The Effects of Heat and Mass Transfer on Magnetohydrodynamic Oscillatory Flow

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Abstract
In this paper, the effects of heat and mass transfer on Magnetohydrodynamic oscillatory flow in a porous medium under optically thick limit radiation was examined. The system of equation (governing equation) was dimensionalised and then solved analytically. Numerical evaluation of the analytical results obtained was performed and results were drawn graphically to illustrate the influence of various parameters on the velocity and temperature. It is observed that an increase in Peclet number increases the temperature and decrease in the velocity. Also, an increase in radiation parameter increase the temperature and the velocity. The concentration decreases with an increase in Reynolds number, Schmidt number and chemical reaction parameter. Furthermore, the magnitude of fluid velocity decreases with an increase in the thermal Grashof number while it increases as Hartmann number increases. Lastly, the amplitude of the profile of Nusselt increases as the frequency of the oscillation increases and the response of the skin friction is negligible with increasing frequency of oscillation.

Keywords: MHD, Oscillatory Flow, Optically Thick Radiation, Porous Medium, Chemical Reaction.

Introduction

Convective heat and mass transfer in a porous media have varied and wide applications in several areas of science and engineering like energy reservoirs, thermal insulation engineering, exploration of fossil fuel and gas fields, water movements in energy reservoirs, drying of porous solids, chemical catalytic reactors, nuclear waste repositories etc. The study of convective heat and mass transfer mechanisms through a porous medium has been examined by Nield and Bejan (1998, 2017). Bejan and Khair (1985) treated one among the foremost basic cases, specifically buoyancy -induced heat and mass transfer from a consistent plate embedded in a saturated porous medium. Unsteady effect on MHD free convective and mass transfer flow through porous medium with constant suction and constant heat flux in a rotating system studied by Sharma (2004). Shao *et al.* (2018) studied the semi-analytical solution for density-driven flow in a porous media. There has been a revised interest in the study of MHD flow and heat transfer in porous and non-porous media because of the impact of magnetic fields on the boundary layer flow control and on the performance of many systems using electrically conducting fluids. This type of flow has attracted the interest of many researchers such as Chamkha (2000) considered MHD free convection flow from a vertical plate embedded in a thermally stratified porous medium with its hall effects. Kumar and Prasad (2014) analyzed the solution for MHD pulsatile flow driven by an unsteady pressure gradient between permeable beds of a viscous incompressible Newtonian fluid-saturated porous medium.

Combined heat and mass transfer problems with chemical reaction are of importance in several processes and have thus, received a substantial quantity of attention in recent years. In processes like drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow of desert cooler heat and mass transfer occur at the same time. Dekha *et al.* (1994) investigated the effect of the first order homogeneous chemical reaction on the process of unsteady flow past a vertical plate with constant heat and mass transfer. Uwanta et al (2011) studied the chemical reaction and thermal radiation effects on free convection flow through a porous medium. Senapati and Dhal (2013) studied the magnetic effect on mass and heat transfer of hydraulics flow, past a vertical oscillating plate in the presence of chemical reaction. Ibrahim *et al.* (2015) presented a study on the radiation and mass transfer effects on MHD oscillatory flow in a channel filled with a porous medium in the presence of chemical reaction. Mohammed and Suneetha (2016) considered the impacts of thermal diffusion and chemical reaction on MHD transient free convection flow past a porous vertical plate with radiation, temperature gradient heat source in slip flow regime. The thermosolutal free convection for Newtonian fluid in a saturated porous medium past a vertical porous plate in the presence of chemical reaction, uniform suction or injection and Soret-Dufour effects has been considered in El Haroui *et al.* (2017). Results revealed that chemical reaction has a significant effect on the concentration field.

However, the interaction of radiation and mass transfer in an electrically conducting optically thick fluid through a channel filled with a porous medium has received little attention. Hence, in this present paper, we investigate the combined effect of magnetic fluid and radiative heat transfer on the unsteady flow of a conducting optically thick fluid through a channel filled with saturated porous medium.

Nomenclature

Thermal Grashof number	G_r		Coefficient of the volume expansion due to temperature	B
Solutal Grashof number	G_c		Coefficient of the volume expansion due to concentration	β^*
Peclet number	Pe		Specific heat at a constant temperature	C_p
Hartmann number	H		Thermal conductivity	K
Schmidt number	S_c		Porous medium permeability coefficient	$\overline{K}$
Concentration reaction parameter	K_r		Electromagnetic induction	B_0
Porous medium shape factor parameters	S		Magnetic permeability	μ_e
Raynolds number	Re		Nusselt number	Nu
Radiation parameter	J		Intensity of the magnetic field	H_0
Constant	Λ		Conductivity of the fluid	σ_e
Concentration	C		Fluid density	P
Skin friction	T		Kinematic viscosity coefficient	V
Magnetic field parameter	M		Friction coefficient	T
Gravitational acceleration	G		Darcy number	Da
Temperature	T		Dimensionless concentration	ϕ
Sherwood number	Sh		Dimensionless velocity	v
Cartesian coordinates along the channel	x,y		Dimensionless temperature Subscripts	θ
Axial velocity	$\bar{u}$		wall condition	W
Pressure	$\bar{p}$			
Radiative heat flux	$\overline{q_r}$			

Formulation of the Problem

Consider an unsteady two-dimensional convective heat and mass transfer flow of a viscous, incompressible, electrically conducting optically thick fluid in a channel filled with saturated porous medium under the influence of an externally applied homogeneous magnetic field and radiative heat transfer. It is assumed that the field has small electrical conductivity and the electromagnetic force produced is very small. A Cartesian coordinate $(\bar{x}, \bar{y})$ is assumed where $\bar{y}$-axis lies along the centre of the channel and $\bar{x}$-axis in the distance measured in the normal direction. Then under the usual Boussinesq's incompressible fluid, the equations governing flow field under consideration are:

Momentum Equation:

$$\frac{\partial \bar{u}}{\partial \bar{t}} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial \bar{x}} + v\frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \frac{v}{k}\bar{u} - \frac{p_e B_0^2}{\rho}\bar{u} + g\beta(\overline{T} - \overline{T_0}) + g\beta^*(\overline{C} - \overline{C_0}) \quad (1)$$

Energy Equation

$$\frac{\partial \overline{T}}{\partial \bar{t}} = \frac{k}{\rho C_p}\frac{\partial^2 \overline{T}}{\partial \bar{y}^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \quad (2)$$

Species Equation:

$$\frac{\partial \overline{C}}{\partial \bar{t}} = D\frac{\partial^2 \overline{C}}{\partial \bar{y}^2} - \overline{K_r}(\overline{C} - \overline{C_0}) \quad (3)$$

The boundary conditions for the velocity, temperature and concentration fields are:

$$\bar{u}=0, \bar{T}=\overline{T_w}, \bar{C}=\overline{C_w} \text{ on } \bar{y}=1$$
$$\bar{u}=0, \bar{T}=\overline{T_0}, C=\overline{C_0} \text{ on } \bar{y}=0 \tag{4}$$

where $\bar{u}$ is the axial velocity, $\bar{t}$ is the fluid temperature, $\bar{p}$ is the pressure, g is the gravitational force, $\overline{q_r}$ is the radiative heat flux, β and β^* are the coefficient of the volume expansion due to temperature and concentration respectively, C_p is the specific heat at constant pressure, K is thermal conductivity, $\bar{K}$ is the porous medium permeability coefficient, $B_0=(\mu_e H_0)$ is the electromagnetic induction, μ_e is the magnetic permeability, H_0 is the intensity of magnetic field, σ_e is the conductivity of the fluid, ρ is the fluid density and v is the kinematic viscosity coefficient.

It is assumed that the temperature of the walls $\overline{T_0}, \overline{T_w}$ are high enough to induce radiative heat transfer. Here, we assume that the fluid is optically thick, where the flow absorbs its own emitted radiation. For optically thick fluid, the radiative flux term using the Rosseland differential approximation is given as

$$\frac{\partial q_r}{\partial y}=-\frac{16\sigma}{3k}\overline{T_w}^3\frac{\partial \bar{T}}{\partial \bar{y}} \tag{5}$$

Hence substituting equation (5) into equation (2), we have

$$\frac{\partial \bar{T}}{\partial \bar{t}}=\frac{k}{\rho C_p}\frac{\partial^2 \bar{T}}{\partial \bar{y}^2}+\frac{1}{\rho C_p}\frac{16\sigma}{3k}\overline{T_w}^3\frac{\partial \bar{T}}{\partial \bar{y}} \tag{6}$$

The following non-dimensional quantities are introduced to write equations (1)-(3) and the boundary condition in dimensionless form:

$$x=\frac{\bar{x}}{a}, y=\frac{\bar{y}}{a^2}, u=\frac{\bar{u}}{U}, t=\frac{\bar{t}U}{a}, J^2=\frac{16\sigma\overline{T_w}^3}{3\rho C_p U a}, Da=\frac{\bar{k}}{a^2}, Re=\frac{Ua}{v}$$
$$\theta=\frac{\bar{T}-\overline{T_0}}{\overline{T_w}-\overline{T_0}}, \phi=\frac{\bar{C}-\overline{C_0}}{\overline{C_w}-\overline{C_0}}, Sc=\frac{v}{D}, P=\frac{a\bar{P}}{\rho v U}, kr=\frac{\overline{kra}}{U}, H^2=\frac{a^2\rho_e B_0^2}{\rho v},$$
$$Pe=\frac{\rho U a C_p}{k}, Gr=\frac{g\beta(\overline{T_w}-\overline{T_0})a^2}{vU}, Gc=\frac{g\beta(\overline{C_w}-\overline{C_0})a^2}{vU}, S^2=\frac{1}{Da}$$

The dimensionalise equations for momentum, energy and species equation are respectively

$$Re\frac{\partial u}{\partial t}=-\frac{\partial P}{\partial x}+\frac{\partial^2 u}{\partial y^2}-(S^2+H^2)u+Gr\theta+Gc\phi \tag{7}$$

$$\frac{\partial \theta}{\partial t}=\frac{1}{Pe}\frac{\partial^2 \theta}{\partial y^2}+J^2\frac{\partial \theta}{\partial y} \tag{8}$$

$$\frac{\partial \phi}{\partial t}=\frac{1}{ScRe}\frac{\partial^2 \phi}{\partial y^2}-k_r\phi \tag{9}$$

The corresponding boundary conditions are:

$$u=0, \quad \theta=1, \quad \phi=1, \qquad \text{on } y=1$$
$$u=0, \quad \theta=0, \quad \phi=0, \qquad \text{on } y=0 \tag{10}$$

where $Gr, H, J, Pe, Re, Da, S=(1/Da)$ are Gashoff number, Hartmann number, Radiation parameter, peclet number, Raynolds number, Darcy number and porous medium shape factor parameter respectively.

Method of Solution

To be able to solve the equations (7)-(9) for pure oscillatory flow, we assume the solution of the form

$$-\frac{\partial P}{\partial x} = \lambda e^{iwt},$$
$$u(y,t) = u_0(y)e^{iwt}, \tag{11}$$
$$\theta(y,t) = \theta_0(y)e^{iwt},$$
$$\phi(y,t) = \phi_0 e^{iwt}$$

where $-\lambda$ is the constant oscillation amplitude for pressure gradient and ω is the frequency of the oscillation. Substituting the values for equation (11) into (7)-(10), we obtain

$$\frac{d^2u_0}{dy^2} - b_1^2u_0 = -\lambda - Gr\theta_0 - Gc\phi_0 \tag{12}$$

Where $b_1^2 = S^2 + H^2 + Reiw$

$$\frac{d^2\theta_0}{dy^2} + J^2Pe\frac{d\theta_0}{dy} - iwPe\theta_0 = 0 \tag{13}$$

$$\frac{d^2\phi_0}{dy^2} - b_2^2\phi_0 = 0 \tag{14}$$

where $b_2^2 = (kr + iw)ScRe$

The corresponding boundary conditions becomes:

$$u_0 = 0, \quad \theta_0 = 1, \quad \phi_0 = 1, \qquad \text{on } y = 1$$
$$u_0 = 0, \quad \theta_0 = 0, \quad \phi_0 = 0, \qquad \text{on } y = 0 \tag{15}$$

Solving equations (12)-(14) subject to boundary condition (15), we obtain the momentum, energy and specie
equation as follows

$$\phi_0 = \frac{\sinh(b_2y)}{\sinh b_2} \tag{16}$$

Therefore,

$$\phi(y,t) = \phi_0(y)e^{iwt} = \frac{\sinh(b_2y)}{\sinh b_2}e^{iwt} \tag{17}$$

$$\theta_0 = \frac{1}{e^{m_2} - e^{m_1}}(e^{m_2y} - e^{m_1y}) \tag{18}$$

$$m_1 = \frac{-J^2Pe + \sqrt{(J^2Pe)^2 + 4(iwPe)}}{2}, \qquad m_2 = \frac{-J^2Pe - \sqrt{(J^2Pe)^2 + 4(iwPe)}}{2}$$

Therefore,

$$\theta(y,t) = \theta_0(y)e^{iwt} = \frac{1}{e^{m_2} - e^{m_1}}(e^{m_2y} - e^{m_1y}) \tag{19}$$

$$u_0 = -\frac{Gr}{(e^{m_2} - e^{m_1})}\left[\frac{e^{m_1}(m_2^2 - b_1^2) - e^{m_2}(m_1^2 - b_1^2)}{(m_1^2 - b_1^2)(m_2^2 - b_1^2)}\right]\frac{\sinh b_1y}{\sinh b_1}$$
$$+ \frac{Gr}{(e^{m_2} - e^{m_1})}\left[\frac{e^{m_1y}(m_2^2 - b_1^2) - e^{m_2y}(m_1^2 - b_1^2)}{(m_1^2 - b_1^2)(m_2^2 - b_1^2)}\right] + \frac{\lambda}{b_1^2}\frac{\sinh b_1y}{\sinh b_1}(\cosh b_1 - 1)$$
$$+ \frac{Gc}{(b_2^2 - b_1^2)}\left(\frac{\sinh b_1y}{\sinh b_1} - \frac{\sinh b_2y}{\sinh b_2}\right) + \frac{\lambda}{b_1^2}(1 - \cosh b_1y)$$

(20)

Therefore,

$$\begin{aligned} u(y,t) &= u_0(y)e^{iwt} \\ &= \left\{ \frac{\lambda}{b_1^2}\frac{\sinh b_1 y}{\sinh b_1}(\cosh b_1 - 1) \right. \\ &- \frac{Gr}{(e^{m_2}-e^{m_1})}\left[\frac{e^{m_1}(m_2^2-b_1^2)-e^{m_2}(m_1^2-b_1^2)}{(m_1^2-b_1^2)(m_2^2-b_1^2)}\right]\frac{\sinh b_1 y}{\sinh b_1} \\ &+ \frac{Gr}{(e^{m_2}-e^{m_1})}\left[\frac{e^{m_1 y}(m_2^2-b_1^2)-e^{m_2 y}(m_1^2-b_1^2)}{(m_1^2-b_1^2)(m_2^2-b_1^2)}\right] \\ &\left. + \frac{Gc}{(b_2^2-b_1^2)}\left(\frac{\sinh b_1 y}{\sinh b_1}-\frac{\sinh b_2 y}{\sinh b_2}\right)+\frac{\lambda}{b_1^2}(1-\cosh b_1 y) \right\} e^{iwt} \end{aligned} \tag{21}$$

The Nusselt number, Sherwood number and skin-friction are important physical parameters for this type of boundary layer flow.

Knowing the temperature field, the rate of heat transfer coefficient at both walls of the channel can be obtained, which in the terms of the Nusselt number, is given by:

$$\begin{aligned} Nu &= -\left(\frac{\partial \theta}{\partial y}\right)_{y=0,1} \\ &= -\frac{m_2 e^{m_2 y} - m_1 e^{m_1 y}}{e^{m_2}-e^{m_1}} e^{iwt} \end{aligned} \tag{22}$$

Knowing the concentration field, the rate of mass transfer coefficient at both walls of the channel can be obtained, which in terms of the Sherwood number, is given by

$$\begin{aligned} Sh &= -\left(\frac{\partial \phi}{\partial y}\right)_{y=0,1} \\ &= -\frac{b_2 \cosh(b_2 y)}{\sinh b_2} e^{iwt} \end{aligned} \tag{23}$$

Knowing the velocity field, the skin friction at both the walls of the channel can be obtained, which in non-dimensional form is given by:

$$\begin{aligned} \tau &= -\mu\left(\frac{\partial u}{\partial y}\right)_{y=0,1} \\ &= -\mu\left\{ \frac{\lambda}{b_1^2}\frac{\cosh b_1 y}{\sinh b_1}(\cosh b_1 - 1) - \frac{\lambda}{b_1^2}\sinh b_1 y \right. \\ &- \frac{Gr}{(e^{m_2}-e^{m_1})}\left[\frac{e^{m_1}(m_2^2-b_1^2)-e^{m_2}(m_1^2-b_1^2)}{(m_1^2-b_1^2)(m_2^2-b_1^2)}\right]\frac{\cosh b_1 y}{\sinh b_1} \\ &+ \frac{Gr}{(e^{m_2}-e^{m_1})}\left[\frac{m_1 e^{m_1 y}(m_2^2-b_1^2)-m_2 e^{m_2 y}(m_1^2-b_1^2)}{(m_1^2-b_1^2)(m_2^2-b_1^2)}\right] \\ &\left. + \frac{Gc}{(b_2^2-b_1^2)}\left(b_1\frac{\cosh b_1 y}{\sinh b_1}-b_2\frac{\cosh b_2 y}{\sinh b_2}\right) \right\} e^{iwt} \end{aligned} \tag{24}$$

Numerical Simulation

Numerical evaluation of the analytical results in the previous section was performed and results are drawn graphically which illustrates the influence of various parameters on the momentum, energy and species. For numerical validation of the analytical results, we considered the real part of the results obtained in the equation. The following parametric values are adopted: Thermal Grashof number $G_{r,}$=1; Solutal Grashof number G_c=1; Peclet number *Pe*=0.75; Hartmann number *H*=1; Schmidt number S_c=1; Concentration reaction parameter K_r=1; porous medium shape factor parameters *S*=1; Reynolds number *Re*=1; Radiation parameter *J*=1; λ=1. The velocity, temperature, Sherwood number, Nusselt number and skin-friction are evaluated computationally for different sets of governing parameters via thermal Grashof number G_r, solutal Grashof number G_c, Hartmann number *H*, Peclet number *Pe*, Concentration reaction parameter k_r, Schmidt number S_c, Raynolds Number *Re*, porous medium shape factor parameters *S* and radiation parameter *J*.

Figure 1 shows the concentration profiles for various values of chemical reaction parameter *Kr*. The results show that, with an increase in the chemical reaction parameter, the concentration decreases.

Figure 2 shows the effect of the Schmidt number *Sc* on the concentration of the channel. It is observed that an increase in the Schmidt number *Sc* results to decrease in the concentration. This causes the concentration buoyancy effects to decrease.

Figure 3 shows the concentration profiles for different values of Reynolds number *Re*. It is noticed that an increase in the Reynolds number results in a decrease in the concentration of the channel.

Figure 4 shows the temperature profiles for different values of radiation parameter *J*. The results show that the effect of increasing values of radiation parameter *J* results in a rise in the temperature.

Figure 5 displays the influence of the Peclet number *Pe* on the temperature of the fluid. It is observed that an increase in the value of *Pe* increases the temperature of the fluid. The reason is that larger values of *Pe* are equivalent to an increase in the thermal conductivity of the fluid and therefore heat can diffuse away from the heated surface more rapidly than smaller values of *Pe*. Hence in the case of larger Peclet number, the rate of heat transfer is reduced.

Figure 6 shows the variation in the Sherwood profile at the upper wall with time. It is observed that there is periodic variation in the Sherwood at the upper wall with time and the amplitude of the profile of Sherwood increases with increasing frequency of oscillation. The pattern of the variation is repeated for higher value of time.

Figure 7 displays the variation in the Nusselt number profile at the upper wall with time. It is observed that there is a periodic variation in the profile of Nusselt at the upper wall with time and the amplitude of the profile of Nusselt increases as the frequency of the oscillation increases. The pattern of the variation is repeated for a higher value of time.

The influence of Peclet number *Pe* on the velocity profile is shown in Figure 8. The Peclet number defines the ratio of momentum diffusivity to thermal diffusivity. The numerical result shows that the effect of increasing the Peclet number *Pe* results in a decrease in the velocity.

The velocity profile for different values of the radiation parameter is illustrated in Figure 9. The results show that the effect of increasing values of radiation parameter *J* increases the magnitude of the fluid velocity.

Figure 10 shows the velocity profile for different values of Grashof number *Gc*. The solutal Grashof number *Gc* define the ratio of the specie buoyancy force to the viscous hydrodynamic force. It is observed that the magnitude of the fluid velocity decreases as the solutal Grashof number *Gc* increases.

Figure 11 illustrates the velocity profile for different values of thermal Grashof number *Gr*. It is observed that the magnitude of fluid velocity decreases with an increase in the Grashof number G_r.

Figure 12 shows the velocity profile in the boundary layer for various values of Hartmann number *H*. It is observed that the magnitude of fluid velocity increases with an increase in the Hartmann number *H*.

Figure 13 presents the variation of the skin friction at the upper wall with time t. It is observed that with an increase in time, the response of the skin is negligible with increasing frequency of oscillation.

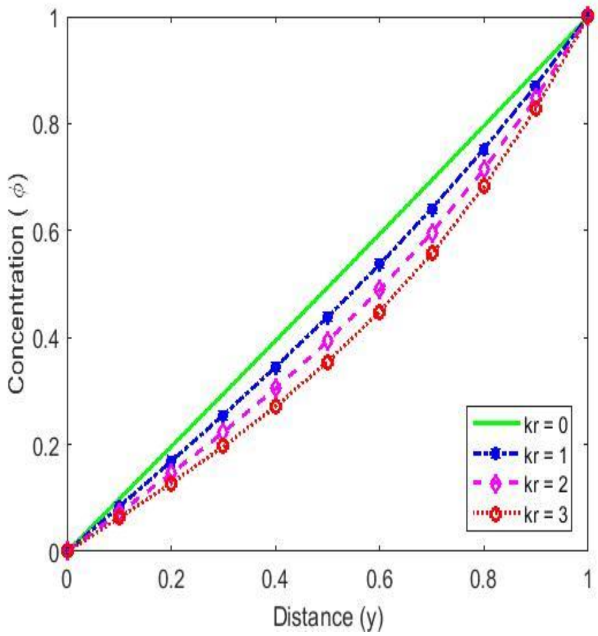

Figure 1: The concentration profile for various values of Kr

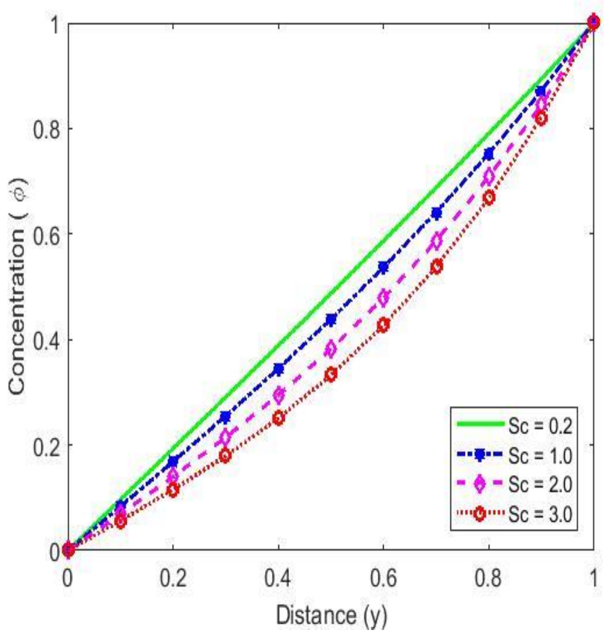

Figure 2: Concentration profile for various values of *Sc*

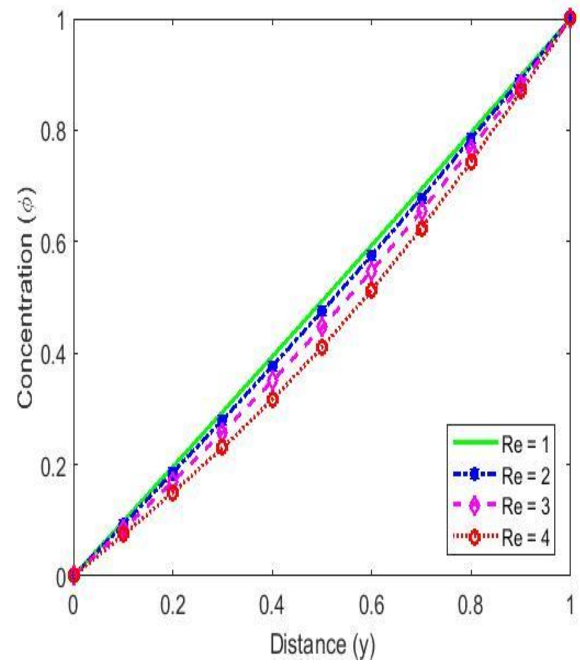

Figure 3: The concentration profile for various values of *Re*

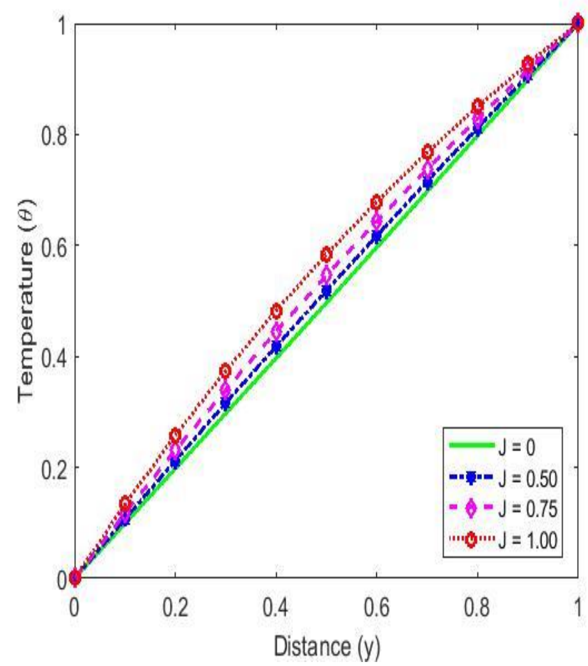

Figure 4: Temperature profile for various values of J

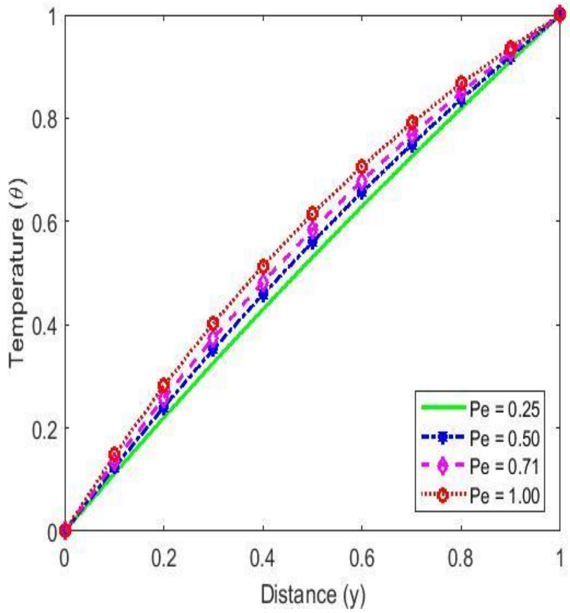

Figure 5: The temperature profile for various values of *Pe*

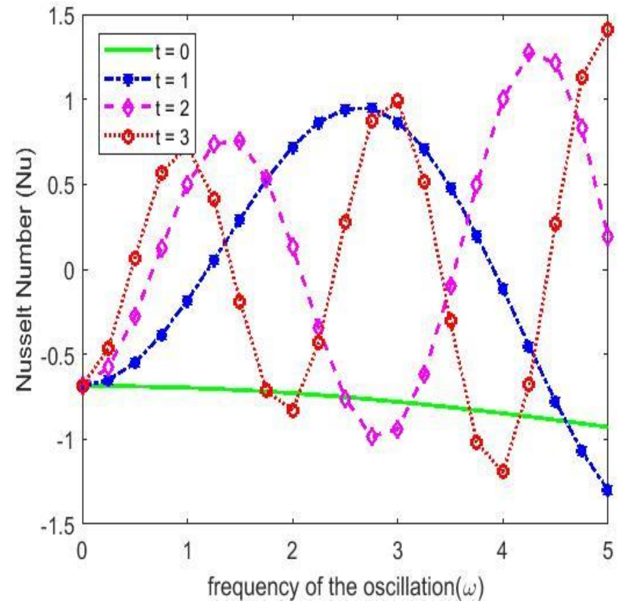

Figure 7: Variation of the Nusselt number for *Pe* = 0.71 at the upper

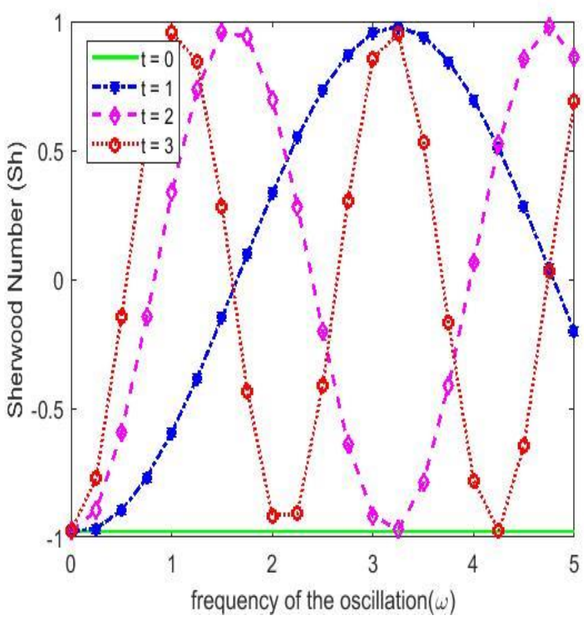

Figure 6: Variation of the Sherwood number for *Pe* = 0.71 at the upper end

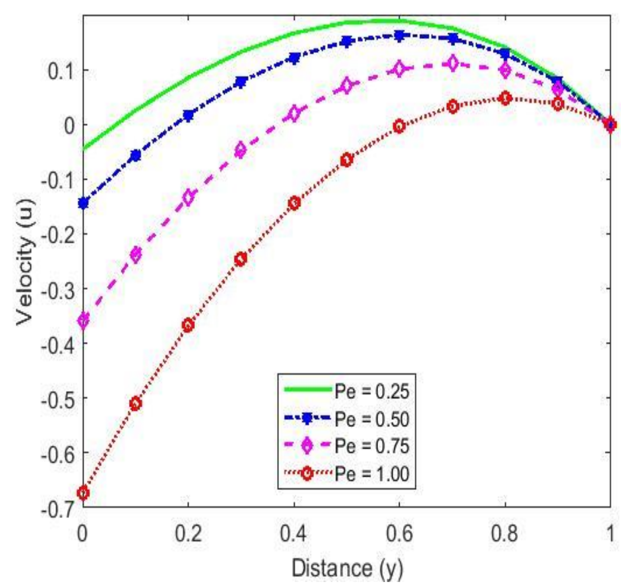

Figure 8: Velocity profile for different values of *Pe*

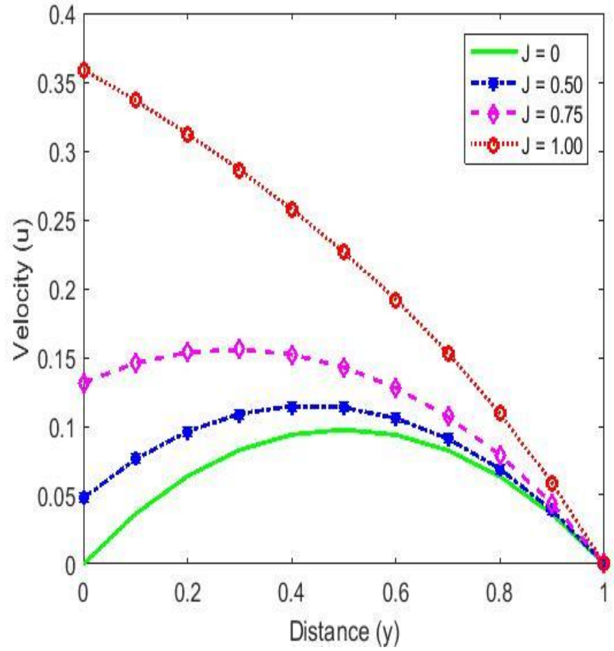

Figure 9: Velocity profile for different values of *J*

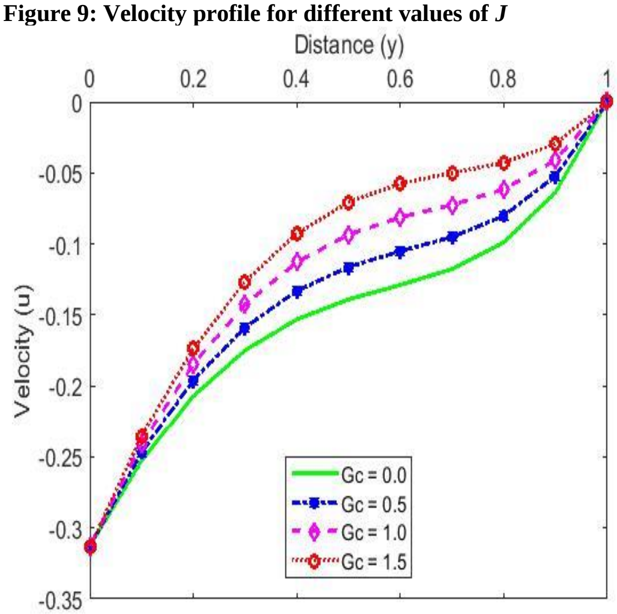

Figure 10: Velocity profile for different values of *Gc*

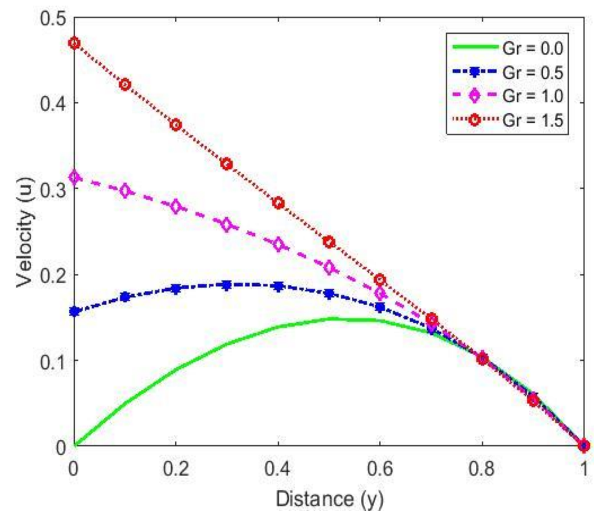

Figure 11: Velocity profile for different values of *Gr*

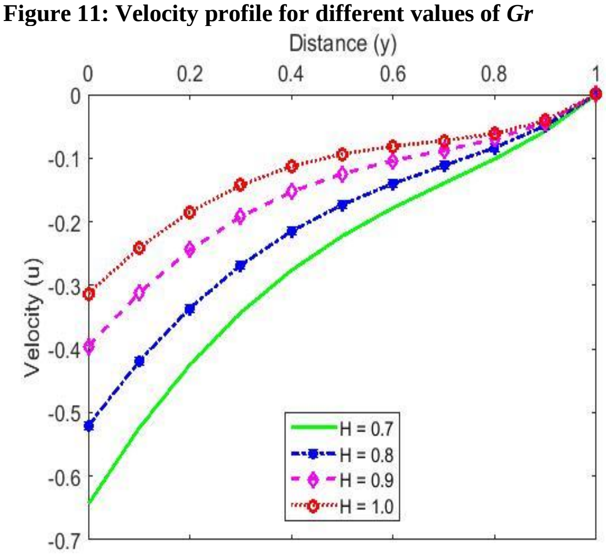

Figure 12: Velocity profile for different values of *H*

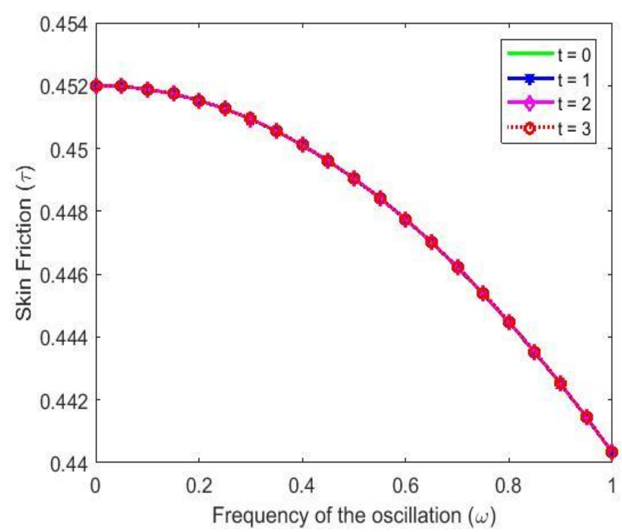

Figure 13: Velocity profile for different values of *H*

Conclusions

In this paper, the effects of heat and mass transfer on Magnetohydrodynamic oscillatory flow in a porous medium under optically thick limit radiation has been studied and numerical results were presented to illustrate the influence of various parameters on the velocity and temperature. From the numerical results, this study concludes that an increase in Peclet number increases the temperature and decrease in the velocity. Also, an increase in radiation parameter results in a rise in the temperature and velocity. More also, the concentration decreases with an increase in Reynolds number, Schmidt number and chemical reaction parameter. Furthermore, the velocity of the fluid flow decreases with an increase in the thermal Grashof number and solutal Grashof number while it increases as the Hartmann number increases. Lastly, the amplitude of the profile of Nusselt and Sherwood increases as the frequency of the oscillation increases and the response of the skin friction is negligible with increasing frequency of oscillation.

Recommendations

The study recommends that under an optically thick limit radiation, the magnitude of fluid velocity in a porous media can be influenced by the radiation on the porous media and the ratio of electromagnetic force acting on the fluid to the viscous force, which should be put into consideration for design purposes. Further study on this research can be extended to MHD double oscillatory flow under optically thick radiation.

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