Effects of Dufour, Thermal Radiation, Absorption of Radiation and Chemical Reaction on MHD Oscillatory Flow in An Asymmetric Wavy Channel

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Abstract- The objective of this paper is to investigate the combined effects of Diffuson – Thermo (Dufour), thermal radiation, absorption of radiation and chemical reaction on MHD oscillatory flow of an optically conducting thin fluid in an asymmetric wavy channel filled with porous medium. Analytical expressions for the velocity, temperature and concentration profiles are obtained. Solutions are analyzed graphically for different values of arising parameters such as Schmidt number (Sc), Peclet number (Pe), Reynolds number (Re), absorption of radiation parameter (Ra), Dufour parameter (DT), thermal Grashof number (Gr), solutal Grashof number (Gm), porous medium shape factor parameter (S), radiation parameter (N), magnetic parameter (M), chemical reaction parameter (K1), the geometric parameter's like amplitude ratio's (a and b), mean half width of the channel (d) and Phase angle (ωt). The expressions for skin friction and the rate of heat and mass transfer coefficients at the channel walls are derived and discussed numerically for different physical parameters and exhibited in tabular form. The velocity and temperature increase with increasing radiation parameter and Dufour number whereas the concentration decreases with increasing chemical reaction parameter and Schmidt number. This study is carried out to obtain a better understanding of the flow instabilities with heat and mass transfer in wavy passages so that design guidelines may be developed.

Indexed Terms- Oscillatory flow, Asymmetric Wavy channel, Dufour effect, Radiation, Absorption of radiation.

I. INTRODUCTION

Flows with heat and mass transfer of electrically conducting fluids in channels under the influence of a transverse magnetic field occur in MHD power generators, the cooling of nuclear reactor and boundary layer control in aerodynamics and crystal growth. Previous studies have focused on the flow with heat and mass transfer on a flat wall or a regular channel. The study of the flow with heat and mass transfer in an irregular channel is necessary because such flows find applications in different areas such as transpiration cooling of reentry vehicles and rocket boosters, crosshatching on ablative surfaces and film vaporization in combustion chambers. The heat transfer of an irregular surface is a crucial topic and is often found in heat transfer systems such as flat plate solar collectors, condensers in refrigerators and fins in electronic equipment cooling systems.

Benjamin [1] was probably the first to consider the problem of the flow over a wavy wall. His analysis was based on the assumption of parallel flow in absence of waviness. The steady streaming generated by an oscillatory viscous flow over a wavy wall under the assumption that the amplitude of the wave is smaller than the Stokes boundary layer thickness was studied by Lyne [2]. Lekoudis et al. [3] made a linear analysis of compressible boundary layer flows over a wavy wall. Yao [4] studied the case of uniform surface temperature laminar free convection along a semi-infinite vertical wavy surface for a Newtonian fluid. Pop and Na [5 and 6] studied the natural convection flow along a vertical wavy cone and a frustum of a wavy cone in porous media. Rees and Pop [7, 8 and 9] carried out some studies to analyze natural convection from vertical and horizontal wavy surfaces embedded in a porous medium.

Hossain and Pop [10] studied the magneto hydrodynamic boundary layer flow and heat transfer on a continuous moving wavy surface in Newtonian fluids. The free convection of a viscous incompressible fluid in porous medium between two long vertical wavy walls was investigated by Patidar and Purohit [11]. Cheng [12 and 13] reported the phenomenon of natural convection heat and mass transfer near a vertical wavy surface with constant wall temperature and concentration in a porous medium, considering the two cases of Darcian and non-Darcian models. Again, the same author [14] studied the phenomenon of natural convection heat and mass transfer near a wavy cone and a frustum wavy cone with constant wall temperature and concentration in a porous medium. Especially the boundary layer concept of electrically conducting fluid flows bounded by wavy wall is of special importance owing to its applications in many engineering fields. In view of these applications, Niceno and Nobile [15], Wang and Chen [16], Jang and Yan [17], Mekheimer et.al.[18] and Sivaraj and Rushi Kumar [19] have analyzed the fluid flow in wavy-walled channels.

Molla et al. [20] presented natural convection flow along a vertical wavy surface with uniform surface temperature in the presence of heat generation/absorption. Kumar and Shalini [21] analyzed the natural convection heat transfer from a vertical wavy surface in a thermally stratified fluid saturated porous medium under Forchheimer based Non-Darcian assumptions. Mahdy et al. [22 and 23] studied the effect of vertical wavy surface (vertical wavy cone) in the presence of heat generation, absorption and magnetic field. Nasser and Nader [24] analyzed the effects of variable properties on MHD unsteady natural convection heat and mass transfer over a vertical wavy surface. Siva Nageswara Rao and Sivaiah [25] have investigated the convective study of heat and mass transfer flow of a viscous electrically conducting fluid in a vertical wavy channel under the influence of an inclined magnetic fluid with heat generating sources.

In nature, there are flows that are caused not only due to the difference of temperature but also due to the concentration differences. The mass transfer differences do affect the rate of heat transfer. In industries, many transport processes exist in which heat and mass transfer take place simultaneously as a result of combined buoyancy effect in the presence of thermal radiation. Radiation is a process of heat transfer through electromagnetic waves. Hence, radiative heat and mass transfer play an important role in manufacturing industries for the design of fins, steel rolling, combustion and furnace design, materials processing, energy utilization, temperature measurements, remote sensing for astronomy and space exploration, food processing and cryogenic engineering as well as numerous agricultural, health and military applications Prakash et al [26]. If the temperature of surrounding fluid is rather high, radiation effects play an important role and this situation does exist in space technology. In such cases, the combined effect of thermal radiation and mass diffusion need to be taken into consideration. The effects of radiation on MHD flow and heat transfer problems have become industrially significant. Numerous engineering processes occur at high temperatures and the knowledge of radiation heat transfer is essential for designing appropriate equipment. Nuclear power plants, gas turbines and various propulsion devices for aircraft, missiles and satellites are examples of such processes Eckert and Drake [27].

The effect of radiation on various convective flows under different conditions has been studied by many researchers including Hussain and Takhar [28], Ghaly [29], Raptis et al. [30], Muthucumaraswamy and Ganesan [31], Ahmed and Sarmah [32], and Rajesh and Varma [33]. Makinde and Mhone [34] analyzed the combined effects of a transverse magnetic field and radiative heat transfer on unsteady flow of a conducting optically thin fluid through a channel filled with saturated porous medium and non-uniform walls temperature. Tak and Kumar [35] investigated the heat transfer with radiation in MHD free convection flow confined between a vertical wavy wall and a flat wall. Mohamed et al. [36] studied the combined radiation and free convection from a vertical wavy surface embedded in porous media. Pal and Mondal [37] studied the effects of radiation on the combined convection flow of an optically dense viscous incompressible fluid over a vertical surface installed in a fluid saturated porous medium of variable porosity with heat generation and absorption. Israel Cookey et al. [38] have studied the combined effects of radiative heat transfer and a transverse magnetic field on the steady flow of an electrically conducting optically thin fluid through a horizontal channel filled with porous medium and non-uniform temperature at the walls. Exact solution of an oscillatory free convective MHD flow in a rotating channel in the presence of radiative heat has also been studied by Singh and Garg [39]. Rakesh Kumar [40] studied the radiation and Soret effects on hydromagnetic purely oscillatory flow in a planer vertical channel.

Radiation and chemical reaction of convective fluids under the influence of heat source within a porous medium have many practical applications in geophysics and energy related problems as in recovery of petroleum resources, cooling of underground electric cables, ground water pollution, fiber and granular insulation, chemical catalytic reactors and solidification of casting. Mass diffusion rates can be changed tremendously with chemical reactions. A few representative areas of interest in which heat and mass transfer combined along with the chemical reaction play significant role in chemical industries like in food processing, polymer production and manufacturing of ceramics or glass ware. Chambre and Young [41] have presented first order chemical reaction in the neighbourhood of a horizontal plate. The idea of first order chemical reaction where the rate of reaction is directly proportional to the concentration itself has been analyzed by Cussler [42].

Ibrahim et al [43] studied the effect of a chemical reaction and radiation absorption on an unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with heat source and suction. Prasad and Reddy [44] investigated radiation and mass transfer effects on an unsteady MHD free convection flow past a semi-infinite vertical permeable moving plate with viscous dissipation. An analytical study for the problem of unsteady mixed convection with thermal radiation and chemical reaction on MHD boundary layer flow of a viscous, electrically conducting fluid past a vertical permeable plate has been presented by Pal and Talukdar [45]. Rajput and Surendra Kumar [46] have studied the influence of the radiation and chemical reaction effect on free convection MHD flow through a porous medium bounded by vertical surface. Kesavaiah et al., [47] have studied the effects of the chemical reaction and radiation absorption in an unsteady MHD convective heat and mass transfer flow past a semi-infinite vertical permeable moving plate installed in a porous medium with heat source and suction. Sudershan Reddy et al. [48] have discussed the chemical and radiation absorption effects on MHD convective heat and mass transfer flow past a semi-infinite vertical moving porous plate with time dependent suction. The effects of radiation on an unsteady laminar flow with heat and mass transfer of an electrically conducting, chemically reactive viscoelastic fluid in irregular channel subject to convective boundary condition has been investigated by Gireesha and Mahanthesh [49]. Manjulatha et al. [50] investigated the radiation and chemical reaction effects on the unsteady MHD oscillatory flow in a channel filled with saturated porous medium in an aligned magnetic field. Again, Manjulatha et.al [51] have discussed the effects of radiation absorption and mass transfer on the steady free convective flow of a viscous, incompressible and electrically conducting fluid past an infinite vertical flat plate through a porous medium with an aligned magnetic field.

The mixture density ρ depends linearly on both temperature and concentration for sufficiently small isobaric changes in temperature and concentration. In some circumstances, there is a link between temperature and concentration and this is where cross-diffusion (Soret and Dufour effects) is not negligible. The energy flux caused by a composition gradient was discovered in 1873 by Dufour and was correspondingly referred to the Dufour effect. It is also called the diffusion-thermo effect. Contrarily, the flux of mass is caused due to temperature gradient which is known as the Soret effect or the thermal diffusion effect. In many studies, Soret and Dufour effects are neglected based on the smaller order magnitude than the effects described by Fourier’s and Fick’s laws. Platten and Legros [52] state that in most liquid mixtures the Dufour effect is inoperate, but this may not be the case in gases.

The effects of diffusion-thermo and thermal-diffusion on the transport of heat and mass were developed from the kinetic theory of gases by Chapman and Cowling [53]. Eckert and Drake [54] found that the diffusion-thermo effect cannot be neglected in concerning isotope separation and in mixtures between gases with very light molecular weight (H2, He) and for medium molecular weight (N2, air). Kafoussias and Williams [55] considered the boundary layer flows in the presence of Soret and Dufour effects associated with thermal-diffusion and diffusion-thermo for the mixed convection. The similarity equations of the problem considered were obtained by using the usual similarity technique. Anghel et al. [56] concluded that thermal-diffusion and diffusion-thermo effects appreciably influence the flow field in free convection boundary-layer over a vertical surface embedded in a porous medium. Postenlnicu [57] discussed numerically the influence of a magnetic field on heat and mass transfer by natural convection from vertical surfaces in porous media with Soret and Dufour effects. Alam et al. [58] studied theoretically the problem of a steady two-dimensional free convection and mass transfer flow past a continuously moving semi-infinite vertical porous plate in a porous medium by including the Soret and Dufour effects. The characteristics of heat and mass transfer in a mixed convection boundary layer flow about a linearly stretching vertical surface in a porous medium filled with a viscoelastic fluid, by taking into account the diffusion-thermo and thermal-diffusion effects was analyzed by Hayat et al. [59]. Lakshmi Narayana and Sibanda [60] investigated free convection heat and mass transfer along a vertical wavy surface in a Newtonian fluid saturated Darcy porous medium by considering the effects of cross diffusion (namely the Soret and the Dufour effects) in the medium.

Rushi Kumar and Sivaraj [61] have analyzed the steady MHD mixed convective boundary layer slip flow in an irregular channel with the influence of thermal radiation, Dufour effect and chemical reaction. Saxena and Dubey [62] reported unsteady MHD heat and mass transfer free convection flow of a polar fluid past a vertical moving porous plate in a porous medium with heat generation and thermal diffusion and the governing equations were solved using perturbation technique. Sreekantha Reddy et al. [63] have discussed the effect of chemical reaction and thermo-diffusion on non-Darcy convective heat and mass transfer flow in a vertical channel with heat sources. Diffusion thermo and radiation effects on MHD free convective heat and mass transfer flow past an infinite vertical plate in the presence of a chemical reaction of first order have been studied by Raveendra Babu et al. [64]. Kumar et al [65] investigated thermal diffusion and radiation effects on unsteady MHD flow through porous medium with variable temperature and mass diffusion in the presence of heat source or sink. Diffusion-thermo (Dufour number) and radiation effects on MHD free convective heat and mass transfer flow of a visco-elastic fluid past an infinite vertical plate with homogeneous chemical reaction of first order has been examined by Rita Choudhaury and Pabandhar [66]. Pandya and Shukla [67] investigated the effects of Soret-Dufour and radiation on inclined porous plate in the presence of variable temperature and concentration. Mohammed Ibrahim [68] studied the Soret and Dufour effects on unsteady MHD convective heat and mass transfer flow past an infinite vertical plate embedded in a porous medium in the presence of radiation.

Due to the importance of the diffusion-thermo effects on the heat and mass transfer related problems, we propose to study the effects of Dufor, thermal radiation, absorption of radiation and chemical reaction on MHD oscillatory flow of an optically conducting thin fluid in an asymmetric wavy channel filled with porous medium. The velocity, temperature, concentration, shear stress and rate of Heat and Mass transfer are evaluated numerically for different variations of parameters.

II. FORMULATION OF THE PROBLEM

Considered the flow of a conducting optically thin fluid in an asymmetric wavy channel whose walls are given by

$$H_1 = d_1 + a_1 \cos(\frac{2\pi x}{\lambda}) \quad (1)$$

$$H_2 = -d_2 - b_1 \cos(\frac{2\pi x}{\lambda} + \phi) \quad (2)$$

where a_1 and b_1 are the amplitudes of the wavy walls, λ is the wave length, $d_1 + d_2$ is the width of the channel and φ is the phase difference which varies in the range $0 \le \varphi \le \pi$ in which $\varphi = 0$ corresponds to symmetric channel with waves out of phase and $\varphi = \pi$ corresponds to the waves in phase. Further a_1, b_1, d_1, d_2 and φ satisfy the following condition:

$$a_1^2 + b_1^2 + 2a_1 b_1 \cos\phi \le (d_1 + d_2)^2 \qquad (3)$$

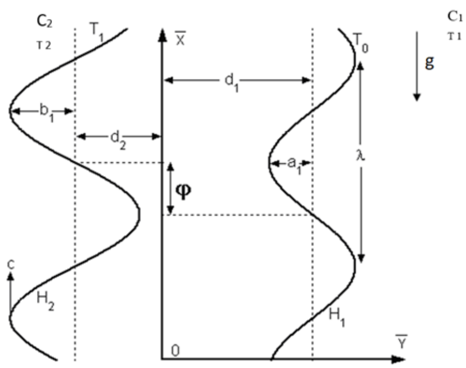

Figure 1 Physical Model

III. PHYISCAL MODEL

The $\bar{X}$-axis is chosen along the walls of channel and $\bar{Y}$-axis is taken normal to the walls. A uniform magnetic field B_0 is applied in the transverse direction to the flow. The walls of the channel are maintained at concentrations C_1, C_2 and temperatures T_1, T_2 respectively which are high enough to induce heat and mass transfer. It is assumed that the magnetic Reynolds number is very small and hence the induced magnetic field is negligible. Viscous resistance term is taken into account with constant permeability of the porous medium. Under these assumptions, the governing equations can be written in a Cartesian frame of reference as follows:

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \nu\frac{\partial^2 w}{\partial y^2} - \frac{\nu}{k}w + g\beta(T - T_2) + g\beta^*(C - C_2) - \frac{\sigma_e B_0^2 w}{\rho} \qquad (4)$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho c_p}\frac{\partial q}{\partial y} + Q_1(C - C_2) + \frac{D_m k_T}{C_s C_p}\frac{\partial^2 C}{\partial y^2} \qquad (5)$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial y^2} - Kr(C - C_2) \qquad (6)$$

together with the boundary conditions

$$w = 0, T = T_1, C = C_1 on y = H_1$$
$$w = 0, T = T_2, C = C_2 on y = H_2 \qquad (7)$$

Here, the fluid is optically thin with a relatively low density. The radiative heat flux given by Ogulu and Bestman [69] is

$$\frac{\partial q}{\partial y} = 4\alpha^2(T_2 - T) \qquad (8)$$

Introducing the following non-dimensional quantities

$$\bar{X} = \frac{x}{d}, \bar{Y} = \frac{y}{d}, \bar{w} = \frac{w}{d}, \bar{t} = \frac{t}{d},$$

$$\bar{P} = \frac{dp}{\rho\nu U}, \theta = \frac{T - T_2}{T_1 - T_2}, \varphi = \frac{C - C_2}{C_1 - C_2}, M^2 = \frac{\sigma_e B_0^2 d^2}{\rho U},$$

$$Gr = \frac{g\beta(T_1 - T_2)d^2}{\rho U}, Gm = \frac{g\beta^*(C_1 - C_2)d^2}{\rho U},$$

$$Pe = \frac{Ud\rho c_p}{K}, N^2 = \frac{4\alpha^2 d^2}{K}, Q_1 = \frac{K(T_1 - T_2)}{\rho c_p (C_1 - C_2)d^2}$$

$$K_1 = \frac{Krd}{U}, Re = \frac{Ud}{\nu}, Sc = \frac{\nu}{d}, S^2 = \frac{d^2}{k}, h_1 = \frac{H_1}{d_1},$$
$$h_2 = \frac{H_2}{d_2}, a = \frac{a_1}{d_1}, b = \frac{b_1}{d_1}, d = \frac{d_2}{d_1}, D_T = \frac{D_m k_T (C_1 - C_2)}{C_s C_p \nu (T_1 - T_2)}.$$
(9)

the boundary walls in non-dimensional form become

$$h_1 = 1 + a\cos(2\pi x)$$
$$h_2 = -d - b\cos(2\pi x + \phi) \qquad (10)$$

where *a*, *b*, *d* and φ satisfy the relation

$$a^2 + b^2 + 2ab\cos\phi \le (1 + d)^2 \qquad (11)$$

where *a* and *b* are amplitude ratio's, *d* is the mean half width of the channel and φ is the phase difference.

Equations (4) – (6) and corresponding boundary conditions (7) reduce to

$$Re\frac{\partial w}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\partial^2 w}{\partial y^2} - (S^2 + M^2)w + Gr\theta + Gm\varphi$$
(12)

$$Pe\frac{\partial\theta}{dt}=\frac{\partial^2\theta}{\partial y^2}+N^2\theta+A\varphi+D_T\frac{\partial^2\varphi}{\partial y^2} \quad (13)$$

$$Re\frac{\partial\varphi}{dt}=\frac{1}{Sc}\frac{\partial^2\varphi}{\partial y^2}-K_1R\,e\,\varphi \quad (14)$$

with the boundary conditions

$$w=0,\theta=1,\varphi=1 on y=h_1,$$
$$w=0,\theta=0,\varphi=0 on y=h_2 \quad (15)$$

IV. SOLUTION OF THE PROBLEM

For purely an oscillatory flow, we take the pressure gradient of the form $-\frac{\partial p}{\partial x}=\lambda e^{i\omega t}$ where λ is constant and ω is the frequency of oscillations. Due to the selected form of pressure gradient, we assume that the solution for $w(y,t),\theta(y,t)$ and $\varphi(y,t)$ to be in the form:

$$w(y,t)=w_0e^{i\omega t},\theta(y,t)=\theta_0e^{i\omega t},\varphi(y,t)=\varphi_0e^{i\omega t} \quad (16)$$

Substituting equation (16) into equations (12), (13) and (14), we get

$$\frac{d^2w_0}{dy^2}-n^2w_0=-\lambda-Gr\theta_0-Gm\varphi_0 \quad (17)$$

$$\frac{d^2\theta_0}{dy^2}+m^2\theta_0=-Q\varphi_0-D_T\frac{d^2\varphi_0}{dy^2} \quad (18)$$

$$\frac{d^2\varphi_0}{dy^2}-l^2\varphi_0=0 \quad (19)$$

with the corresponding boundary conditions

$$w_0=0,\theta_0=1,\varphi_0=1 on y=h_1,$$
$$w_0=0,\theta_0=0,\varphi_0=0 on y=h_2 \quad (20)$$

Solving the equations (17), (18) and (19) using the boundary conditions (20), we obtain

$$\varphi=\left[\frac{sinh(l(y-h_2))}{sinh(l(h_1-h_2))}\right]e^{i\omega t} \quad (21)$$

$$\theta=\left[\frac{B_1\sin(m(y-h_2))}{\sin(m(h_2-h_1))}+\frac{B}{l^2+m^2}\frac{sinh(l(y-h_2))}{sinh(l(h_1-h_2))}\right]e^{i\omega t} \quad (22)$$

$$w=\left[\begin{array}{l}\left\{\frac{\lambda_1 sinh(nh_1)-B_4 sinh(nh_2)}{sinh(n(h_2-h_1))}\right\}cosh(ny)+\\ \left\{\frac{B_4 cosh(nh_2)-\lambda_1 cosh(nh_1)}{sinh(n(h_2-h_1))}\right\}sinh(ny)\\ +\lambda_1-\left\{\frac{B_2\sin(m(y-h_2))}{\sin(m(h_1-h_2))}\right\}-\left\{\frac{B_3 sinh(l(y-h_2))}{sinh(l(h_1-h_2))}\right\}\end{array}\right]e^{i\omega t} \quad (23)$$

The skin friction across the channel's wall is given by

$$\tau=\left[\frac{\partial w}{\partial y}\right]_{y=h_1,y=h_2} \quad (24)$$

Substituting (23) into equation (24), we obtain

$$\tau_{y=h_1}=\left[\begin{array}{l}\left\{\frac{\lambda_1 sinh(nh_1)-B_4 sinh(nh_2)}{sinh(n(h_2-h_1))}\right\}n\,sinh(nh_1)+\\ \left\{\frac{B_4 cosh(nh_2)-\lambda_1 cosh(nh_1)}{sinh(n(h_2-h_1))}\right\}n\,cosh(nh_1)\\ -\left\{\frac{B_2m\cos(m(h_1-h_2))}{\sin(m(h_1-h_2))}\right\}-\left\{\frac{B_3l\,cosh(l(h_1-h_2))}{sinh\,l(m(h_1-h_2))}\right\}\end{array}\right]e^{i\omega t} \quad (25)$$

$$\tau_{y=h_2}=\left[\begin{array}{l}\left\{\frac{\lambda_1 sinh(nh_1)-B_4 sinh(nh_2)}{sinh(n(h_2-h_1))}\right\}n\,sinh(nh_2)+\\ \left\{\frac{B_4 cosh(nh_2)-\lambda_1 cosh(nh_1)}{sinh(n(h_2-h_1))}\right\}n\,cosh(nh_2)\\ -\left\{\frac{B_2m}{\sin(m(h_1-h_2))}\right\}-\left\{\frac{B_3l}{sinh(l(h_1-h_2))}\right\}\end{array}\right]e^{i\omega t} \quad (26)$$

The rate of heat transfer across the channel's wall is given by

$$Nu=\left[-\frac{\partial\theta}{\partial y}\right]_{y=h_1,y=h_2} \quad (27)$$

Substituting (22) into equation (27), we obtain

$$Nu_{y=h_1}=-\left[\left\{\frac{B_1m}{\sin(m(h_2-h_1))}\right\}+\left\{\frac{Bl}{(l^2+m^2)\,sinh(l(h_1-h_2))}\right\}\right]e^{i\omega t} \quad (28)$$

$$Nu_{y=h_1}=-\left[\left\{\frac{B_1m}{\sin(m(h_2-h_1))}\right\}+\left\{\frac{Bl}{(l^2+m^2)\,sinh(l(h_1-h_2))}\right\}\right]e^{i\omega t} \quad (29)$$

The rate of mass transfer across the channel's wall is given by

$$Sh=\left[\frac{\partial\varphi}{\partial y}\right]_{y=h_1,y=h_2} \quad (30)$$

Substituting (21) into equation (30), we obtain

$$Sh_{y=h_1} = \left[\frac{l\,cosh(l(h_1-h_2))}{sinh(l(h_1-h_2))}\right] e^{i\omega t} \qquad (31)$$

$$Sh_{y=h_2} = \left[\frac{l}{sinh(l(h_1-h_2))}\right] e^{i\omega t} \qquad (32)$$

V. RESULTS AND DISCUSSION

In order to get a deep understanding of the physical problem, numerical results are displayed with the help of graphical illustrations. Computations were carried out for various values of the physical parameters such as Schmidt number (*Sc*), Reynolds number (*Re*), Peclet number (*Pe*), absorption of radiation parameter *(Ra),* thermal Grashof number (*Gr*), solutal Grashof number *(Gm),* porous medium shape factor parameter (*S),* radiation parameter (*N*), magnetic parameter (*M),* Dufour number *(D_T),* chemical reaction parameter (K_1) ,the geometric parameters like amplitude ratios (*a* and *b*), mean half width of the channel (*d*) and Phase angle (ωt).

Figures 2–26 illustrate the influence of the material parameters on the velocity, temperature and the concentration profiles while Tables 1- 4 summarize the effects of these parameters on the values of the Sherwood number, Nusselt number and the skin-friction coefficient. Throughout the computations, we employ the arbitrary values for $Sc = 0.66$, $Ra = 1$, $Pe = 1$, $Re = 1$, $Gr = 5$, $Gm = 5$, $S = 1$, $N = 1$, $M = 1$, $K_1 = 1$, $D_T = 1$, $\omega = 1$, $t = 1$, $\lambda = 0.001$, $x = 0.5$, $a = 0.2$, $b = 1.2$, $d = 2$ and $\varphi = 0$ unless and otherwise mentioned.

The concentration profiles have been studied and presented in figures 2, .3 and 4. In figure 2 it is observed that the concentration profile decreases with increase in Schmidt number because this happens as Sc increases there is decrease in molecular diffusivity which leads to less concentration of the fluid. The effect of concentration for different values of Reynolds number is presented in figure 3. The trend shows that the concentration decreases with increasing values of Reynolds number. The fluid flow is treated as a first order chemical reaction and it reduces the fluid concentration, that is. the concentration distribution across the boundary layer decreases with an increase in chemical reaction parameter, which is showed in figure 4.

The effects of radiation parameter, Dufour number and Peclet number on temperature profile is elucidated in figures 5, .6 and 7 respectively. It is observed that temperature increases with increasing values of radiation parameter or Dufour number or Peclet number.

Figures 8-18 exhibit the behavior of the velocity field against y under the influence of parameters such as radiation parameter (*N*), magnetic parameter (*M),* porous medium shape factor parameter (*S),* Reynolds number (*Re*), Peclet number (*Pe*), absorption of radiation parameter *(Ra),* chemical reaction parameter (K_1), Schmidt number (*Sc*), thermal Grashof number (*Gr*), solutal Grashof umber *(Gm)* and Dufour number *(D_T).*

For different values of radiation parameter (*N*), the velocity profiles are plotted in figure 8. As the value of *N* increases the velocity increases with an increasing in the flow boundary layer thickness. Thus, thermal radiation enhances convective flow. The variation of velocity profile on porous medium shape factor parameter (*S)* is demonstrated in figure 9. It is observed that velocity decreases with increase in porous medium shape factor parameter. The effect of magnetic field parameter on velocity profile is shown in figure 10 and it is observed that velocity decreases with increase in magnetic field parameter because the presence of magnetic field yields a drag force called Lorentz force which retards the fluid velocity. Figure 11 elucidates the effect of Reynolds number on velocity and it is found that it increases with an increase in Reynolds number. It is revealed from figure 12 that the velocity increases with an increase in the Peclet number. From figure 13 it is evident that, an increase in absorption of radiation parameter leads to increase in the velocity.

For different values of the chemical reaction parameter (K_1), the velocity profiles are plotted in figure 14. It is observed that the influence of increasing values of K_1, decreases the velocity.. Figure 15 depict the influence of the Schmidt number on the velocity. It is observed that increase in the Schmidt number increases the magnitude of the velocity. Figure 16 depicts the effects of thermal Grashof number on velocity profile for Gr = 0, 5, 10 and 15. It is noticed that the magnitude of velocity increases with an increase in the thermal Grashof number. It is evident from the figure 17 that the velocity profile decreases with an increase in solutal Grashof number. Velocity of the fluid with respect to Dufour number is specified in figure 18 and it is observed that the velocity decreases with an increase in Dufour number.

The influences of geometric parameters such as amplitude ratios (a and b), mean half width of the channel (d) and Phase angle (ωt) on velocity field is represented in figures 19-26 for the cases of phase difference $\varphi = 0$ (symmetric channel) and $\varphi = \pi/4$ or $\pi/2$ (wavy channel). Figures 19 and 20 reflect the effect of amplitude ratio parameter (a) on the velocity profiles when $\varphi = 0$ and $\varphi = \pi/4$. It is found that velocity increases with increase in amplitude ratio parameter (a) in both the cases $\varphi = 0$ and $\varphi = \pi/2$. Figures 21 and 22 show representative dimensionless velocity profiles for different values of amplitude ratio parameter (b) corresponding to $\varphi = 0$ and $\varphi = \pi/4$. Figures indicate that the increases of amplitude ratio parameter (b) has the tendency to increase the velocity. Figures 23 and 24 illustrate the velocity profiles for different values of the mean half width parameter of the channel (d) for $\varphi = 0$ and $\varphi = \pi/2$. It is observed that the velocity increases as the mean half width parameter of the channel increases for $\varphi = 0$ whereas it decreases for $\varphi = \pi/2$. Figures 25 and 26 characterize the velocity profile for various values of phase angle parameter (ωt) when $\varphi = 0$ and $\varphi = \pi/4$ .A diminishing behavior is noticed in both $\varphi = 0$ as well as $\varphi = \pi/4$ for increasing values of phase angle parameter. But it is noticed that there is a back flow for $\omega t = 3\pi/4$,π in the case of wavy channel.

The Sherwood number which measures the rate of mass transfer at the walls $y = h_1$ and $y = h_2$ is shown in Table 1 for different parametric values. It is found that the rate of mass transfer enhances with increase in Sc or Re or K_1 at the wall $y = h_1$ and reduces at the wall $y = h_2$.

The rate of heat transfer (Nusselt number) is shown in Table 2 for different values of radiation parameter, Dufour number, Reynolds number, Peclet number and absorption of radiation parameter for both the walls $y = h_1$ and $y = h_2$. It is observed that the rate of heat transfer at $y = h_1$ increases with increase in N or D_T or Re or Pe or Ra while it depreciates at $y = h_2$.

The influence of various parameters on the skin-friction coefficient at the walls $y = h_1$ and $y = h_2$ are shown in Table 3. It is observed that the skin-friction coefficient decreases with an increase of thermal Grashof number or Reynolds number or absorption of radiation parameter or Dufour number or magnetic parameter or porous medium shape factor parameter but this trend is reversed in solutal Grashof number at both the walls $y = h_1$ and $y = h_2$. Increasing Peclet number suppresses the skin friction at the wall $y = h_1$ but it enhances at the wall $y = h_2$. It is observed that the skin-friction coefficient increases with an increase of radiation parameter at the wall $y = h_1$ and it decreases at the wall $y = h_2$.

The variation of skin friction at the walls $y = h_1$ and $y = h_2$ with geometric parameters is presented in Table 4 corresponding to the phase difference $\varphi = 0$ (symmetric channel case) and $\varphi = \pi/2$ (wavy channel case). It is observed that the Skin friction decreases with increasing amplitude ratio parameter (a) when $\varphi = 0$ while it increases when $\varphi = \pi/2$ at the wall $y = h_1$. Further the skin friction decreases for increasing amplitude ratio parameter (a) for a = 0.0, 0.2, 0.4 and it increases for a = 0.6 corresponding to $\varphi = 0$ whereas it decreases corresponding to $\varphi = \pi/2$ at the wall $y = h_2$. It is found that skin friction decreases with increasing amplitude ratio parameter (b) corresponding to $\varphi = 0$ at the walls $y = h_1$ but it decreases for b =1.2, 1.3 then it increases for b =1.5, 1.8 at the wall $y = h_2$ while it remains constant corresponding to $\varphi = \pi/2$ at both the walls $y = h_1$ and $y = h_2$.

The skin friction leads to decrease with the increase of mean half width of the channel (d) at the wall $y = h_1$ whereas an opposite behavior is noticed at the wall $y = h_2$ corresponding to $\varphi = 0$. It is also noticed that skin friction increases with increasing mean half width of the channel (d) for d = 2.2, 2.4, 2.6 and it decreases for d =2.8 at the wall $y = h_1$ and it decreases at the wall $y = h_2$ corresponding to $\varphi = \pi/2$. The magnitude of skin friction decreases with an increase of phase angle for $\omega t = 0, \pi/6$ but this behavior is reversed for $\omega t = \pi/3, \pi/2, 3\pi/4, \pi$ corresponding to $\varphi = 0$ at both the walls y = h_1 and y = h_2. Furthermore, the skin friction decreases for increasing phase angle for $\omega t = 0, \pi/6, \pi/3$ and increases for $\omega t = \pi/2, 3\pi/4, \pi$ at the wall y = h_1 while it increases for $\omega t = 0, \pi/6, \pi/3, \pi/2, 3\pi/4$ and increases for $\omega t = \pi$ at the wall y = h_2 corresponding to $\varphi = \pi/2$.

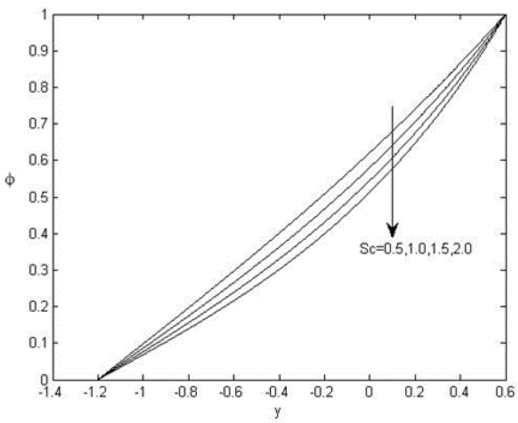

Figure 2 Effect of Sc on concentration field when Re =1, K_1= 0.5, $\omega = 0.1$ and t=0

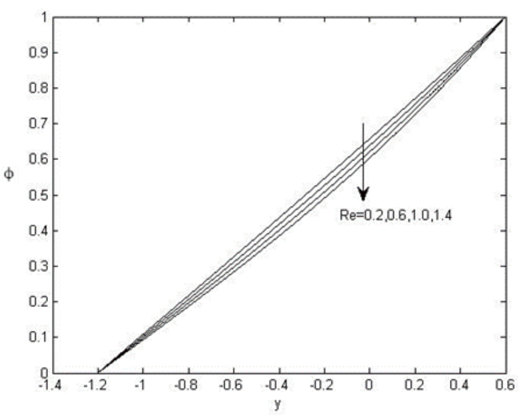

Figure 3 Effect of Re on concentration field when Sc = 0.5, K_1= 0.5, ω = 0.1and t = 0.1

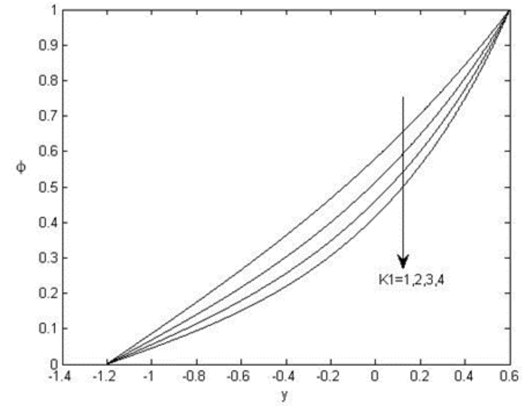

Figure 4 Effect of K_1 on concentration field when Sc=0.5, Re=1 , ω =0.1and t=0.1

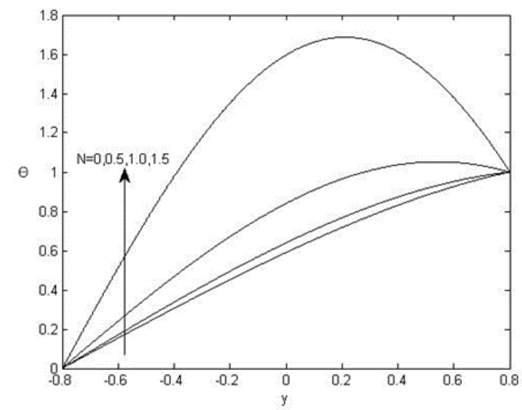

Figure 5 Effect of N on temperature field when ω= 0.1, t = 0.1

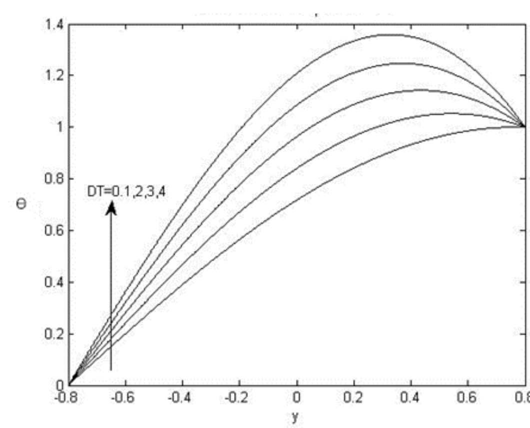

Figure 6 Effect on D_T on temperature field when ω = 0.1and t = 0.1

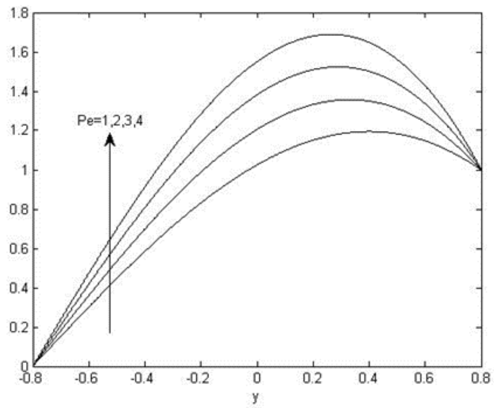

Figure 7 Effect of *Pe* on temperature field when ω = 0.1and t = 0.1

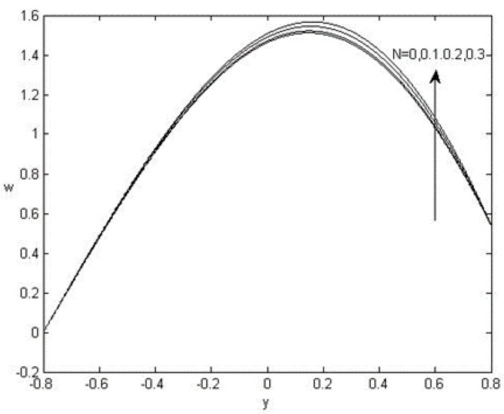

Figure 8 Effect of *N* on velocity field

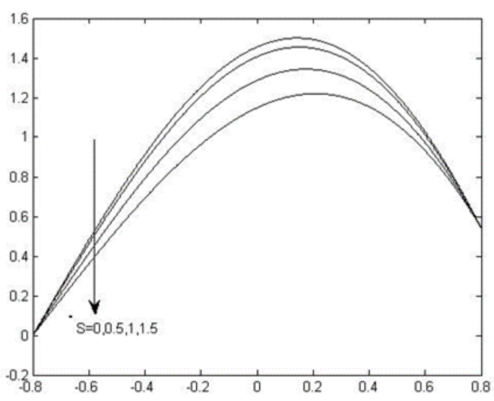

Figure 9 Effect of *S* on velocity field

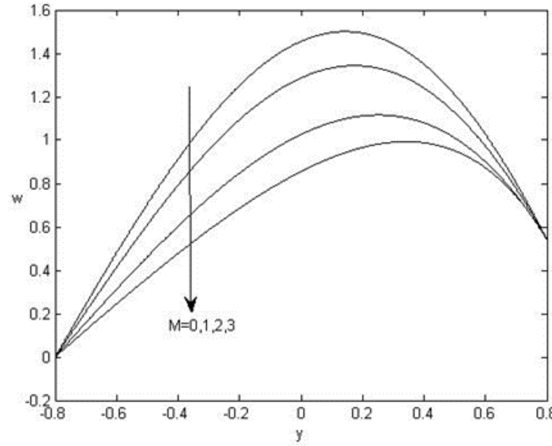

Figure 10 Effect of M on velocity field

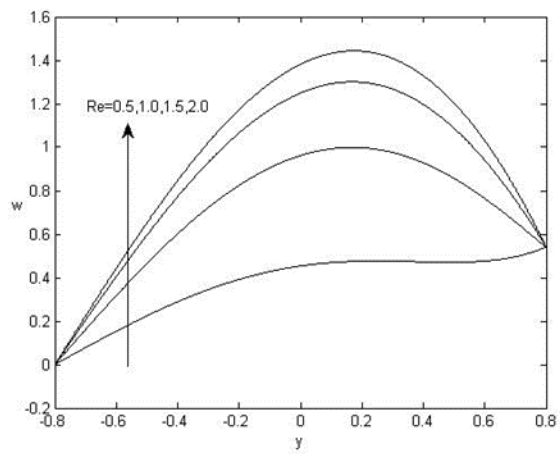

Figure 11 Effect of Re on velocity field

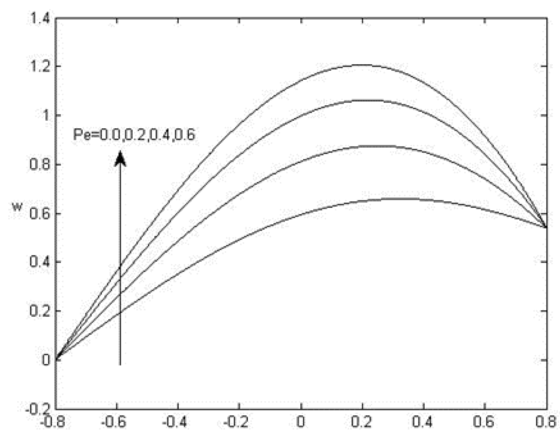

Figure 12 Effect of Pe on velocity field

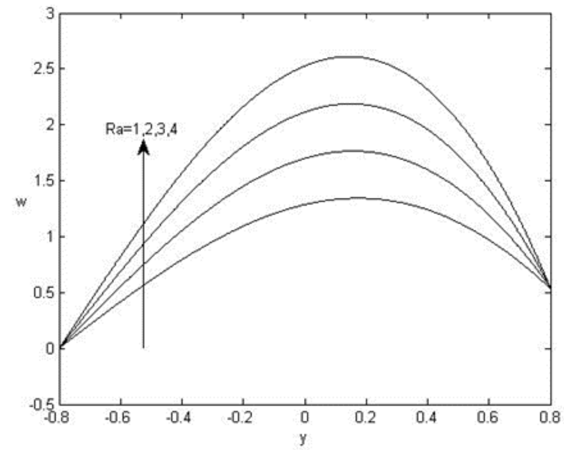

Figure 13 Effect of Ra on velocity field

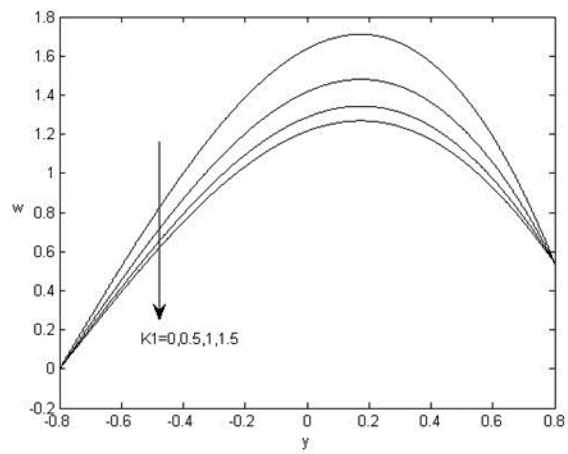

Figure 14 Effect of K1 on velocity field

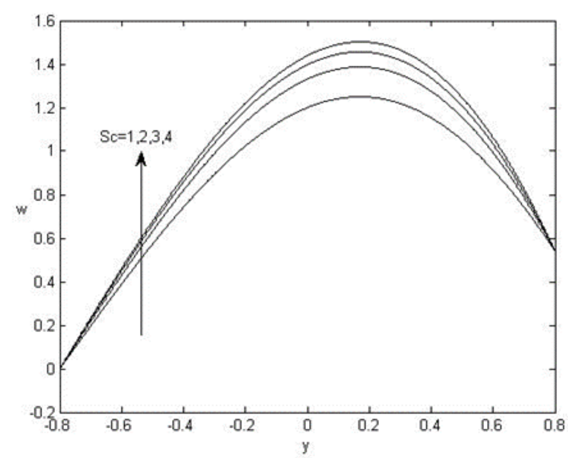

Figure 15 Effect of Sc on velocity field

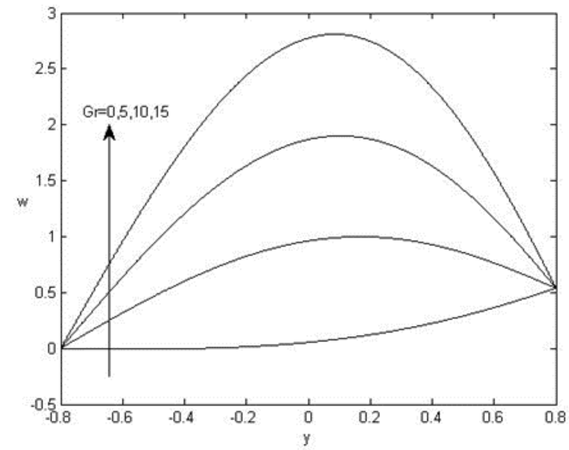

Figure 16 Effect of Gr on velocity field

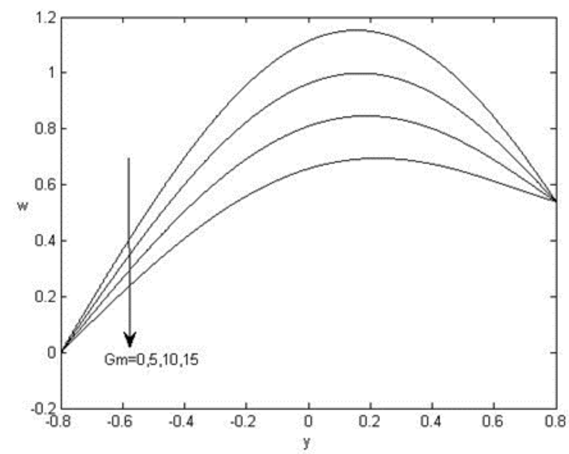

Figure 17 Effect of Gm on velocity field

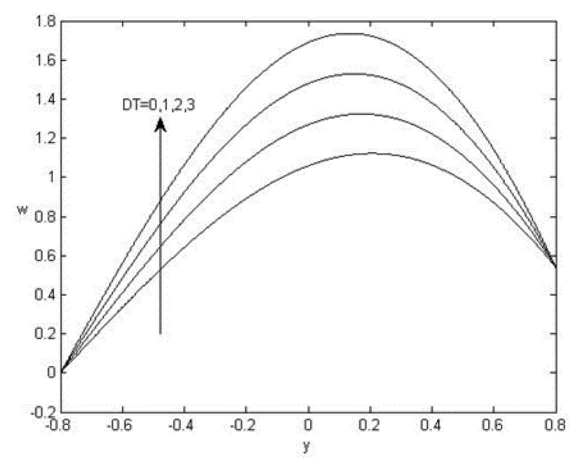

Figure 18 Effect of D_T on velocity field

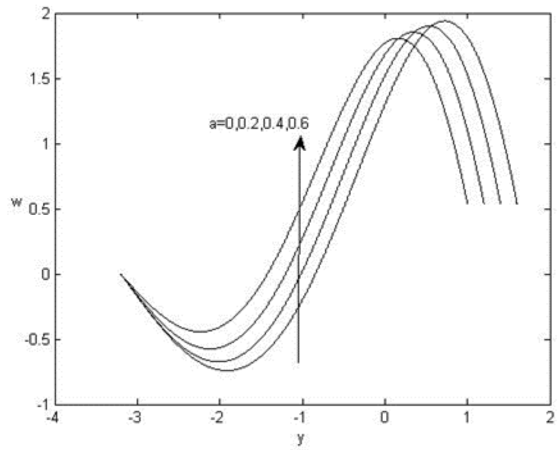

Figure 19 Effect of a on velocity field when $\varphi = 0$

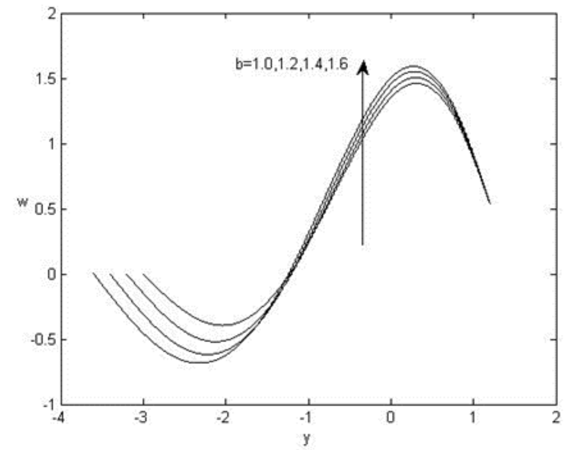

Figure 22 Effect of b on velocity field when $\varphi = \pi/4$

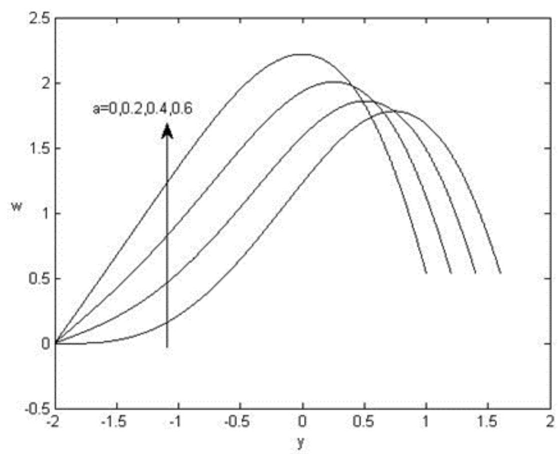

Figure 20 Effect of a on velocity field when $\varphi = \frac{\pi}{2}$

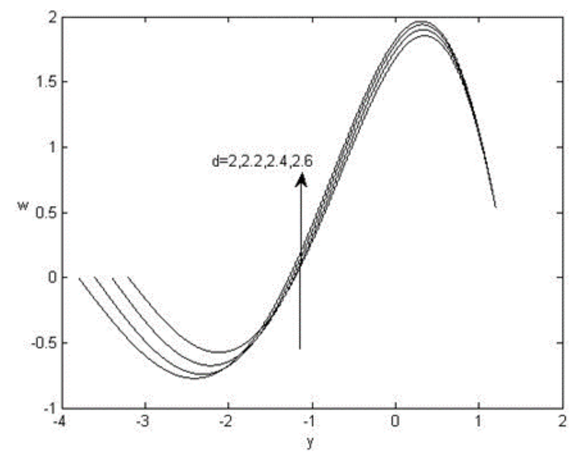

Figure 23 Effect of d on velocity field when $\varphi = \frac{\pi}{2}$

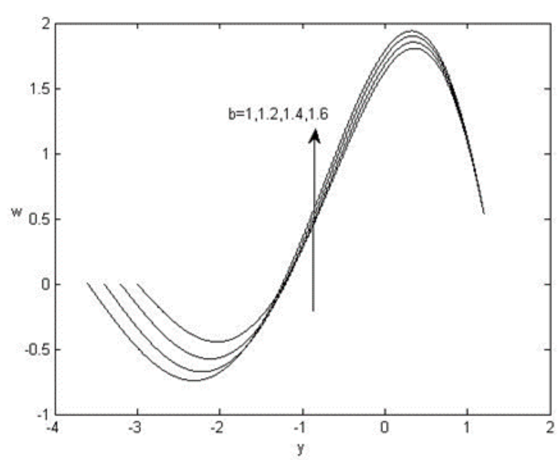

Figure 21 Effect of b on velocity field when $\varphi = 0$

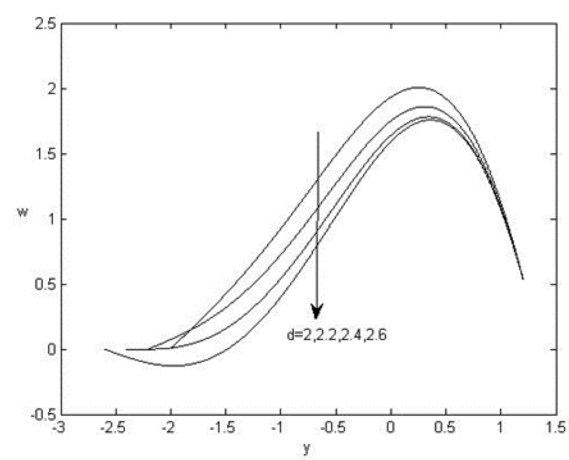

Figure 24 Effect of d on velocity field when $\varphi = \frac{\pi}{2}$

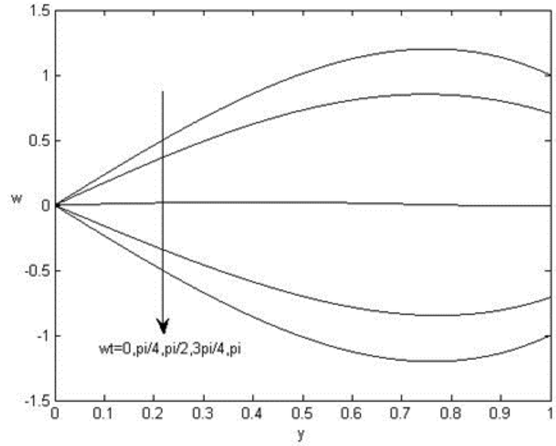

Figure 25 Effect of ωt on velocity field when $\varphi = 0$

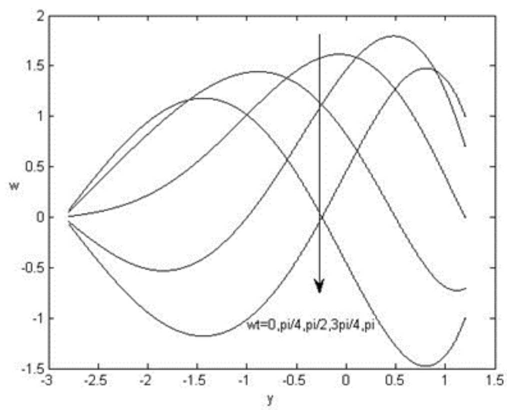

Figure 26 Effect of ωt on velocity field when $\varphi = \frac{\pi}{4}$

Table 1: Rate of mass transfer at the plates $y = h_1$ and$y = h_2$
(a = 0.2, d =2, b =1.2, ω = 0.1, t = 0.1, x = 0.5, φ = 0)

Sc	*Re*	K_1	*Sh* at $y = h_1$	*Sh* at $y = h_2$
0.66	1	1	0.9427	0.4783
1	1	1	1.0850	0.4207
1.5	1	1	1.2746	0.3517
2	1	1	1.4456	0.2969
1	1.5	1	1.2746	0.3517
1	3	1	1.7465	0.2167
1	4	1	2.0078	0.1622
1	1	0	0.6253	0.6244
1	1	0.5	0.8715	0.5088
1	1	2	1.4451	0.2974
1	1	3	1.7455	0.2176
1	1	4	2.0065	0.1633

Table 2: Rate of heat transfer at the plates $y = h_1$ and$y = h_2$
(a = 0.2, d =2, b =1.2, ω = 0.1, t = 0.1, x = 0.5, φ = 0)

N	DT	Re	Pe	Ra	Nu at y=h1	Nu at y=h2
0	1	1	1	1	0.1741	-0.9932
0.2	1	1	1	1	0.2008	-1.0085
0.4	1	1	1	1	0.2834	-1.0567
1	0	1	1	1	0.6129	-1.3128
1	2	1	1	1	1.3869	-1.7291
1	3	1	1	1	1.7739	-1.9372
1	4	1	1	1	2.1609	-2.1453
1	1	0.5	1	1	0.5402	-1.2832
1	1	2	1	1	1.7989	-1.8935
1	1	3	1	1	2.4799	-2.1693
1	1	4	1	1	3.0762	-2.3792
1	1	1	0	1	0.4156	-1.2080
1	1	1	0.5	1	0.7086	-1.3652
1	1	1	1	1	0.9999	-1.5209
1	1	1	1.5	1	1.2892	-1.6747
1	1	1	1	0	0.4149	-1.2070
1	1	1	1	0.5	0.7074	-1.3640
1	1	1	1	1.5	1.2924	-1.6779
1	1	1	1	2	1.5849	-1.8348

Table 3: Skin friction at the plates $y = h_1$ and $y = h_2$
(Sc =1, K_1 =1, a = 0.2, d =2, b =1.2, ω =1, t =1, x = 0, φ = 0)

Gr	Gm	Re	Pe	Ra	DT	M	N	S	τ at $y=h_1$	τ at $y=h_2$
0	5	1	1	1	1	1	1	1	1.0966	0.0289
5	5	1	1	1	1	1	1	1	-3.1563	-0.8094
10	5	1	1	1	1	1	1	1	-7.4092	-1.6478
15	5	1	1	1	1	1	1	1	-11.6621	-2.4861
5	0	1	1	1	1	1	1	1	-3.7562	-0.8331
5	10	1	1	1	1	1	1	1	-2.5565	-0.7858
5	15	1	1	1	1	1	1	1	-1.9567	-0.7621
5	20	1	1	1	1	1	1	1	-1.3569	-0.7385
5	5	0.5	1	1	1	1	1	1	-2.8436	-0.3631
5	5	1.5	1	1	1	1	1	1	-3.5820	-1.0648
5	5	2	1	1	1	1	1	1	-3.9057	-1.1614
5	5	2.5	1	1	1	1	1	1	-4.0977	-1.1516
5	5	1	0	1	1	1	1	1	-0.1514	-1.8653
5	5	1	0.5	1	1	1	1	1	-2.4904	-1.2284
5	5	1	1.5	1	1	1	1	1	-2.9672	-0.5090
5	5	1	1	0	1	1	1	1	-2.0393	-0.5675
5	5	1	1	0.3	1	1	1	1	-2.3744	-0.6401
5	5	1	1	0.6	1	1	1	1	-2.7095	-0.7127
5	5	1	1	0.9	1	1	1	1	-3.0446	-0.7853
5	5	1	1	1	2	1	1	1	-4.0580	-0.9221
5	5	1	1	1	3	1	1	1	-4.9598	-1.0347
5	5	1	1	1	4	1	1	1	-5.8615	-1.1473
5	5	1	1	1	5	1	1	1	-6.7632	-1.2600
5	5	1	1	1	1	0	1	1	-3.8675	-1.2815

Table 4: Skin friction at the plates $y = h_1$ and$y = h_2$ for geometric parameters when Gr = Gm = 5, Sc = D_T = Re = Pe = Ra = M = N = S = K_1=1, x=0

a	B	D	ωt	τ at y=h_1 for $\varphi = 0$	τ at y=h_2 for $\varphi = 0$	τ at =h_1 for $\varphi = \frac{\pi}{2}$	τ at y=h_2 for $\varphi = \frac{\pi}{2}$
0.0	1.2	2.0	$\pi/4$	-3.2855	-0.8891	-3.5873	0.9333
0.2	1.2	2.0	$\pi/4$	-3.3577	-0.9470	-3.3464	0.3996
0.4	1.2	2.0	$\pi/4$	-3.4188	-0.9540	-3.2047	-0.0293
0.6	1.2	2.0	$\pi/4$	-3.4613	-0.9144	-3.1514	-0.3582
0.2	1.1	2.0	$\pi/4$	-3.3223	-0.9246	-3.3464	0.3996
0.2	1.3	2.0	$\pi/4$	-3.3902	-0.9566	-3.3464	0.3996
0.2	1.5	2.0	$\pi/4$	-3.4427	-0.9397	-3.3464	0.3996
0.2	1.8	2.0	$\pi/4$	-3.4827	-0.8346	-3.3464	0.3996
0.2	1.5	2.2	$\pi/4$	-3.4188	-0.9540	-3.2047	-0.0293
0.2	1.5	2.4	$\pi/4$	-3.4613	-0.9144	-3.1514	-0.3582
0.2	1.5	2.5	$\pi/4$	-3.4746	-0.8791	-3.1507	-0.4900
0.2	1.5	2.8	$\pi/4$	-3.4849	-0.7232	-3.2148	-0.7762
0.2	1.2	2.0	0	-2.7870	-1.0542	-2.3609	-1.1040
0.2	1.2	2.0	$\pi/6$	-3.3943	-1.0555	-3.2304	-0.1215
0.2	1.2	2.0	$\pi/3$	-3.0922	-0.7740	-3.2343	0.8935
0.2	1.2	2.0	$\pi/2$	-1.9615	-0.2851	-2.3716	1.6692
0.2	1.2	2.0	$3\pi/4$	0.5837	0.5439	-0.0075	1.9609
0.2	1.2	2.0	π	2.7870	1.0542	2.3609	1.1040

CONCLUSION

An analysis of a homogeneous first order chemical reaction between the fluid and species concentration to study the diffusion thermo (Dufour effect), radiation and absorption of radiation effects on MHD oscillatory flow in an asymmetric wavy channel in the presence of transverse applied magnetic field is performed. This study leads to following conclusions:

The concentration decreases when there is an increase in the strength of chemical reacting substances and Schimdt number.

The temperature of the fluid flow increases for increase in radiation parameter, Dufour number.

The velocity profile increases with increasing radiation parameter, Dufour number, absorption of radiation parameter and thermal Grashof number while it decreases for chemical reaction parameter, magnetic parameter, solutal Grashof number.

Increasing of chemical reaction parameter enhances the rate of mass transfer at the wall y = h_1 but this trend is reversed at the wall y = h_2.

The presence of radiation parameter, Dufour number and absorption of radiation parameter leads to increase the rate of heat transfer at the wall
y = h_1 and decrease at the wall y = h_2.

The coefficient of skin-friction decreases for increase in absorption of radiation parameter, Dufour number at both the walls at y = h_1 and y = h_2.

The skin-friction increases as radiation parameter increases at the wall y = h_1 and it decreases at the wall y = h_2.

NOMENCLATURE

g: Acceleration due to gravity
$B_0(=\mu_e H_0)$: Electromagnetic induction
μ_e : Magnetic permeability
H_0 : Intensity of magnetic field
Cp: Specific heat at constant pressure
C_s : Concentration Susceptibility
D_m : Coefficient of mass diffusivity
k_T : Thermal diffusion ratio
α : Mean radiation absorption coefficient
k : Porous medium permeability coefficient
w : Axial velocity
T: Temperature of the fluid
C: Concentration of the fluid
D: Chemical molecular diffusivity
Kr: Chemical reaction rate constant
Gr: Grashof number for heat transfer
Gm: Grashof number for mass transfer
Sc: Schmidt number
Re : Reynolds number
Pe: Peclet number
M: Magnetic field parameter
Pr: Prandtl number
N: Radiation parameter
K1: Chemical reaction parameter
Ra: Absorption of radiation parameter
D_T : Dufour number
Nu: Nusselt number
Sh : Sherwood number

APPENDIX

$$n=\sqrt{S^2+M^2+i\,Re\,\omega}$$
$$m=\sqrt{N^2-iPe\omega}$$
$$l=\sqrt{Sc\,Re(K_1+i\omega)}$$
$$\lambda_1=\frac{\lambda}{n^2}$$
$$B=-(Q+D_T l^2)$$
$$B_1=\frac{B}{l^2+m^2}-1$$
$$B_2=\frac{GrB_1}{m^2+n^2}$$
$$B_3=\frac{1}{l^2-n^2}\left(\frac{GrB_1}{l^2+m^2}+Gm\right)$$
$$B_4=\lambda_1-B_2-B_3-1$$

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