Fig.3: Effect of 'Gm' on velocity field u
(Gr=3.0, Gm=3.0, Re=3.0, K_0 =1.0, Pr=0.71, Sc=0.66, ε =0.1 and Z=0.0)

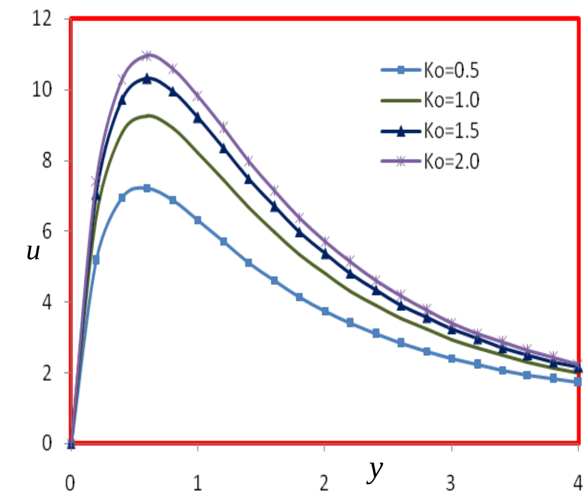

Fig.4: Effect of permeability parameter on velocity field u
(Gr=3.0, Gm=3.0, Re=3.0, K_0 =1.0, Pr=0.71, Sc=0.66, ε =0.1 and Z=0.0)

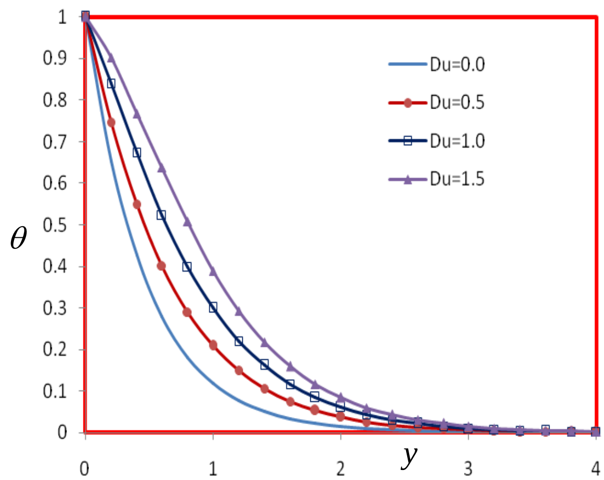

Fig.5-Effects of Dufour 'Du' on temperature profile θ
($Pr=0.71$, $Re=3.0$, $K_0=1.0$, $\varepsilon=0.1$ and $Z=0.0$)

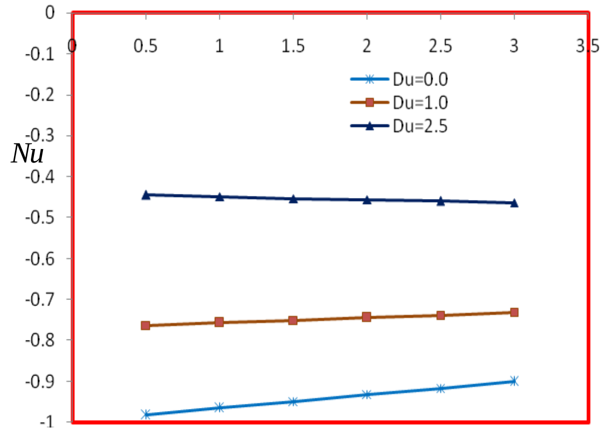

Fig 8-Nusselt number 'Nu' versus 'Re' in the presence of Dufour ($Pr=0.71$, $Re=3.0$, $Ko=1.0$, $\varepsilon=0.1$ and $Z=0.0$)

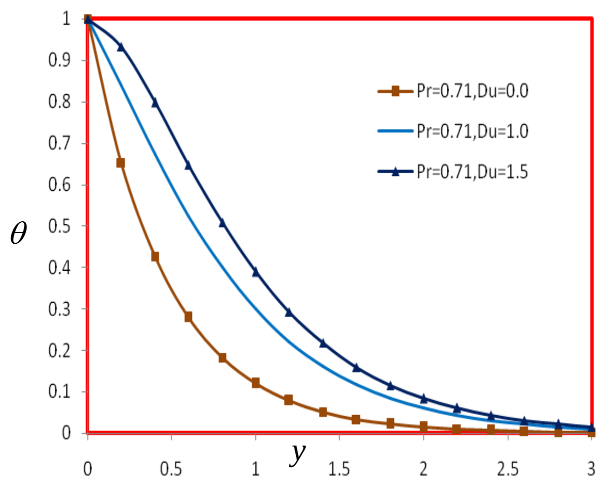

Fig.6-Effects of Pr on temperature profile θ in the presence of Dufour
($K_0=1.0$, $Re=3.0$, $\varepsilon=0.1$ and $Z=0.0$)

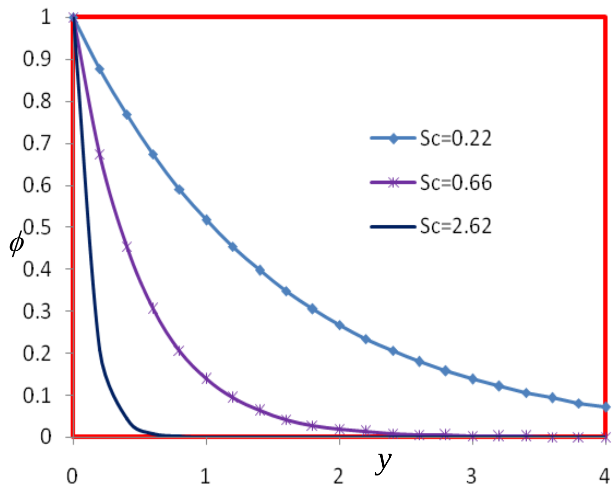

Fig 9-Effect of Schmidt number on Concentration field
($Pr=0.71$, $Re=2.0$, $Ko=1.0$, $\varepsilon=0.1$ and $Z=0.0$)

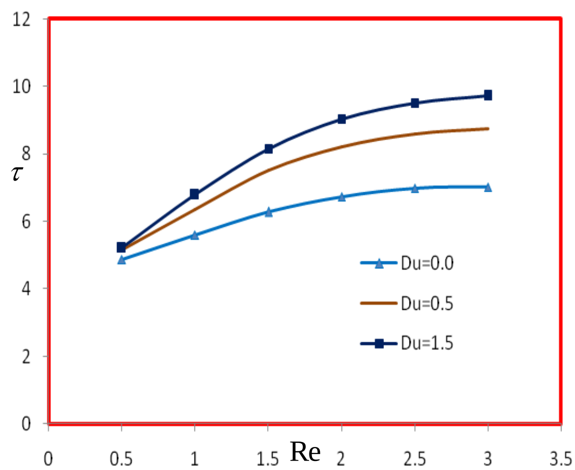

Fig 7- Skin-friction τ versus 'Re' in the presence of Dufour
($Gr=5.0$, $Gm=5.0$, $Re=3.0$, $Ko=1.0$, $Pr=0.71$, $Sc=0.66$, $\varepsilon=0.1$ and $Z=0.0$)

Re

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