Journal of Magnetism and Magnetic Materials 394 (2015) 335–348

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magnetohydrodynamic peristaltic transport of couple stress fluid through porous medium in an inclined asymmetric channel with heat transfer

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
20 May 2015
Accepted 20 June 2015
Available online 23 June 2015

Keywords:
Peristaltic transport
Couple stress fluid
Magnetic field
Porous medium
Heat transfer
Inclined asymmetric channel

ABSTRACT

In the present paper, the effects of magnetic field and heat transfer on the peristaltic flow of an incompressible couple stress fluid through porous medium in an inclined asymmetric channel have been studied under the long wavelength approximation. The exact solutions of the resultant governing equations have been obtained for the stream function, pressure gradient, temperature and heat transfer coefficients. The pressure difference and frictional forces have been computed numerically. The effects of Hartmann number, Darcy number, Grashof number, couple stress parameter, heat generation parameter and inclination angle on the heat characteristics, velocity characteristics, pumping characteristics and trapping phenomena are discussed in detail. It is found that the pressure gradient increases from horizontal channel to vertical channel. The best pumping can be seen at higher Hartmann number. The size of trapped bolus decreases with the increase of couple stress parameter and the strength of the magnetic flied. Increase of heat generation parameter increases the pressure gradient, temperature and the size of the bolus.

1. Introduction

Bio-fluids propel from one place to another place by continuous process of muscle contraction and relaxation. This process is known as peristaltic transport. The peristaltic transport phenomenon is mainly due to the neuromuscular property of any tubular smooth muscle structure. This mechanism is responsible for the transport of biological fluids in several physiological processes such as urine transport from kidney to the bladder, the movement of chyme into the gastrointestinal tract, fluids in the lymphatic vessels, bile from the gallbladder into the duodenum, the embryo transport in non-pregnant uterus, the movement of spermatozoa in the ducts efferent of the male reproductive tract, the movement of the ovum in the fallopian tube and the circulation of blood in small blood vessels. Improper peristalsis can cause pathological transport of bacteria, thrombus formation of blood and infertility in human uterus [1]. This peristaltic mechanism also finds many applications in bio-medical systems such as design of roller and finger pumps, heart–lung machine, blood pump machine and dialysis machine. Latham [2], in his thesis, initiated the study of peristaltic flows through analytical and experimental approaches. Later on, this mechanism has become an important topic of research due to the aforesaid mentioned applications in bio-mechanical engineering and bio-medical technology. Numerous investigators have studied peristaltic flow problems in different geometries during the past five decades. Hayat et al. [3] have studied the peristaltic flow of a viscoelastic fluid in an asymmetric channel using regular perturbation technique. Tripathi et al. [4] have used Adomian decomposition method to investigate the peristaltic transport of generalized Burgers' fluid with fractional element model in a channel. Nadeem et al. [5] have made a theoretical and mathematical study of peristaltic transport of a Jeffrey fluid in a rectangular duct with compliant walls using eigen function expansion method. Usha and Rao [6] have studied the effects of curvature and inertia on the peristaltic pumping of two immiscible Newtonian fluids of different viscosities.

In recent years, the studies on the magnetohydrodynamic peristaltic flows of electrically conducting physiological fluids have become a subject of growing interest for researchers due to many applications in bio-engineering and medical sciences. The motion of the conducting fluid across the magnetic field generates electric currents which change the magnetic field, and the action of the magnetic field on these currents gives rise to mechanical forces which modify the flow of the fluid [7]. The magnetohydrodynamic

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http://dx.doi.org/10.1016/j.jmmm.2015.06.052
0304-8853/

principles are employed in the design of heat exchangers, pumps, flow meters, radar systems, power generation, etc. The principles of magnetohydrodynamics also find extensive applications in bioengineering and medical sciences such as the development of magnetic devices for cell separation, targeted transport of drugs using magnetic particles as drug carriers, reduction of bleeding during surgeries and development of magnetic tracers. Specifically, the magnetohydrodynamic flows of non-Newtonian fluids are of great interest in magneto therapy. The non-invasive radiological tests use the magnetic field to evaluate organs in abdomen [8]. The magnetohydrodynamic peristaltic flows have also been explored in treating the problems related to urinary tract, modifying the behavior of cells and tissues and for curing a variety of gastrointestinal motility related disorders [9]. In view of the aforesaid applications, many researchers have studied the peristaltic transport problems under magnetohydrodynamic effects. Kumari and Radhakrishnamacharya [10] have studied the peristaltic transport of a Newtonian incompressible fluid in the presence of applied magnetic field in an inclined channel with slip and wall effects using perturbation method. Akram et al. [11] have presented the perturbation and numerical solutions to study the effect of induced magnetic field on the peristaltic transport of a Williamson fluid in an asymmetric channel. Some more works on the magnetohydrodynamic peristaltic flows can be seen in [12,13] and the references therein.

The flow through porous medium is an interesting subject of engineering and bio-fluid dynamics. The environmental problems such as the spread of contaminants in soil, the prediction of landslides caused by heavy rainfall, filtration of fluids, water seepage in the river bed and underground movement of water and oil are some examples of flows through porous medium. The physiological flows through porous medium include the transport process in human lung, bile duct, kidneys, gall bladder with stones, small blood vessels, etc. Most of the tissues in the body (such as bone, cartilage and muscle) are deformable porous media. The proper functioning of such materials depends crucially on the flow of blood and nutrients through them. The lumen of the coronary artery (which is composition of fatty cholesterol) and artery clogging can be regarded as a porous medium under some pathological conditions [14]. The porous medium models are also used to understand medical conditions such as tumor growth. In view of these applications, many researchers have studied the peristaltic flow problems through the porous medium. Misra et al. [15] have made a theoretical investigation on the peristaltic transport of a physiological fluid in a porous asymmetric channel under the action of a magnetic field using analytical and numerical techniques. Abd Alla et al. [16] have studied the effects of induced magnetic field and rotation in peristaltic motion of a two dimensional micropolar fluid through a porous medium.

Temperature plays an important role in bio-fluid dynamics [17]. Heat transfer process is involved in radio frequency therapy which is useful to treat diseases such as tissue coagulation, the primary liver cancer, the lung cancer and the reflux of stomach acid [18]. The peristalsis together with heat transfer is an important topic of research because of its significant applications in medical sciences. In gastrointestinal transport, the transport of bolus behaves differently under different thermal conditions [19]. Motivated by these applications many researchers have studied the peristaltic flows with heat transfer. Akram and Nadeem [20] have discussed the peristaltic motion of a two dimensional Jeffrey fluid in an asymmetric channel under the effects of induced magnetic field and heat transfer using Adomian decomposition method. Khan et al. [21] have studied the peristaltic motion of Oldroyd fluid in an asymmetric channel in the presence of an inclined magnetic field and heat transfer. Alla et al. [22] have investigated the effect of rotation and initial stress on the peristaltic flow of an incompressible fourth grade fluid in asymmetric channel with magnetic field and heat transfer. Some more works on the MHD peristaltic flows through porous medium with heat transfer can be seen in [23–26].

The couple stress fluid model, developed by Stokes [27], is considered as a simple generalization of the Newtonian fluid model which accounts for the couple stresses and body couples in the fluid medium. It is known to be a better model for studying the flows of bio-fluids, lubricants containing small amount of high polymer additives and synthetic fluids. The distinguishing feature of couple stress fluids is that the stress tensor for this fluid is not symmetric. Many researchers have studied the couple stress fluid flow problems in different situations. Devakar and Iyengar [28] have studied the Stokes' problems for an incompressible couple stress fluid under the isothermal conditions. Akbar and Nadeem [29] have presented the homotopy perturbation method to discuss the influence of nanofluid on the peristaltic flow of an incompressible couple stress fluid in a two-dimensional uniform tube. Devakar and Iyengar [30] have discussed the run up flow of a couple stress fluid between parallel plates. Devakar et al. [31] have obtained the exact solutions for fundamental flows namely Couette, Poiseuille and generalized Couette flows of an incompressible couple stress fluid between parallel plates using slip boundary conditions. Tripathi [32] investigated the peristaltic hemodynamic flow of couple stress fluid through a porous medium. Abd elmaboud et al. [33] have presented a theoretical analysis of the peristaltic flow of a couple stress fluid in a two-dimensional asymmetric channel. Shit and Roy [34] have discussed the effect of channel inclination on the peristaltic transport of a couple stress fluid in the presence of externally applied magnetic field.

In general, the ducts/channels in physiological systems are neither horizontal nor vertical; they have some inclination with axis. In view of this and the aforesaid applications, in this paper, we have studied the magnetohydrodynamic peristaltic flow of couple stress fluid through homogeneous porous medium in an inclined asymmetric channel with heat transfer. Cartesian coordinate system has been used to model and present the mathematical equations. The exact solutions for the stream function, temperature and pressure gradient have been obtained under the long wavelength approximation. A numerical integration is used to compute the pressure difference and frictional forces. The effects of pertinent parameters on fluid flow are studied and the results are illustrated through graphs.

2. Mathematical formulation

Consider magnetohydrodynamic flow of an electrically conducting couple stress fluid in an inclined asymmetric channel of width of $d_1 + d_2$ through a porous medium. The Cartesian coordinate system (X, Y) is chosen such that the direction of wave propagation is in X-direction and Y-coordinate is perpendicular to the flow direction. Asymmetry in the channel is produced by choosing the peristaltic wave trains propagating with constant speed c along the walls (H_1 is the lower wall and H_2 is the upper wall) with different amplitudes and phases. The upper wall of the peristaltic channel is maintained at temperature T_1 while the lower wall is maintained at temperature T_0. The fluid is subject to a constant transverse magnetic field B_0 (see Fig. 1). A very small magnetic Reynolds number is assumed and hence the induced magnetic field can be neglected. The sinusoidal waves propagating along the channel walls are

$$Y = H_1(X, Y, t) = d_1 + a_1 \cos\left(\frac{2\pi}{\lambda}(X - ct)\right) \tag{1}$$