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CHEMICAL REACTION EFFECTS ON RADIATIVE MHD OSCILLATORY FLOW IN A POROUS CHANNEL WITH HEAT AND MASS TRANSFER IN AN ASYMMETRIC CHANNEL

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ABSTRACT

This paper deals with the effect of heat and mass transfer with chemical reaction on MHD oscillatory flow through porous medium in the presence of heat source/sink in an asymmetric channel. Based on some simplifying assumptions, the governing momentum, energy and diffusion equations are solved and the analytical solutions for fluid velocity, temperature distribution, mass concentration, skin friction, Nusselt number and Sherwood number are obtained. The effects of radiation parameter, porous medium shape factor, Schmidt number, Peclet number, Hartmann number, chemical reaction parameter, heat source/sink parameter, geometric parameters on flow and heat transfer characteristics have been examined in detail. It is observed that velocity profiles increase due to an increase in Grashof number, while the profiles decrease for an increase in Hartmann number or an increase in radiation parameter or an increase in Reynolds number. It is noted that concentration profiles decrease whenever there is an increase in chemical reaction parameter or an increase in Schmidt number.

Keywords: MHD, oscillatory flow, heat and mass transfer, chemical reaction, Schmidt number, Nusselt number, heat source/sink, porous medium.

1. INTRODUCTION

Recently researchers have considerable interest in the study of flow in an asymmetric channel. The study of electrically conducting fluids bounded by an asymmetric channel is of special interest due to its application in transpiration cooling of re-entry vehicles, rocket boosters, cross-hatching on ablative surfaces, film vaporization in a rocket combustion chamber etc. Oscillatory flow is a periodic flow that oscillates around a zero value. It is always important because it has many practical applications, for example, in the aerodynamics of helicopter rotor, fluttering airfoil and in a variety of bio-engineering problems. Flows passing through porous media are frequently used in filtering gases, liquids and drying of bulk materials. This also plays an important role in human body particularly the breathing and discharge of excretes through porous skin. In the field of agricultural engineering, porous media and heat transfer play an important role in germination of seeds. The study of oscillatory flow in a porous channel has been receiving considerable attention in the recent times due to its impact in soil mechanics, ground water hydrology, irrigation, drainage, water purification processes, absorption and filtration processes in chemical engineering. A chemical reaction involves the breaking of bonds in the reactive substances and formulation of bonds to form different products. The study of combined heat and mass transfer with chemical reaction on oscillatory flow has great practical applications in design of chemical processing equipments, formation and dispersion of FLOG (Fast Light Optical Gyroscopes), food processing and cooling of tower.

Muthuraj et al. [1] extended the work by considering heat transfer effects on MHD oscillatory flow in an asymmetric channel. Singh [2] obtained an exact solution of an oscillatory MHD flow in a channel filled with porous medium. Kapoor et al. [3] made an analytical study about MHD natural convective flow of incompressible fluid flow from a vertical flat plate in porous medium. Kai-Long Siao [4] discussed about computational unsteady forced convection over a stretching sheet with magnetic and radiative physical effects to the fluid flow field. Denno et al [5] studied the effects of the induced magnetic field on the magneto hydrodynamic channel flow. Makinde et al. [6] discussed the heat transfer effects to MHD oscillatory flow in a channel filled with porous medium. Taklifi et al. [7] made a note on oscillatory MHD gas flows in the slip flow regimes. Srinivas et al. [8] studied the effects of chemical reaction and space porosity on MHD mixed convective flow in a vertical asymmetric channel with peristalsis. Niranjan et al. [9] discussed about free convection effects on HMD horizontal channel flow with Hall currents. Chaudhary et al. [10] studied the combined heat and mass transfer by laminar mixed convection flow from a vertical surface with induced magnetic field. Ogulu and Bestman [11] have numerically obtained the radiative flux of an optically thin fluid with relatively low density. Devika et al. [12] have discussed the problem of MHD oscillatory flow of a visco elastic fluid in a porous channel with chemical reaction. Rabi et al. [13] reported a study of the phenomenon of chemical reaction effect on MHD oscillatory flow through a porous medium bounded by two vertical porous plates with heat source and Soret effect. Recently, Govindarajan et al. [14] have analysed the chemical reaction effects on unsteady MHD free

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convective flow in a rotating porous medium with mass transfer. To the best of the author's knowledge, the effect of heat and mass transfer with chemical reaction on the radiative MHD oscillatory flow in an asymmetric channel has not been studied in the literature. The main purpose of the present paper is to investigate the MHD oscillatory flow in an asymmetric channel with non-uniform wall temperatures. The governing equations of fluid flow are solved subject to relevant boundary conditions. The influence of several pertinent parameters on velocity, temperature distribution, and species concentration has been studied and numerical results obtained are presented graphically. The problem is formulated in Section II. Section III comprises the solutions for flow and heat and mass transfer analysis. The graphical results are presented and discussed in Section IV. Section V contains the summary and conclusions.

2. FORMULATION OF THE PROBLEM

Consider the flow of an electrically conducting, heat generating, optically thin and chemical reacting oscillatory fluid in an asymmetric channel filled with saturated porous medium under the influence of an externally applied homogeneous magnetic field and radiative heat transfer. The walls of the channel are given by

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

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

$a_1, b_1,\ d_1,\ d_2$ and ϕ satisfies the condition

$$a_1^{\,2} + b_1^{\,2} + 2\,a_1\,b_1 \cos\phi \le (d_1 + d_2)^2 \tag{3}$$

The fluid is assumed not to absorb its own emitted radiation but that of the boundaries also. The walls of the channel are maintained at temperatures T_1 and T_2 respectively with heat heat source/sink parameterα. It is also assumed that the transversely applied magnetic field and magnetic Reynolds number are very small and hence the induced magnetic field is negligible. Viscous and Darcy's resistance terms are taken into account with constant permeability of the porous medium. C_1 and C_2 are the species concentrations at the walls with mass diffusion coefficient D_m. Under these assumptions, the governing equations for a MHD oscillatory flow in an asymmetric channel with Boussinesq approximation may be written as:

Momentum equation

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

Energy equation

$$\frac{\partial T}{\partial t} = \frac{K}{\rho C_P}\frac{\partial^2 T}{\partial y^2} + \frac{1}{\rho C_P}\frac{\partial q}{\partial y} + \frac{Q}{\rho C_P} \tag{5}$$

Concentration equation

$$\frac{\partial C}{\partial t} = D_m\frac{\partial^2 C}{\partial y^2} - K_c'(C - C_2) \tag{6}$$

together with the boundary conditions

$$u = 0;\ T = T_1;\ C = C_1 \ \text{ on } \ y = H_1 \tag{7}$$

$$u = 0; T = T_2;\ C = C_2 \ \text{ on } \ y = H_2 \tag{8}$$

Since the fluid is optically thin with a relatively low density, the radiative heat flux is given by Ogulu and Bestman [11].

$$\frac{\partial q}{\partial y} = 4\alpha^2 (T_2 - T) \tag{9}$$

In non-dimensionalizing the governing equations, the following dimensionless variables were introduced.

$$\bar{x} = \frac{x}{\lambda};\quad \bar{y} = \frac{y}{d};\quad \bar{u} = \frac{u}{U};\quad \mathrm{Re} = \frac{U\,d}{\nu};\quad \theta = \frac{T - T_2}{T_1 - T_2};$$
$$\phi = \frac{C - C_2}{C_1 - C_2}; M^2 = \frac{\sigma B_0^{\,2} d^2}{\rho\nu};\ \bar{t} = \frac{tU}{d};$$
$$\bar{P} = \frac{P\ d}{\rho\nu U}; Da = \frac{k}{d^2}; s^2 = \frac{1}{D_a}; Sc = \frac{U\,d}{D_m};$$
$$Gr = \frac{g\,\beta(T_1 - T_2)\,d^2}{\nu U}; Gc = \frac{g\,\beta^*(C_1 - C_2)\,d^2}{\nu U};$$
$$Pe = \frac{U\,d\,\rho\,C_P}{K}; N^2 = \frac{4\alpha^2 d^2}{K}; h_1 = \frac{H_1}{d_1}; h_2 = \frac{H_2}{d_1}$$
$$; a = \frac{a_1}{d_1}; b = \frac{b_1}{d_1}; d = \frac{d_2}{d_1}; K_c = \frac{K_c'\,d}{U};$$
$$\alpha = \frac{Q\,d^2}{K(T_1 - T_2)} \tag{10}$$

The boundary in non-dimensional form becomes (after dropping bar symbol)

$$h_1 = 1 + a\cos(2\pi x); h_2 = -d - b\cos(2\pi x + \phi) \tag{11}$$

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

$$a^2+b^2+2ab\cos\phi \le (1+d)^2 \tag{12}$$

3. SOLUTION OF THE PROBLEM

Equations (4), (5), (6) reduce to (removing bar symbol)

$$\mathrm{Re}\frac{\partial u}{\partial t} = -\frac{\partial P}{\partial x}+\frac{\partial^2 u}{\partial y^2}-\left(s^2+M^2\right)u+Gr\,\theta+Gc\,\phi \tag{13}$$

$$Pe\frac{\partial \theta}{\partial t}=\frac{\partial^2\theta}{\partial y^2}+N^2\theta+\alpha \tag{14}$$

$$\frac{\partial\phi}{\partial t}=\frac{1}{Sc}\frac{\partial^2\phi}{\partial y^2}-K_C\,\phi \tag{15}$$

with the boundary conditions

$$u=0;\ \theta=1;\ \phi=1 \ \text{ on } y=h_1 \tag{16}$$

$$u=0;\ \theta=0;\ \phi=0 \ \text{ on } y=h_2 \tag{17}$$

For a purely 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 solutions for $u(y,t)$, $\theta(y,t)$, $\phi(y,t)$ be in the form

$$u(y,t)=u_0(y)e^{i\omega t}\ ;\theta(y,t)=\theta_0(y)e^{i\omega t}\ ;$$
$$\phi(y,t)=\phi_0(y)e^{i\omega t} \tag{18}$$

Substituting Equation (18) in Equations (13), (14), (15), we obtain $\frac{d^2\theta_0}{\partial y^2}+m^2\,\theta_0=-\alpha\, e^{-i\omega t}$

(19)

$$\frac{d^2\phi_0}{\partial y^2}-Sc\,Y^2\,\phi_0=0 \tag{20}$$

$$\frac{d^2u_0}{\partial y^2}-n^2u_0=-\lambda-Gr\,\theta_0-Gc\,\phi_0 \tag{21}$$

together with the boundary conditions

$$u_0=0;\ \theta_0=1;\ \phi_0=1\ \text{ on } y=h_1 \tag{22}$$

$$u_0=0;\ \theta_0=0;\ \phi_0=0\ \text{ on } y=h_2 \tag{23}$$

where $m=\sqrt{N^2-i\omega Pe}$, $Y=\sqrt{K_c+i\omega}$ and

$$n=\sqrt{s^2+H^2+i\omega\mathrm{Re}}\,.$$

Equations (19), (20), (21) are solved using equations (22) and (23). We obtain

$$\theta(y,t)=\left(\begin{array}{l}\dfrac{X\sin mh_1-(1+X)\sin mh_2}{\sin m(h_1-h_2)}\cos my+\\[2mm] \dfrac{\cos mh_2-X(\cos mh_1-\cos mh_2)}{\sin m(h_1-h_2)}\sin my-X\end{array}\right)e^{i\omega t} \tag{24}$$

$$\phi(y,t)=\left(\frac{\sinh F(y-h_2)}{\sinh F(h_1-h_2)}\right)e^{i\omega t} \tag{25}$$

$$u(y,t)=\left(\begin{array}{l}\dfrac{1}{\sinh n(h_1-h_2)}\left[\begin{array}{l}\dfrac{Gc}{F^2-n^2}\sinh n(y-h_2)+\dfrac{Gr\,X}{m^2+n^2}\sinh n(y-h_1)\\ -\dfrac{Gr(1+X)}{m^2+n^2}\sinh n(y-h_2)+\\ \left[\dfrac{\lambda-Gr\,X}{n^2}\right]\left[\sinh n(h_2-y)+\sinh n(y-h_1)\right]\end{array}\right]\\ +\left[\dfrac{\lambda-Gr\,X}{n^2}\right]\\ +\dfrac{Gr}{m^2+n^2}\cdot\dfrac{1}{\sin m(h_1-h_2)}\left[\begin{array}{l}(1+X)\cos mh_2\sin my-(1+X)\sin mh_2\cos my\\ +X\sin mh_1\cos my-X\cos mh_1\sin my\end{array}\right]\\ -\dfrac{Gc}{F^2-n^2}\left[\dfrac{\sinh F(y-h_2)}{\sinh F(h_1-h_2)}\right]\end{array}\right)e^{i\omega t}$$

$$\text{where } X=\frac{\alpha}{m^2}e^{-i\omega t}\ \text{ and }\ F=\sqrt{Sc}\,Y\,. \tag{26}$$

Skin Friction

The skin friction at the wall is given by

$$\tau=\left[\mu\frac{\partial u}{\partial y}\right]at\ y=h_1,\ y=h_2\,. \tag{27}$$

On simplification, we get

$$\tau=\mu\left(\begin{array}{l}\dfrac{1}{\sinh n(h_1-h_2)}\left[\begin{array}{l}\dfrac{n\,Gc}{F^2-n^2}\cosh n(y-h2)\\ +\dfrac{n\,Gr\,X}{m^2+n^2}\cosh n(y-h_1)\\ -\dfrac{n\,Gr\,(1+X)}{m^2+n^2}\cosh n(y-h2)\\ +\left(\dfrac{\lambda-Gr\,X}{n^2}\right)\left(-n\cosh n(h_2-y)+n\cosh n(y-h_1)\right)\end{array}\right]\\ +\dfrac{Gr}{m^2+n^2}\cdot\dfrac{1}{\sin m(h_1-h_2)}\left[\begin{array}{l}m(1+X)\cos mh_2\cos my\\ -m(1+X)\sin mh_2\sin my\\ -m\,X\sin mh_1\sin my\\ -X\cos mh_1\cos my\end{array}\right]\\ -\dfrac{F\,Gc}{F^2-n^2}\cdot\dfrac{\sinh F(y-h_2)}{\sinh F(h_1-h_2)}\end{array}\right)e^{i\omega t}\Bigg|_{at\ y=h_1,\ y=h_2} \tag{28}$$

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Nusselt Number

The rate of heat transfer across the channel is given by

$$Nu = \left[-\frac{\partial \theta}{\partial y}\right] at\ y = h_1, y = h_2 \tag{29}$$

$$Nu = -\left(\begin{array}{l} (-m)\dfrac{X \sin m h_1 - (1+X)\sin mh_2}{\sin m(h_1 - h_2)} \sin my + \\ (m)\dfrac{\cos m h_2 - X(\cos mh_1 - \cos mh_2)}{\sin m(h_1 - h_2)} \cos my \end{array} \right) e^{i\omega t} \quad at\ y = h_1, y = h_2 \tag{30}$$

Sherwood Number

The rate of mass transfer across the channel is given by

$$Sh = \left[\frac{\partial C}{\partial y}\right] at\ y = h_1, y = h_2 \tag{31}$$

$$Sh = \left(F\frac{\cosh F(y-h_2)}{\sinh F(h_1-h_2)} \right) e^{i\omega t}\ at\ y = h_1,\ y = h_2 \tag{32}$$

4. GRAPHICAL RESULTS AND DISCUSSIONS

To study the effects of heat and mass transfer, chemical reaction on a radiative MHD oscillatory flow in an asymmetric channel, the velocity u, temperature θ and the species concentration profiles C are depicted graphically against y for different values of different parameters: Grashof number for heat transfer, Grashof number for mass transfer, radiation parameter N, Hartmann number M, Reynolds number Re, Schmidt number Sc, chemical reaction parameter K_c. The graphs are plotted using MATLAB 6.5.

Figure-1 and Figure-2 show the effect of Grashof number Gr and Gc on velocity u. It is noted that as Grashof number increase, the velocity profiles increase. All the profiles start increasing steadily near the lower end of the asymmetric channel upto the midpoint of the channel, thereafter they start decreasing steadily at the upper end of the channel.

Figure-3 shows the effect of radiation parameter N on the velocity profiles u. It is found that the velocity profiles decrease steadily as the radiation parameter increases. All the profiles increase steadily from the lower plate and reach the maximum value at a point little away from the upper plate and thereafter they decrease steadily and reach the value zero at the upper plate.

Figure-4 depicts the effect of Hartmann number M on the velocity profiles u. It is observed that the velocity decelerates when there is an increase in Hartmann number. The profiles retard continuously. This is due to Lorentz force.

Figure-5 illustrates the effect of Reynolds number on the velocity profile u. It is seen that the velocity profiles decrease as Reynolds number Re increases.

The effect of Schmidt number on concentration profiles are shown in Figure-6. The values of Sc are chosen as 0.5, 0.6, 0.78, 1.0 and 2.0, which correspond to Hydrogen gas, water vapour, Ammonia, Carbon dioxide at 25°C and ethyl benzene in air respectively. It is clear that the concentration profiles decrease uniformly whenever there is an increase in Schmidt number Sc.

The effect of chemical reaction parameter K_c on the concentration profiles is plotted in Figure-7. It is seen that the profiles decrease steadily whenever there is an increase in chemical reaction parameter K_c ($K_c > 0$). For $K_c < 0$, the profiles show a reverse trend. Due to the sake of brevity, it is not plotted.

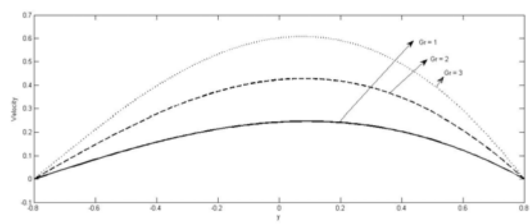

Figure-1. Effect of Grashof number for heat transfer Gr on velocity u with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, Re = 1, ϕ = 0, λ = 0.001, N = 1, s = 1, M = 1, Pe = 1,Sc = 1, K = 1, Gc = 1, α = 1.

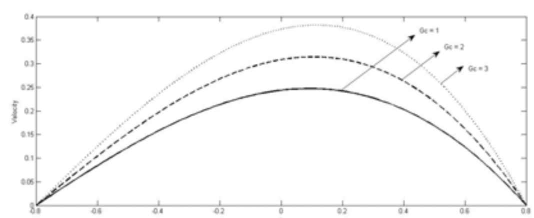

Figure-2. Effect of Grashof number for mass transfer Gc on velocity u with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, Re = 1, ϕ = 0, λ = 0.001, N = 1, s = 1, M = 1, Pe = 1,Sc = 1, K = 1, Gr = 1, α = 1.

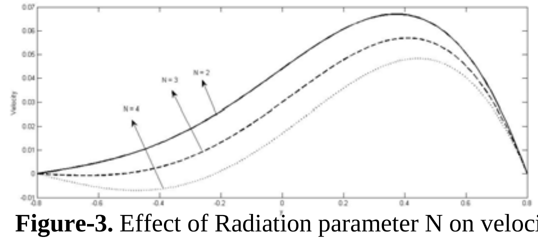

Figure-3. Effect of Radiation parameter N on velocity u with = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, Re = 1, ϕ = 0, λ = 0.001, s = 1, H = 1, Pe = 1,Sc = 1, K = 1, Gc=1, Gr = 1, α = 1.

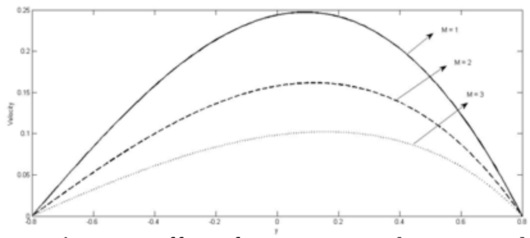

Figure-4. Effect of Hartmann number M on velocity u with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, Re = 1, ϕ = 0, λ = 0.001, s = 1, N = 1, Pe = 1,Sc = 1, K = 1, Gc=1, Gr = 1, α = 1.

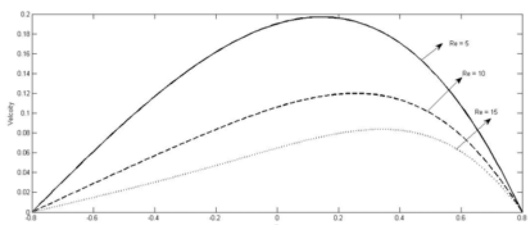

Figure-5. Effect of Reynolds number Re on velocity u with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, ϕ = 0, λ = 0.001, s = 1, H=1, N = 1, Pe = 1, Sc = 1, K = 1, Gc=1, Gr = 1, α = 1.

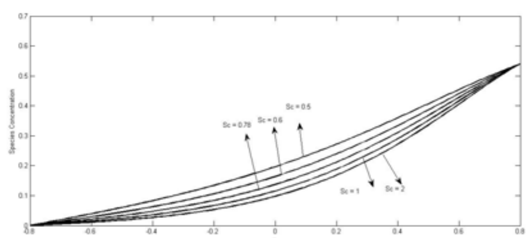

Figure-6. Effect of Schmidt number Sc on Concentration with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, ϕ = 0, λ = 0.001, s = 1, M=1, N = 1, Pe = 1, Re = 1, K = 1, Gc=1, Gr = 1, α = 1.

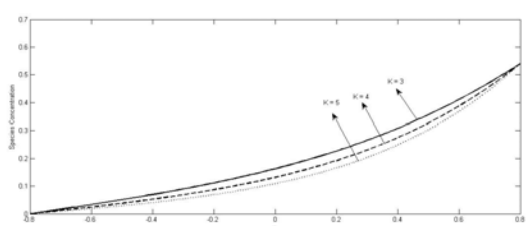

Figure-7. Effect of Chemical reaction parameter K on Concentration with a = 0.2, b = 1.2, d = 2, ω = 1, t = 1, x = 0.5, Re = 1, ϕ = 0, λ = 0.001, N = 1,s = 1, H = 1, Pe = 1, K = 1, Gc = 1, Gr = 1, α = 1.

5. SUMMARY AND CONCLUSIONS

In this section, we studied the effect of heat and mass transfer with chemical reaction on the radiative MHD oscillatory flow in an asymmetric channel. The governing equations of momentum, energy and species concentration have been written in dimensionless form using dimensionless parameters. A closed form of analytical solution using Perturbation method has been employed to evaluate and to solve the dimensionless velocity u, the dimensionless temperature θ, the dimensionless species concentration C, skin friction τ, Nusselt number Nu and Sherwood number Sh.

The main findings are summarized below:

- Decrease in Grashof number for heat transfer Gr and Grashof number for mass transfer Gc have accelerating effects on velocity of the flow field.
- Increase in Hartmann number M decreases the velocity of the flow field at all points, due to the magnetic pull of the Lorentz force acting on the flow field.
- Increase in the radiation parameter N and Reynolds number Re decrease the velocity of the flow field.
- Increase in Schmidt number Sc and chemical parameter K_c decrease the species concentration. Hence the consumption of chemical species causes a fall in the concentration field, which in turn diminishes the buoyancy effects due to concentration gradients.

When there is no chemical reaction and radiation effects, the results found in this section are in good agreement with the results obtained by Muthuraj and Srinivas [1].

This study is indeed useful in understanding the concept of the MHD oscillatory flow of fluid in a porous channel with heat and mass transfer and chemical reaction in an asymmetric channel. The study have potential applications in transpiration cooling of re-entry vehicles, rocket boosters, cross-hatching on ablative surfaces, film vaporization in a rocket combustion chamber as mentioned earlier.

Further investigations can be made by introducing slip effects, Soret and Dufour effects for the fluid in an asymmetric channel.

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Table-1.

Nomenclature	
a_1, b_1	amplitudes of the wavy walls
a, b	amplitude ratios
$B_0 = \mu_e H_0$	electromagnetic induction
H_0	intensity of the magnetic field
C_P	specific heat at constant pressure
$d_1 + d_2$	width of the channel
d	mean half width of the channel
g	gravitational force
D_a	Darcy number
D_m	mass diffusion coefficient
Gr	Grashof number for heat transfer
Gc	Grashof number for mass transfer
K	thermal conductivity
k	porous medium permeability coefficient
N	radiation parameter
P	pressure
q	radiative heat flux
s	porous medium shape factor
t	time
T	fluid temperature
u	axial velocity
U	flow mean velocity
K_c	chemical reaction parameter
Q	heat absorption/generation at the channel
M	Hartmann number
Sc	Schmidt number
Pe	Peclet number
Re	Reynolds number
Nu	Nusselt number
Sh	Sherwood Number
Greek symbols	
θ	dimensionless fluid temperature function
α	heat source/sink parameter
β	coefficient of thermal expansion due to temperature
β^*	coefficient of thermal expansion due to concentration
μ_e	magnetic permeability
σ	conductivity of the fluid
ρ	fluid density
ν	kinematics viscosity coefficient
λ	wavelength
ω	frequency of the oscillation
τ	skin friction

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