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Combined effects of magnetic field and rheological properties on the peristaltic flow of a compressible fluid in a microfluidic channel

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HIGHLIGHTS

- MHD peristaltic flow of compressible Jeffrey fluid is modeled in a microchannel.
- Combined effects of magnetic field and viscoelastic fluid are discussed.
- Increasing the magnetic parameter makes the fluid less prone to nonlinear effects.
- Flow becomes slow due to the suppression effect of the retardation time.
- Quadratic effects of acoustic streaming cause reverse flow to traveling waves.

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ABSTRACT

The MHD peristaltic motion of a compressible and electrically conducting Jeffrey fluid induced by a surface acoustic wave in a confined parallel-plane microchannel through a porous medium is analytically investigated. A proper attention is given to the combined effects of physical parameters and magnetic field on the rheological aspects of the considered flow. The slip velocity is considered and the problem is discussed for free pumping case. The wave amplitude is related to the power output of an acoustic source. A perturbation technique is employed to analyze the problem in terms of a small amplitude ratio. In the second order approximation, the net axial velocity is calculated for various values of the fluid parameters. Finally, the effects of the parameters of interest on the mean axial velocity, the reversal flow, and the perturbation function are discussed and shown graphically. The critical value of the magnetic parameter M is discussed such that an optimum M is shown where some physical variables are obtained maximum. It is noticed that, for the Jeffrey fluid, oscillations decay rapidly as we move from the hydrodynamic to the hydromagnetic fluid, and the effect of retardation time becomes weak. It is inferred that increasing the magnetic parameter makes the fluid less prone to nonlinear effects. Several results of other fluid models are deduced as the limiting cases of our problem. This work is the most general model of peristalsis created to date with wide-ranging applications in biological microfluidic networks.

1. Introduction

The characteristics of fluid flow in microchannels have become the topic of extensive research lately with the rapid developments in industry. Several investigations have been undertaken to understand the variations between macro and microscale flows since microfluidic channels are utilized in many industrial applications such as micro-electric chip cooling, biomedical applications, and microelectro-mechanical systems [1–3]. Microfluidic channels, or tubes built in biomicroelectro-mechanical systems, are easily subjected to environment noises (oscillation or vibrations) and externally excited traveling waves (surface acoustic wave), where it is normally related to the peristaltic transport since the walls are flexible. These kinds of dynamic effects cannot be neglected when compressible fluids are flowing in such conduits [4,5]. Vafai and Khaled [6,7] analyzed the single and double layered flexible 2D microchannel heat sinks which have important applications in design and control of the flow.

Acoustic streaming has thus far been representing one of very few inertial phenomena that may actually play a considerable

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role in microfluidics. Due to the significant small sizes of the microfluidic devices, they prevent flow velocities from being high enough to yield high Reynolds numbers. However, acoustic waves of high frequency can circumvent such a difficulty. Although periodic wave motion might seem to be of small use to fluid manipulation, the inertial nonlinearity can rectify oscillatory fluid motion to give a time-averaged flow called acoustic streaming [8–11]. Chen [12] investigated the influence of ultrasonic radiation on the flow of water or oil through a stainless steel filter and on the flow of oil segments through a capillary. Chu [13] studied the flow induced by surface acoustic waves (SAW) in a microscale tube, and showed that the flow velocity of the gas is proportional to the second power of the SAW displacement velocity in these microchannels. Also, the effects of compressibility induced by SAW in a microchannel with compliant walls were studied by Mekheimer and Abdel-Wahab [14].

The key quantity in the study of microchannels is Knudsen number (K_n), which is the ratio between molecular mean free path to the representative physical length scale ($=A/l$). In fact, Knudsen number is very small for continuum flows. However, for gas flows in microdomains, the gas mean free path becomes comparable with the characteristic dimension of the conduit and K_n is greater than 0.001, and thus, the continuum approach assumption of fluid mechanics would no longer be a good approximation. A classification of different flow regimes in microchannels based on K_n shall be given later on [15,16].

There are two types of motions in the body of living organism; involuntary and voluntary. Both motions are characterized by muscular movements stimulated by nerve cells, yet the involuntary movement cannot be controlled by the will of organism himself. Normally in the human body, the peristaltic motion is an example of an involuntary wavelike contractions and relaxations of cardiac and smooth muscles. It occurs in transport tubes such as the oesophagus, urine transport from kidney to bladder or in some blood vessels [17–21]. Vafai et al. [22] studied the effect of Hall current and heat transfer on the peristaltic transport of a third grade fluid. Hayat et al. investigated the peristaltic transport for a compressible and incompressible Jeffrey fluid in a conduit with compliant walls [23,24].

Biological tissues are viscoelastic materials; their behavior is both viscous and elastic. A viscoelastic material possesses characteristics of stress-relaxation, creep, strain-rate sensitivity, and hysteresis [25]. The new ontology of nonlinear viscoelasticity enables a better understanding of biological materials by improving the ability to distinguish between different materials and providing insight into the physical mechanisms that cause material response [26,8,1]. Biological tissues generally contain blood vessels which can be categorized as vascular regions, one of which, stenosed artery through which the hyperthermia was analyzed in [27]. The characteristics of bioheat transfer through annular region were given by Wang et al. [28]. Gao and Jian [29] studied the MHD flow of the Jeffrey fluid in a circular microchannel taking the retardation time smaller than the relaxation time. Mekheimer et al. [4] investigated the peristaltic transport for a compressible Maxwell model in the presence of magnetic field where the wave amplitude was related to the power output of an acoustic source. Hayat et al. [30] gave a thorough analysis comparing the viscoelastic properties of Maxwell and Jeffrey fluids. Flow through a porous medium has been of considerable interest in recent years particularly among geophysical fluid dynamicists. A basic introduction is given by Aarts and Ooms, and Chen in [9,12], respectively. More comprehensive treatments can be found in [26,31], and detailed reviews are given by Elkoumy et al. [32].

The above mentioned investigations and existing literature on the peristaltic flows show that only few attempts study the peristaltic flows of compressible fluid. The most general study of stimulation of compressible fluid flow in porous media via peristaltic mechanism is presented in [9]. The combined effect of a weakly compressible non-Newtonian fluid with wall slip on peristaltic flow has recently been investigated by Damianou and Georgiou [33]. Mekheimer and Abdel-Wahab investigated the peristaltic flow of a compressible Newtonian fluid through the microchannel and via the annulus in [14,5], respectively. However these studies did not take into account the effect of magnetic field on the flow properties. In fact, magnetohydrodynamic flows of fluids in conduits with elastic, rhythmically contracting walls (peristaltic flow) is of interest in connection with certain problems of the movement of conductive physiological fluids. Mekheimer et al. [4] extended the analysis of Ref. [14] to include the effects of the relaxation time of a Maxwell fluid together with the magnetic field in a microchannel. It was shown that there is a possibility of a fluid flow in the direction opposite to the propagation of the traveling wave. Elkoumy et al. [32] investigated the effect of strong magnetic field with Hall effect on the peristaltic flow of a Maxwell fluid in a channel. Recently, the MHD flow of an incompressible Jeffrey fluid in a circular microchannel has been studied in [29].

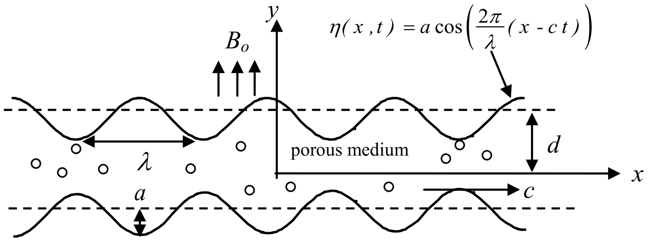

Fig. 1. Schematic showing the flow domain and its geometrical parameters.

Nevertheless, the aforementioned investigations did not take into consideration the combined effect of magnetic field with viscoelastic parameters on the flow, and to the best of the authors' knowledge, this has not been done in the open literature. Under the purview of the present study, the aim of this article is to extend our interest in studying the arisen effects generated by introducing constant magnetic field and rheological properties in a microdomian of which the wave amplitude is related to the power output of an acoustic source. We suppose that the porous medium constitutes a compressible fluid which is originally stationary. That is, the zeroth-order pressure gradient is neglected at the beginning. Since the motion of MHD fluid across the magnetic field induces electric currents which change the magnetic field and the flow of the fluid, our work can help in better understanding of the behavior of complex nonlinear viscoelastic properties of biomaterials in MHD.

2. Formulation of the problem

A viscous, compressible, and electrically conducting Jeffrey fluid in a 2D symmetric channel of uniform width $2d$ is considered as shown in Fig. 1. The flow in the porous space is due to sinusoidal small-amplitude traveling waves on the flexible walls of the channel. A uniform magnetic field B_o is acting along the y-axis and the induced magnetic field is assumed negligible. We introduce the Cartesian coordinate system with the x-axis along the centerline of the channel and the y-axis normal to it. Let u and v denote the velocity components along x- and y-directions, respectively.

The flow is governed by the continuity equation

$$\frac{\partial \rho}{\partial t} + (\mathbf{V} \cdot \nabla \rho) + \rho(\nabla \cdot \mathbf{V}) = 0, \tag{1}$$

and the equations of motion

$$\rho\frac{\partial \mathbf{V}}{\partial t} + \rho(\mathbf{V}.\nabla)\mathbf{V} = -\nabla p + \nabla \cdot \mathbf{S} + \mathbf{R} + \mathbf{J} \times \mathbf{B} + \frac{\mu}{3}\nabla(\nabla \cdot \mathbf{V}), \tag{2}$$

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