



Magnetohydrodynamic oscillatory flow of a physiological fluid in an irregular channel

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Abstract

The impact of heat source on magnetohydrodynamic oscillatory flow of a chemically reacting viscoelastic fluid in an asymmetric wavy channel is analysed. The governing flow equations are transformed into ODEs by utilizing proper non-dimensional variables. The subsequent ordinary differential equations are solved analytically. The effects of different flow parameters on the fluid flow, thermal and species distributions as well as rate of heat and mass transfer coefficients are examined graphically. It is pointed out that the velocity of fluid is parabolic with extreme value along the channel centreline and minimum at the walls. The magnitude of fluid velocity increases with an increase in porous parameter and high heat transport of a system is due to the presence of oscillatory flow.

Keywords Visco-elastic fluid · Heat source · MHD · Oscillatory flow · Asymmetric channel

List of symbols

a_1, b_1	Amplitudes of the wavy walls
a, b	Amplitude ratios
B_0	Electromagnetic induction
C^*	Fluid concentration
C_1, C_2	Concentrations at walls
C_p	Specific heat at constant pressure
$d_1 + d_2$	Width of channel
d	Mean half width of the channel
D_a	Darcy number
g	Gravitational force
Gc	Modified Grashof number
Gr	Grashof number
H_0	Intensity of magnetic field
H_1, H_2	Inner and outer walls
K	Porous medium shape factor
Kr	Chemical reaction parameter
k^*	Porous permeability coefficient
k	Thermal conductivity
M	Hartmann number
Nu	Nusselt number
Pe	Peclet number

p	Pressure
Q	Heat source parameter
q	Radiative heat flux
Re	Reynolds number
R	Radiation parameter
Sc	Schmidt number
Sh	Sherwood number
T	Fluid temperature
T_1, T_2	Temperatures at walls
t	Time
U	Flow mean velocity
u	Axial velocity

Greek symbols

θ	Fluid temperature
β_T	Coefficient of thermal expansion
β_C	Coefficient of mass expansion
μ	Coefficient of viscosity
μ_e	Magnetic permeability
σ_c	Conductivity of the fluid
ρ	Fluid density
ν	Kinematics viscosity coefficient

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- λ Wave length
- ω Frequency of the oscillation
- α Radiation absorption coefficient
- τ Skin friction coefficient

1 Introduction

Recently, many researchers [1–10] explored the MHD non-Newtonian fluid flows over various geometrical models in view of their significance in many engineering and industrial applications such as food processing, making a paper, slurry transporting etc.,. Physiological fluid is one of the non-Newtonian viscoelastic fluids which play an important role in many transport phenomenon’s (such as blood circulation, cancer treatment, transport of drugs, drug carriers). It is observed that the viscoelastic property of blood is less prominent with rising shear rate and gliding of cells (see Refs. [11, 12]). The blood flow properties are determined by the cell aggregation tendency, red cell concentration and mechanical relation between the particles (see Refs. [13–19]). The experimental studies reveal that, in case of cancer treatment by radiotherapy, chemotherapy or surgery, they destroy both malignant and normal cells. In view of these issues, Nikiforov [20] developed an electromagnetic hyperthermia technique where the dangerous cancer cells are exposed to a temperature field greater than 41 °C with the help of thermal radiation. In this method a magnetic liquid is injected to the malignant tissues and then exposing the framework to an alternative current. Due to this, the temperature is produced in the infused magnetic fluid and there by the cancer cells get destroyed (see Ref. [21]). Raftari and Vajravelu [22] studied the impact of magnetic field on a visco-elastic fluid flow through a channel by applying HAM analysis. Singh [23, 24] investigated the influence of slip and thermal radiation on visco-elastic fluid flow past a vertical channel. Abdalla and Abo Dahab [25] explored the rotating and non-Newtonian fluid effects in an asymmetric channel with peristaltic transport. Many researchers [26–29] considered the different mathematical models to study the impact of viscoelastic fluid flow through porous channels.

Now a days chemical reactions play a significant role in many science and engineering applications at different stages such as; chemical engineering processes, moisture over agricultural fields, energy transfer in a cooling tower power, cooling industry for drying, and the flow in desert cooler etc.,. In view of these, the visco-elastic fluid flow through a porous channel with chemical reaction was estimated analytically by Devika et al. [30]. Giresha and Mahanthesh [31] explored the chemically reacting heat transfer flow of viscoelastic fluid through non uniform channels. Nayak et al. [32] analyzed the first order chemical

reaction effects on viscoelastic fluid in the presence of porous medium. Venkateswarlu et al. [33] contemplated the chemically reacting viscoelastic fluid flow past a vertical channel.

It is also worth noting that most of afore mentioned studies have been considered in channels. Therefore, it would be interesting to explore the study of non-Newtonian fluid in an asymmetric wavy channel. In this way, the main aim of the present work is to investigate the visco-elastic fluid behavior of MHD oscillatory flow in an irregular channel. The governing equations are solved analytically. Impact of various flow parameters on the fluid flow characteristics are analyzed through graphs. Further, the comparison of the skin friction coefficient and Nusselt number for various values of magnetic field and heat source parameters are displayed in Table 1.

2 Mathematical formulation

Unsteady incompressible, chemically reacting and thermally radiating non-Newtonian fluid is considered in an irregular channel with heat source. A constant magnetic field of strength B_0 is assumed normal to the flow. The fluid flow along x -direction is generated due to the oscillatory pressure gradient at the walls as shown in Fig. 1. T_1 and T_2 are respectively the temperatures of the fluid at walls of the channel. The magnetic Reynolds number is assumed to be very small compared to the external one and hence the induced magnetic field can be negligible. The inner and outer walls H_1 and H_2 are respectively given by [2, 34]

$$H_1 = d_1 + a_1 \cos \frac{2\pi x}{\lambda} \quad \text{and} \quad H_2 = -d_2 - b_1 \cos \left(\frac{2\pi x}{\lambda} + \phi \right), \tag{1}$$

where a_1, b_1, d_1, d_2 and ϕ satisfies the condition $a_1^2 + b_1^2 + 2a_1b_1 \cos \phi \leq (d_1 + d_2)^2, 0 \leq \phi \leq \pi$.

The governing flow, energy and concentration equations are given by [2, 26, 34]

Table 1 Comparison of skin friction coefficient and Nusselt number for different values of M and Q respectively

M	τ		Q	Nu	
	Ref. [2]	Present		Ref. [2]	Present
1.0	3.2578	3.257683	0.1	1.4152	1.415587
2.0	3.2847	3.284695	0.3	2.0280	2.028342
3.0	3.3297	3.322859	0.5	3.1336	3.133548
4.0	3.3928	3.392673	0.7	5.8087	5.808621

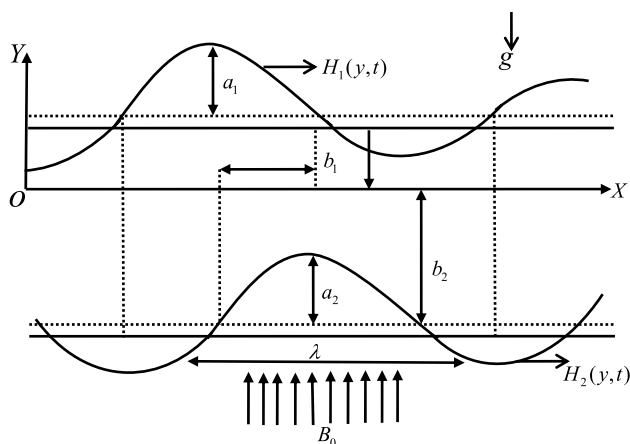


Fig. 1 Physical model of the problem

$$\frac{\partial U^*}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 U^*}{\partial y^2} + g\beta_T(T^* - T_2) + g\beta_C(C^* - C_2) - \frac{\sigma B_0^2 U^*}{\rho} - \frac{\nu}{k^*} U^* + \beta_0 \frac{\partial^3 U^*}{\partial y^2 \partial t}, \tag{2}$$

$$\frac{\partial T^*}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T^*}{\partial y^2} - \frac{1}{\rho c_p} \frac{\partial q}{\partial y} + \frac{Q_H}{\rho c_p} (T^* - T_2), \tag{3}$$

$$\frac{\partial C^*}{\partial t} = D \frac{\partial^2 C^*}{\partial y^2} - K_r^* (C^* - C_2), \tag{4}$$

The boundary conditions are defined as [2, 34]

$$\begin{aligned} U^* = 0, \quad T^* = T_1, \quad C^* = C_1, \quad \text{on } y = H_1, \\ U^* = 0, \quad T^* = T_2, \quad C^* = C_2, \quad \text{on } y = H_2, \end{aligned} \tag{5}$$

The thermal radiative is defined by Ogulu and Bestman [35] as

$$\frac{\partial q}{\partial y} = 4\alpha^2 (T_2 - T^*), \tag{6}$$

where $\alpha^2 = \int_0^\infty K_{\lambda w} \frac{\partial e_{b\lambda}}{\partial T} d\lambda$. The dimensionless variables are:

$$\begin{aligned} \bar{x} = \frac{x}{\lambda}, \quad \bar{y} = \frac{y}{d_1}, \quad \bar{u} = \frac{U^*}{U}, \quad \bar{t} = \frac{tU}{d_1}, \quad h_1 = \frac{H_1}{d_1}, \quad h_2 = \frac{H_2}{d_1}, \quad d = \frac{d_2}{d_1}, \\ a = \frac{a_1}{d_1}, \quad b = \frac{b_1}{d_1}, \quad D_a = \frac{k^*}{d_1^2}, \quad \text{Re} = \frac{Ud_1}{\nu}, \quad Q = \frac{Q_H d_1^2}{k}, \quad K = \frac{d_1^2}{k^*}, \quad \text{Sc} = \frac{D}{Ud_1}, \\ Kr = \frac{d_1 K_r^*}{U}, \quad \bar{p} = \frac{d_1^2 p}{\rho \nu \lambda U}, \quad Pe = \frac{Ud_1 \rho c_p}{k}, \quad R = \frac{4\alpha^2 d_1^2}{k}, \quad M = \frac{\sigma B_0^2 d_1^2}{\rho \nu}, \quad \beta = \frac{B_0 U}{\nu d_1}, \\ Gr = \frac{g\beta_T (T_1 - T_2) d_1^2}{\nu U}, \quad Gc = \frac{g\beta_C (C_1 - C_2) d_1^2}{\nu U}, \quad \theta = \frac{T^* - T_2}{T_1 - T_2}, \quad \phi = \frac{C^* - C_2}{C_1 - C_2}, \end{aligned} \tag{7}$$

The corresponding boundary conditions are

$$h_1 = 1 + a \cos 2\pi x, \quad \text{and} \quad h_2 = -d - b \cos(2\pi x + \phi), \tag{8}$$

where a, b, d and ϕ satisfies the form $a^2 + b^2 + 2ab \cos \phi \leq (1 + d)^2$.

In view of non-dimensional quantities Eqs. (2)–(4) can be written as (neglecting bar symbols)

$$\text{Re} \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} + Gr\theta + Gc\phi - (M + 1/K)u + \beta \frac{\partial^3 u}{\partial y^2 \partial t}, \tag{9}$$

$$Pe \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} + (R + Q)\theta \tag{10}$$

$$\frac{\partial \phi}{\partial t} = \text{Sc} \frac{\partial^2 \phi}{\partial y^2} - Kr\phi, \tag{11}$$

The corresponding non-dimensional boundary conditions are

$$\begin{aligned} u = 0, \quad \theta = 1, \quad \phi = 1, \quad \text{on } y = h_1, \\ u = 0, \quad \theta = 0, \quad \phi = 0, \quad \text{on } y = h_2, \end{aligned} \tag{12}$$

3 Method of solution

In order to solve the system of PDEs (9)–(11) the following pressure gradient for purely oscillatory flow, velocity, thermal and concentrations fields are assumed as (see Refs. [34, 36–39])

$$-\frac{\partial p}{\partial x} = \lambda e^{i\omega t}, \quad \text{and} \quad f(y, t) = f_0(y) e^{i\omega t}, \tag{13}$$

where f is the u, θ and ϕ, f_0 is the u_0, θ_0 and ϕ_0 .

In view of Eq. (13), the Eqs. (9)–(11), are reduced to

$$(1 + i\omega\beta) \frac{d^2 u_0}{dy^2} - n^2 u_0 = -\lambda - Gr\theta_0 - Gc\phi_0, \tag{14}$$

$$\frac{d^2 \theta_0}{dy^2} + m^2 \theta_0 = 0, \tag{15}$$

$$\frac{d^2\phi_0}{dy^2} - l^2\phi_0 = 0, \tag{16}$$

The boundary conditions are

$$\begin{aligned} u_0 = 0, \quad \theta_0 = 1, \quad \phi_0 = 1, \quad \text{on } y = h_1, \\ u_0 = 0, \quad \theta_0 = 0, \quad \phi_0 = 0, \quad \text{on } y = h_2, \end{aligned} \tag{17}$$

Solving the Eqs. (14)–(16) with the help of boundary conditions Eq. (17), we get the solutions for velocity, temperature and concentration are as follows

$$\begin{aligned} u(y, t) = \frac{\lambda}{n^2}(1 + i\omega\beta)e^{i\omega t} + (1 + i\omega\beta) \left\{ \frac{\lambda}{n^2} + \frac{Gr}{m^2 + n^2} - \frac{Gc}{l^2 - n^2} \right\} \frac{\sinh n(h_2 - y)}{\sinh n(h_1 - h_2)} e^{i\omega t} \\ + (1 + i\omega\beta) \left\{ \frac{\lambda \sinh n(y - h_1)}{n^2 \sinh n(h_1 - h_2)} + \frac{Gr}{m^2 + n^2} \frac{\sin m(y - h_2)}{\sin m(h_1 - h_2)} - \frac{Gc}{l^2 - n^2} \frac{\sinh l(y - h_2)}{\sinh l(h_1 - h_2)} \right\} e^{i\omega t}, \end{aligned} \tag{18}$$

$$\theta(y, t) = \frac{\sin m(y - h_2)}{\sin m(h_1 - h_2)} e^{i\omega t}, \tag{19}$$

$$\phi(y, t) = \frac{\sinh l(y - h_2)}{\sinh l(h_1 - h_2)} e^{i\omega t}, \tag{20}$$

The skin friction coefficient, Nusselt and Sherwood number at the wall are define as follows

$$\begin{aligned} \tau = \mu \left\{ \frac{\partial u}{\partial y} \right\}_{y=h_1, h_2} = \mu(1 + i\omega\beta) \left\{ \frac{nGc}{l^2 - n^2} - \frac{nGr}{m^2 + n^2} - \frac{\lambda}{n} \right\} \frac{\cosh n(y - h_2)}{\sinh n(h_1 - h_2)} e^{i\omega t} \\ + \mu(1 + i\omega\beta) \left\{ \frac{\lambda \cosh n(y - h_1)}{n \sinh n(h_1 - h_2)} - \frac{mGr}{m^2 + n^2} \frac{\cosh m(y - h_2)}{\sinh m(h_1 - h_2)} - \frac{lGc}{l^2 - n^2} \frac{\cosh l(y - h_2)}{\sinh l(h_1 - h_2)} \right\} e^{i\omega t}, \end{aligned} \tag{21}$$

$$Nu = - \left(\frac{\partial \theta}{\partial y} \right)_{y=h_1, h_2} = - \frac{m \cos m(y - h_2)}{\sin m(h_1 - h_2)} e^{i\omega t} = |J| \cos(\omega t + \psi), \tag{22}$$

$$Sh = - \left(\frac{\partial \phi}{\partial y} \right)_{y=h_1, h_2} = - \frac{l \cosh l(y - h_2)}{\sinh l(h_1 - h_2)} e^{i\omega t} = |F| \cos(\omega t + \psi), \tag{23}$$

The amplitude and phase angle of the rate of heat and mass transfer are respectively given by $J = J_r + iJ_i$, $\psi = \tan^{-1}(J_i/J_r)$, $F = F_r + iF_i$, $\psi = \tan^{-1}(F_i/F_r)$ where $l^2 = Kr + i\omega/Sc$, $m^2 = Q + R - i\omega Pe$, $n^2 = M + 1/K + i\omega Re$.

4 Results and discussion

The aim of this paper is to analyze the non-Newtonian fluid behavior and oscillatory flow of visco-elastic fluid in an irregular channel. The solutions of the Eqs. (18)–(20) are obtained by using MATLAB code and the results are displayed through Figs. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 for various parameters entering into the problem. Table 1 displays the comparative study of skin friction and rate of heat transfer coefficients for Newtonian fluid with those of Ref. [2] by choosing $\omega=0.1, \lambda=0.1, t=0.1, \pi=3.14$,

$a=0.2, b=1.2, d_1=2.0$ and $Re=0.1$. It is found to be good agreement between them.

Figure 2 displays the influence of porous parameter K on the velocity profile for both Newtonian ($\beta=0$) and non-Newtonian ($\beta \neq 0$) cases. It is noticed that the velocity profiles attains the maximum value with increase of K . Physically, rising estimations of K results the larger holes of porous medium and henceforth resistivity of the medium might be disregarded. Further, the velocity of Newtonian fluid is more than that of non-Newtonian fluid.

The impact of M on u is discussed in Fig. 3. It is noticed that the velocity along the boundary layer pulverizes with raising values of M . This is because of the way that the Lorentz force has the tendency to diminish the motion of the fluid and henceforth the fluid velocity diminishes.

The influence of Gr and Gc on u is displayed in Fig. 4. It is observed that the velocity mounting with rising values of Gr and decline with Gc values. Physically, Gr signifies the general impact of the thermal buoyancy force to the viscous hydrodynamic force in the boundary layer. Thus, as Gr increases the velocity of the fluid reaches maximum

Fig. 2 Influence of K on u

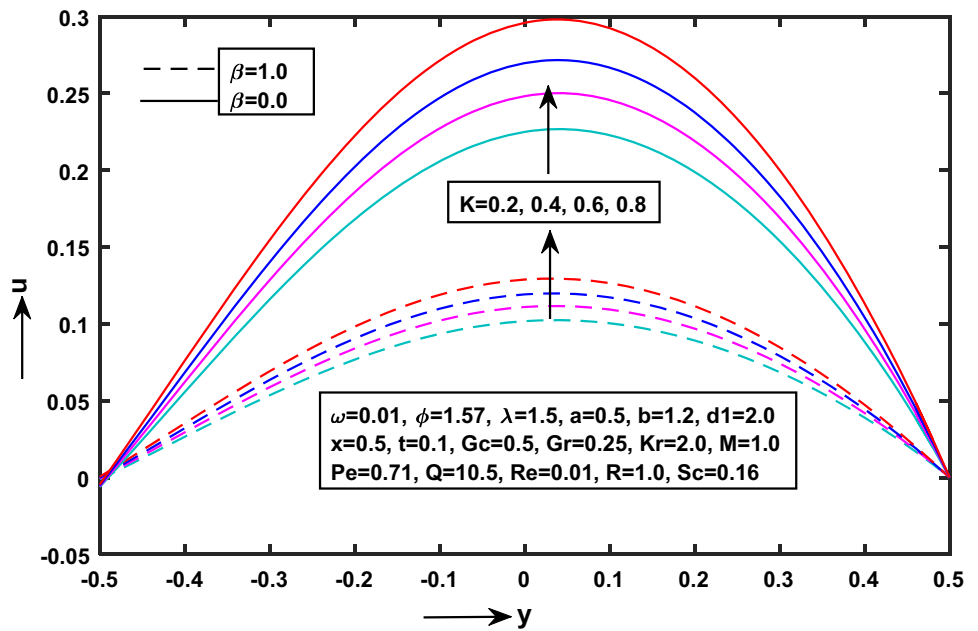
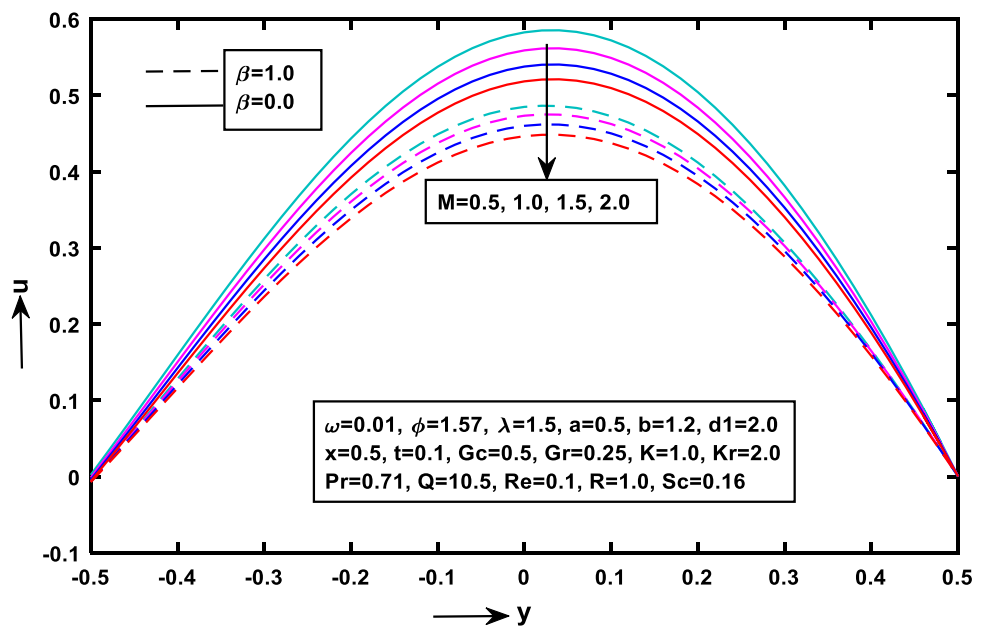


Fig. 3 Influence of M on u



value in the middle region of the asymmetric channel and after that rots easily to the free stream velocity.

The influence of various values of Pe and Reynolds number Re on u across the boundary layer is shown in Fig. 5. The Peclet number is the ratio of thermal energy

convected to the fluid to the thermal energy conducted within the fluid and the Reynolds number is the ratio of inertial forces to viscous forces. The results of velocity profile increase with increase in Pe and reverse effect with

Fig. 4 Influence of Gr and Gc on u

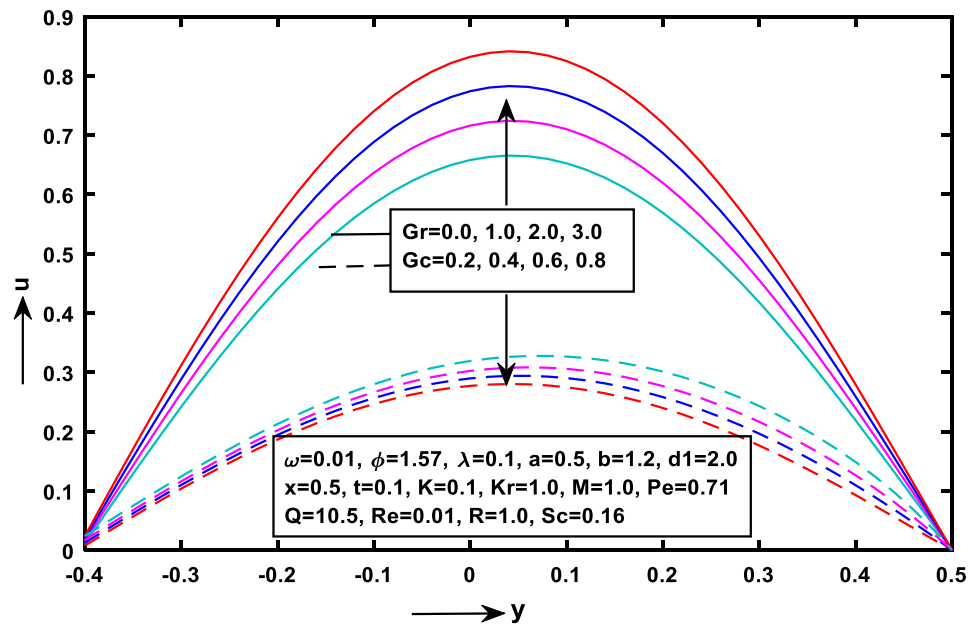
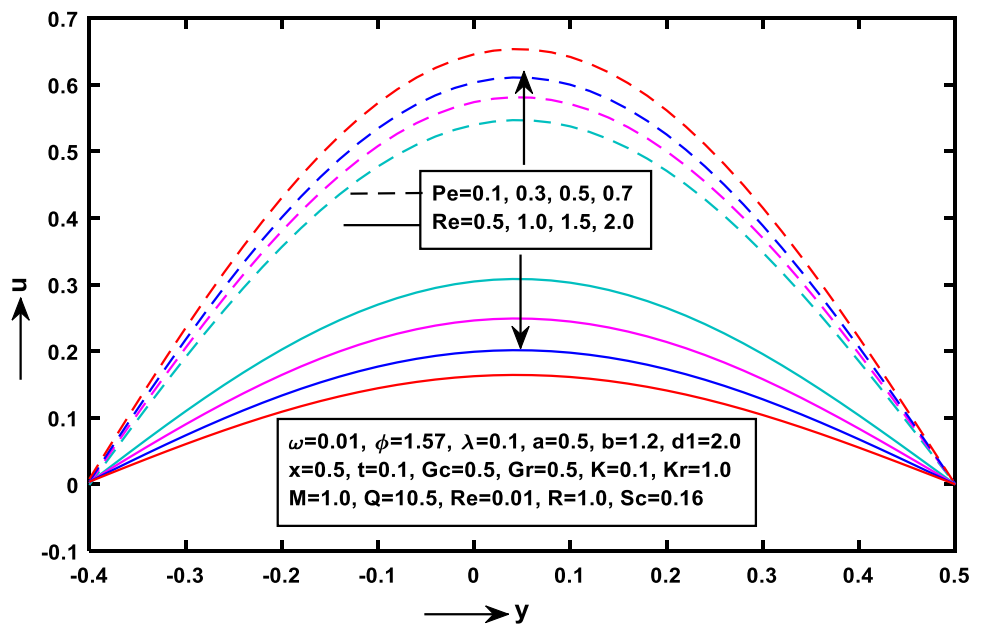


Fig. 5 Influence of Pe and Re on u



rise of Re . These parameters may play an important role in convective heat transfer processes.

Figures 6 and 7 display the consequences of velocity and concentration of dissimilar values of Kr and Sc respectively. It is noticed that the velocity of the fluid increases and concentration decreases with rising values of chemical reaction parameter. In addition, Schmidt number shows reverse effect on these two profiles.

Physically, Schmidt number Sc is characterized as the ratio of momentum and mass diffusivity. Hence, as Sc increases the velocity and boundary layer thickness reduces and concentration of the fluid increases.

The influence of R on u is outlined in Fig. 8. It is seen that the velocity elevate with the ascent of R in the flow regime. This is due to the fact that the fluid particles get the heat energy from the electromagnetic waves and

Fig. 6 Influence of Kr and Sc on u

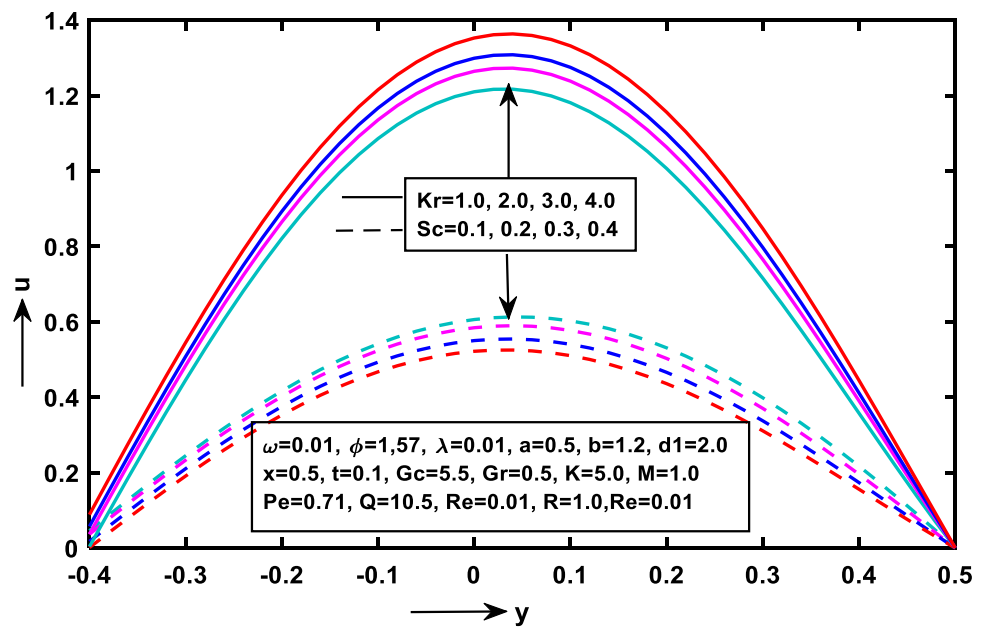
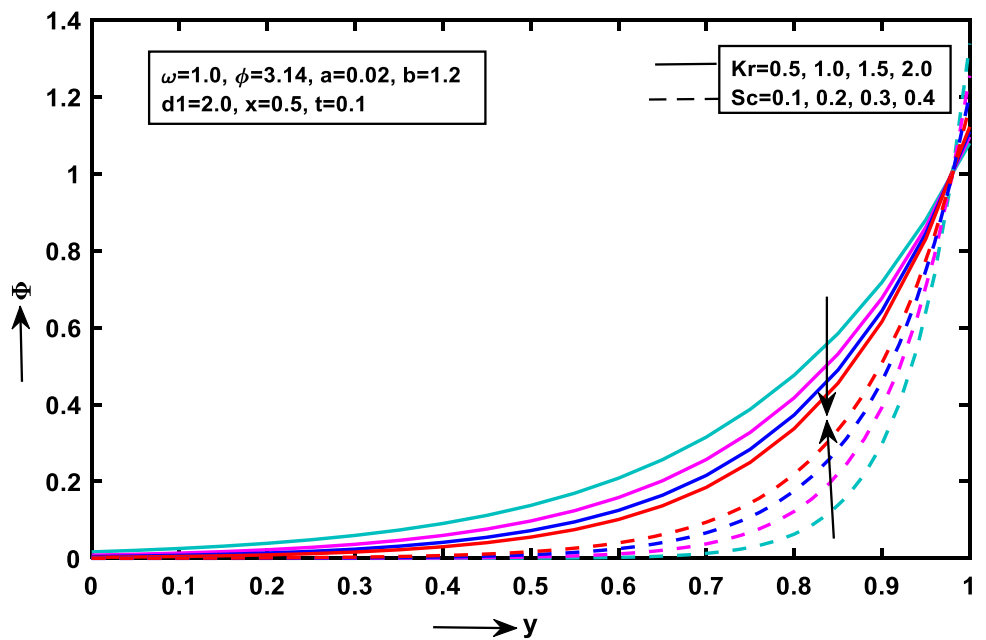


Fig. 7 Influence of Kr and Sc on ϕ



hence move very fast. Also the velocity of viscous fluid ($\beta=0$) is more than that of non-Newtonian fluid ($\beta \neq 0$).

Figure 9 represents the impact of R , Q and Pe respectively on θ . Plainly the temperature increment for every single developing value of R , Q and Pe in the stream locale. Physically, the thermal radiation is responsible for energy transfer by the emission of electro-magnetic waves which carry energy away as the fluid flows along asymmetric

wavy channels and consequently the thermal boundary layer thickness winds up more slender. Experimentally, when blood flow in capillaries, there is a significant increase in the thickness of boundary layer due to rise in thermal radiation. Hence, the temperature of the boundary layer is raised by an appreciable extent.

Figures 10 and 11 display τ for diverse values of K and M respectively, for both Newtonian and non-Newtonian

Fig. 8 Influence of R on u

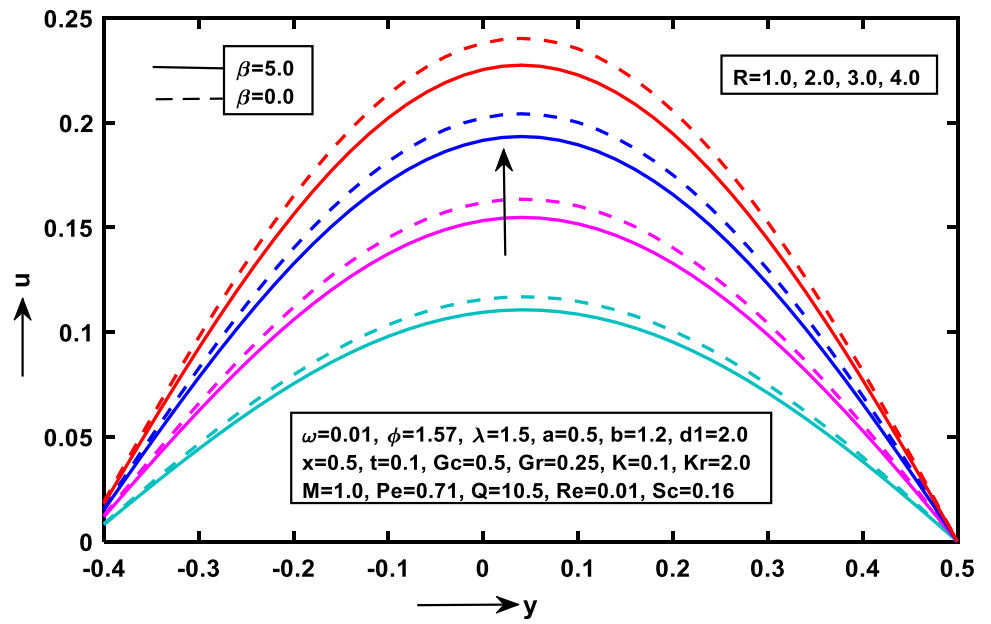


Fig. 9 Influence of Pe, Q and R on θ

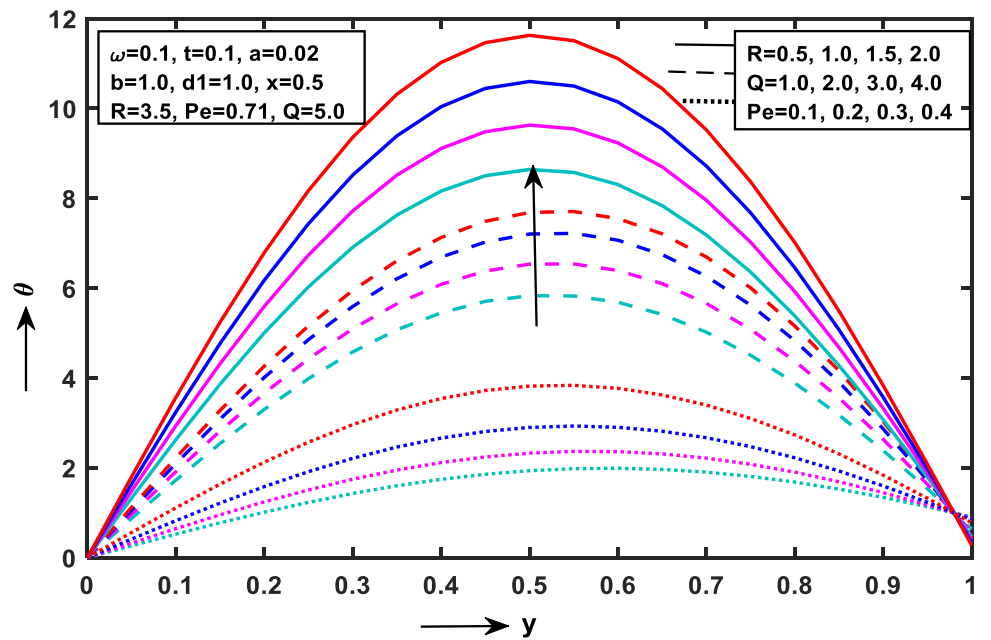


Fig. 10 Influence of K on skin friction coefficient

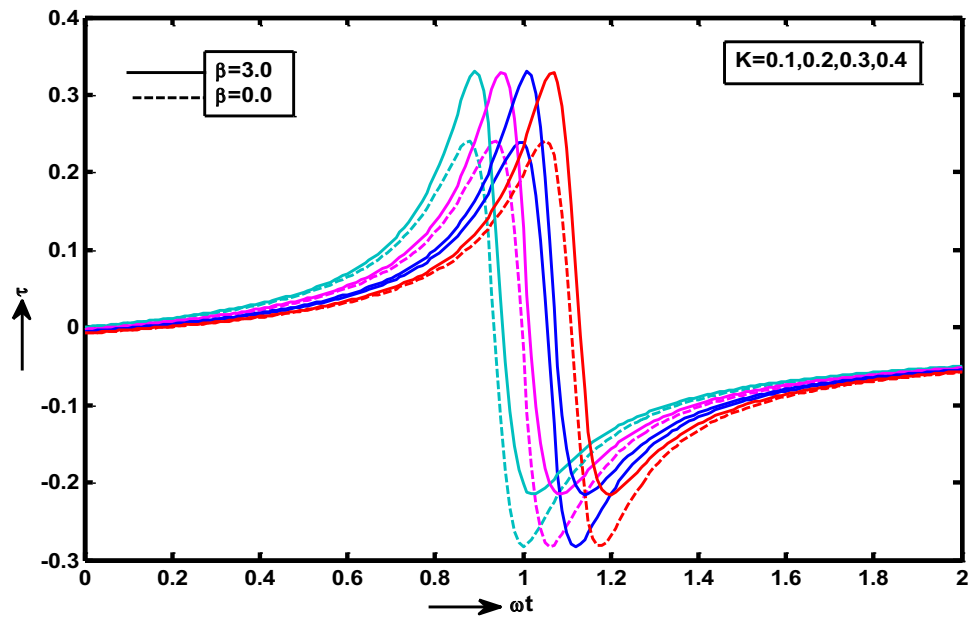
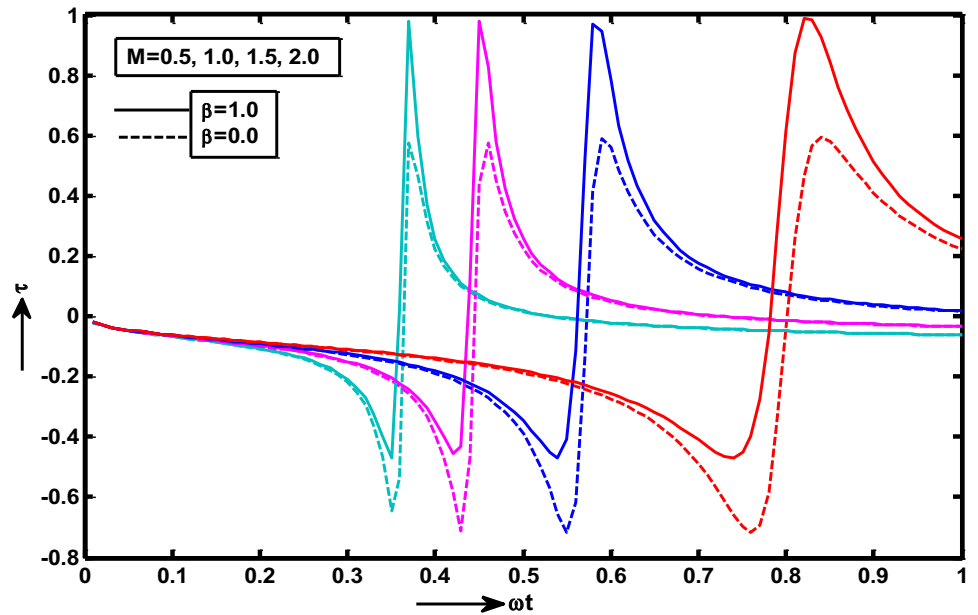


Fig. 11 Influence of M on skin friction coefficient



cases ($\beta=0$ and $\beta \neq 0$). It is clear that the skin friction coefficient vary periodically at asymmetric surface. The variations of heat and mass transfer rates against the time series for different values of R and Kr are respectively plotted in Figs. 12 and 13. From these graphs it is clear that Nu and Sh both vary periodically due to asymmetric surface motion.

Figure 14 illustrates the rate of heat transfer against H for dissimilar values of R at the walls $y=h_1$ and $y=h_2$. It is observed that the growth in R leads to a rise in the values of Nu at $y=h_1$ and opposite behaviour at $y=h_2$. Thus, the rate of heat transfer from the porous asymmetric channel decreases with the increase of R .

Fig. 12 Influence of R on Nusselt number

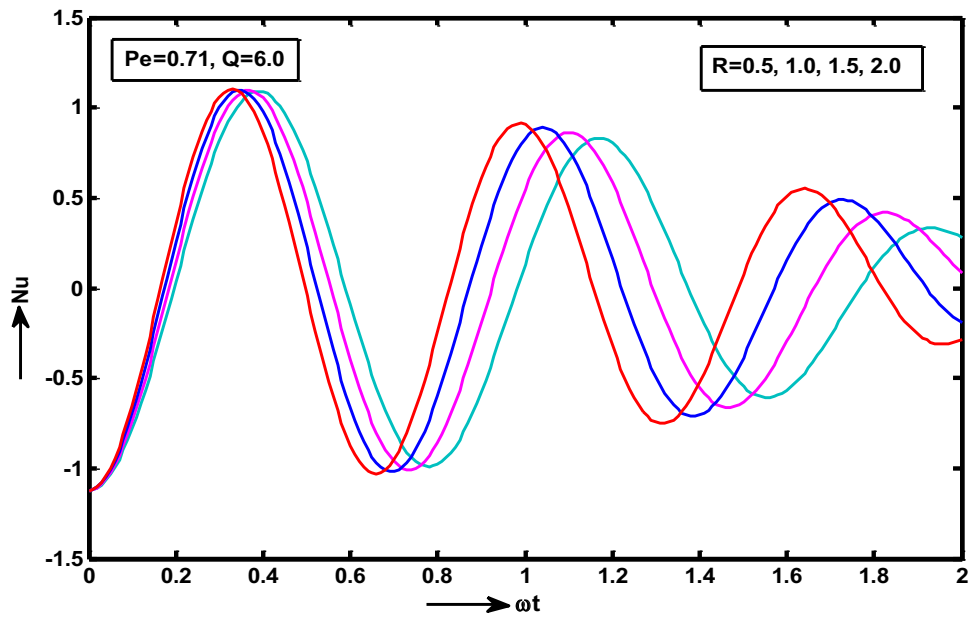


Fig. 13 Influence of Kr on Sherwood number

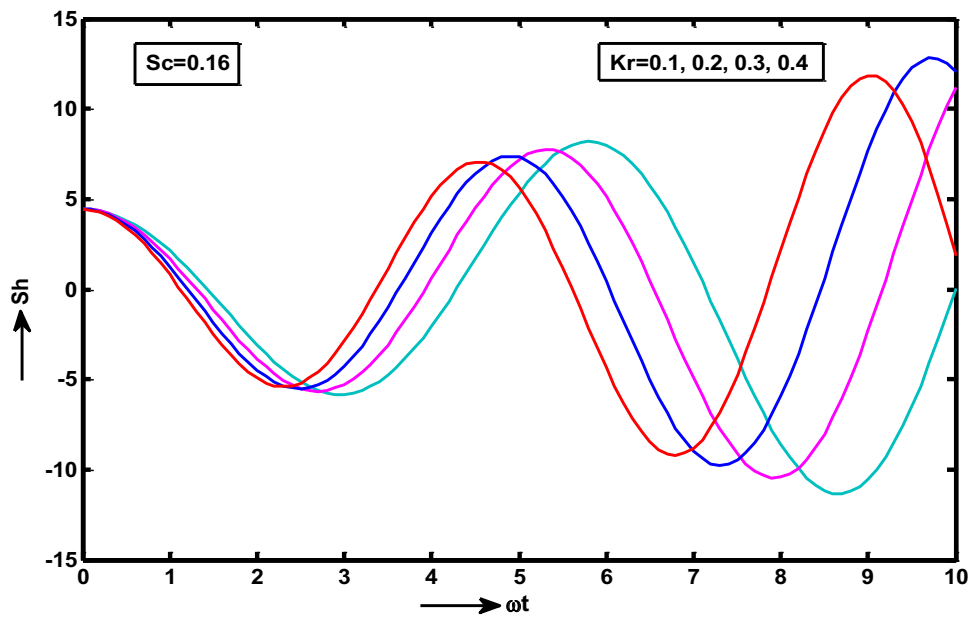


Figure 15 displays the variations of Sh against Kr for different values of Sc . It is clear that the rate of mass transfer decline with increase of Sc at the wall $y = h_1$ whereas the opposite effect at $y = h_2$.

5 Conclusion

The present study describes the effect of non-Newtonian visco-elastic fluid behaviour of MHD oscillatory flow in an irregular channel. The main conclusions of this study are:

Fig. 14 Influence of R on Nusselt number

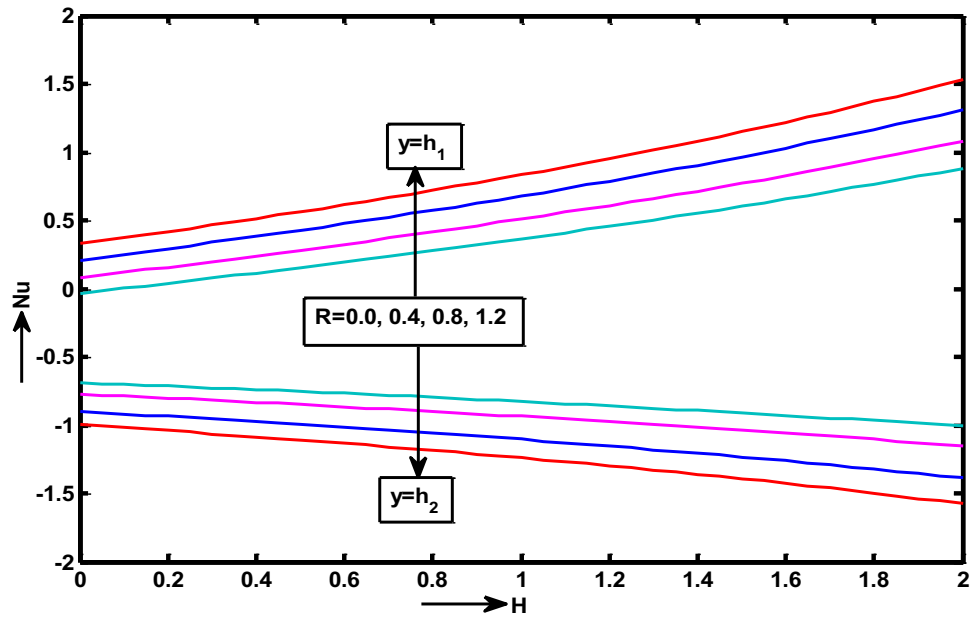
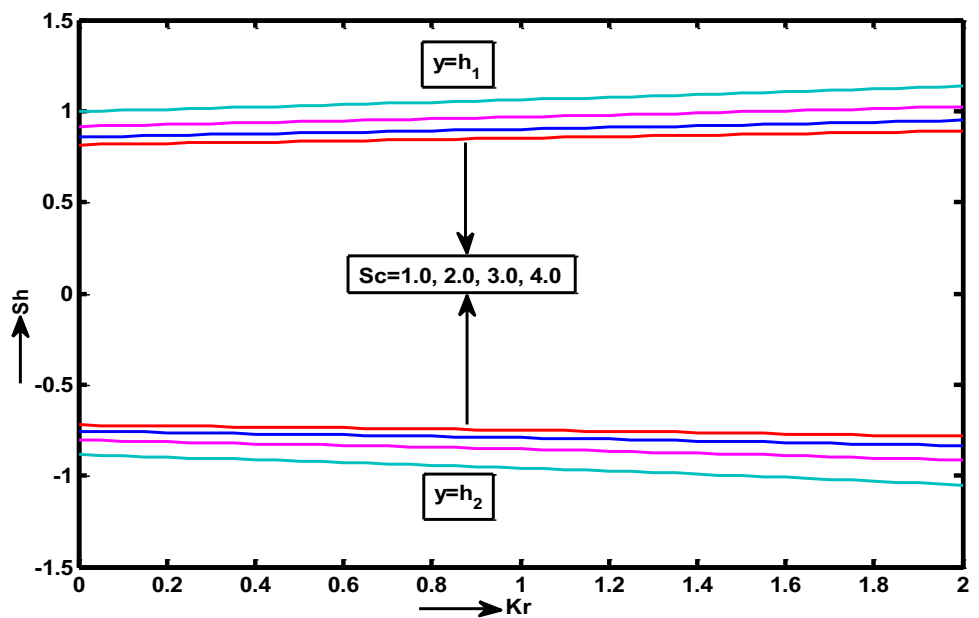


Fig. 15 Influence of Sc on Sherwood number



- The temperature profiles increase for all increasing values of R , Q and Pe in the fluid flow along an asymmetric wavy channel.
- The velocity and skin friction coefficient in case of Newtonian fluid is more than that of non-Newtonian fluid. This is due to the presence of high viscosity.
- The skin friction coefficient, Nu and Sh are varying periodically due to surface motion.
- The heat transfer near the wall decrease with the rise of R .
- The Sherwood number reduces with rise of Sc at the walls $y = h_1$ and $y = h_2$.

Authors' contribution All authors contributed equally to the writing of this paper. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Research involving human participants and/or animals This article does not contain any studies with human participants or animals performed by any of the authors.

References

- Venkateswarlu B, Satya Narayana PV (2015) MHD visco-elastic fluid flow over a continuously moving vertical surface with chemical reaction. *Walailak J Sci Technol* 12(9):1–9
- Satya Narayana PV, Venkateswarlu B, Devika B (2016) Chemical reaction and heat source effects on MHD oscillatory flow in an irregular channel. *Ain Shams Eng J* 7:1079–1088
- Misra JC, Mallick B, Sinha A (2016) Heat and mass transfer in asymmetric channels during peristaltic transport of an MHD fluid having temperature-dependent properties. *Alex Eng J* 57(1):391–406
- Ramesh K (2016) Influence of heat and mass transfer on peristaltic fluid of a couple stress fluid through porous medium in the presence of inclined magnetic field in an inclined asymmetric channel. *J Mol Liq* 219:256–271
- Ramesh K, Devakar M (2017) Effect of heat transfer on the peristaltic transport of a MHD second grade fluid through a porous medium in an inclined asymmetric channel. *Chin J Phys* 55(3):825–844
- Shamsi MR, Akbari OA, Marzban A, Toghraie D, Mashayekhi R (2017) Increasing heat transfer of non-Newtonian nanofluid in rectangular microchannel with triangular ribs. *Phys E* 93:167–178
- Eldabe NT, Abou-zeid MY (2017) Homotopy perturbation method for MHD pulsatile non-Newtonian nanofluid flow with heat transfer through a non-Darcy porous medium. *J Egypt Math Soc* 25(4):375–381
- Kefayati GHR, Tang H (2017) Simulation of natural convection and entropy generation of MHD non-Newtonian nanofluid in a cavity using Buongiorno's mathematical model. *Int J Hydrog Energy* 42(27):17284–17327
- Khan Z, Shah RA, Altaf M, Islam S, Khan A (2018) Effect of thermal radiation and MHD on non-Newtonian third grade fluid in wire coating analysis with temperature dependent viscosity. *Alex Eng J* 57(3):2101–2112
- Abdul Hakeem AK, Saranya S, Ganga B (2017) Comparative study on Newtonian/non-Newtonian base fluids with magnetic/non-magnetic nanoparticles over a flat plate with uniform heat flux. *J Mol Liq* 230:445–452
- Thurston GB (1979) Rheological parameters for the viscosity, viscoelasticity and thixotropy of blood. *Biorheol* 16:149–162
- Thurston GB (1972) Viscoelasticity of human blood. *Biophys J* 12:1205–1217
- Misra JC, Paul B, Gupta AS (1998) Hydromagnetic flow of a second-grade fluid in a channel—some applications to the physiological systems. *Math Models Methods Appl Sci* 8(8):1323–1342
- Misra JC, Maiti S, Shit GC (2008) Peristaltic transport of a physiological fluid in an asymmetric porous channel in the presence of an external magnetic field. *J Mech Med Biol* 8(4):507–525
- Misra JC, Shit GC, Chandra S, Kundu PK (2011) Electro-osmotic flow of a viscoelastic fluid in a channel: applications to physiological fluid mechanics. *Appl Math Comput* 217(20):7932–7939
- Tripathi D, Anwar Beg O (2012) A study of unsteady physiological magneto-fluid flow and heat transfer through a finite length channel by peristaltic pumping. *J Eng Med* 226(8):631–644
- Hayat T, Yasmin H, Al-Yami M (2014) Soret and Dufour effects in peristaltic transport of physiological fluids with chemical reaction: a mathematical analysis. *Comput Fluids* 89:242–253
- Misra JC, Adhikary SD (2016) MHD oscillatory channel flow, heat and mass transfer in a physiological fluid in presence of chemical reaction. *Alex Eng J* 55(1):287–297
- Ponalagusamy R (2018) Mathematical analysis of flow of non-Newtonian fluid due to metachronal beating of cilia in a tube and its physiological applications. *Appl Math Comput* 337:545–561
- Nlkiforov VN (2007) Magnetic induction hyperthermia. *Russ Phys J* 50(9):913–924
- Jordan A, Wust P, Scholz R, Tesche B, Fahling H, Mitrovics T, Vogl T, Carvos-Navarro J, Felix R (1996) Cellular uptake of magnetic fluid particles and their effects on human adenocarcinoma cells exposed to AC magnetic fields in vitro. *Int J Hyperth* 12(6):705–722
- Raftari Behrouz, Vajravelu Kuppalapalle (2012) Homotopy analysis method for MHD viscoelastic fluid flow and heat transfer in a channel with a stretching wall. *Commun Nonlinear Sci Numer Simul* 17(11):4149–4416
- Singh KD (2013) Effect of slip condition on viscoelastic MHD oscillatory forced convection flow in a vertical channel with heat radiation. *Int J Appl Mech Eng* 18(4):1237–1248
- Singh KD (2013) MHD mixed convection visco-elastic slip flow through a porous medium in a vertical porous channel with thermal radiation. *Kragujev J Sci* 35:27–40
- Abd-Alla AM, Abo-Dahab SM (2015) Magnetic field and rotation effects on peristaltic transport of a Jeffrey fluid in an asymmetric channel. *J Magn Magn Mater* 374:680–689
- Makinde OD, Mhone PY (2015) Heat transfer to MHD oscillatory flow in a channel filled with porous medium. *Rom J Phys* 20:931–938
- Ghosh SK (2007) Hydromagnetic fluctuating flow of a viscoelastic fluid in a porous channel. *J Appl Mech* 74(2):177–180
- Mehmood A, Ali A (2007) Effect of slip condition on unsteady MHD Oscillatory flow of a viscoelastic fluid in a planar channel. *Rom J Phys* 52:85–91
- Ali F, Khan I, Mustapha N, Shafie S (2012) Unsteady MHD oscillatory flow of viscoelastic fluids in a porous channel with heat and mass transfer. *J Phys Soc Jpn* 81(6):064402
- Devika B, Satya Narayana PV, Venkataramana S (2013) MHD oscillatory flow of a Visco elastic fluid in a porous channel with chemical reaction. *Int J Eng Sci Invent* 2:2319–2672
- Gireesha BJ, Mahanthesh B (2013) Perturbation solution for radiating viscoelastic fluid flow and heat transfer with convective boundary condition in non uniform channel with Hall current and chemical reaction. *Thermodynamics* 1–14
- Nayak MK, Dash GC, Singh LP (2014) Effect of chemical reaction on MHD flow of a visco-elastic fluid through porous medium. *J Appl Anal Comput* 4(4):367–381
- Venkateswarlu B, Satya Narayana PV, Devika B (2017) Effects of chemical reaction and heat source on MHD oscillatory flow with heat and mass transfer of a viscoelastic fluid in a vertical channel with porous medium. *Int J Appl Comput Math* 3:937–952
- Muthuraj R, Srinivas S (2010) A note on heat transfer to MHD oscillatory flow in an asymmetric wavy channel. *Int Commun Heat Mass Transf* 37:1255–1260

35. Ogulu A, Bestman AR (1993) Deep heat muscle treatment—a mathematical model—I. *Acta Phys Hung* 73:3–16
36. Ogulu A, Abbey TM (2005) Simulation heat transfer on an oscillatory blood flow in an indented porous artery. *Int Commun Heat Mass Transf* 32:983–989
37. Makinde OD (2007) Asymptotic approximations for oscillatory flow in a tube of varying cross-section with permeable isothermal wall. *Rom J Phys* 52(1–2):59–72
38. Mishra SR, Dash GC, Acharya M (2013) Mass and heat transfer effect on MHD flow of a visco-elastic fluid through porous medium with oscillatory suction and heat source. *Int J Heat Mass Transf* 57(2):433–438
39. Oahimire JI, Olajuwon BI (2014) Effect of Hall current and thermal radiation on heat and mass transfer of a chemically reacting MHD flow of a micropolar fluid through a porous medium. *J King Saud Univ Eng Sci* 26:112–121

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