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Mathematical modeling of heat and mass transfer effects on MHD peristaltic propulsion of two-phase flow through a Darcy-Brinkman-Forchheimer porous medium

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ABSTRACT

This article deals with the combined effects of heat and mass transfer on the peristaltic propulsion of two-phase fluid flow through a Darcy-Brinkman-Forchheimer porous medium with compliant walls. The Sisko fluid model together with small particles is considered in the presence of extrinsic magnetic field and chemical reaction. It is well-known that different biological fluids behave like a Newtonian or non-Newtonian fluid depending upon the shear rates. The non-Newtonian fluid models are more complicated than Newtonian fluid and difficult to express using the single constitutive relationship between stress and strain rate. These constitutive equations provide a complex mathematical formulation and become numerous challenges to find numerical and analytical solutions. Small magnetic particles are helpful to manipulate and control the two-phase flow by magnetic force. Moreover, it is also beneficial in drug targeting for the treatment of different diseases. Further, two-phase flow plays an important role to examine the muscular expansion and contraction during the propagation of various biological fluids. An appropriate approximation is considered such as long wavelength and creeping flow regime to model the governing equations. Analytical solutions are obtained using the perturbation method. Moreover, numerical computations are performed to determine the features of peristaltic pumping. The results of different rheological properties for particle and fluid phase are discussed mathematically as well as graphically for different sundry parameters. The current analysis has an extensive amount of applications in medical engineering and also significant importance of smart fluid pumping systems in various engineering processes.

1. Introduction

Peristaltic transport of two-phase (fluid-particle) flow has a wide range of applications in industry and biomedical engineering. It is a symmetrical process in smooth muscles that originated during the propagation of biological fluids (or physiological fluids in particular). This motion can be observed easily during the spontaneous oscillation in blood vessels, propagation of urine from the kidney to the bladder, propagation of food through the mouth to esophagus and movement of Chyme in the gastrointestinal tract. Moreover, during the sperm ejaculation from testicles to a urethra, the smooth walls contraction and expansion followed by a peristaltic mechanism. Further, various devices are manufactured that exactly works on the principle of peristalsis which is beneficial in different laboratories of pharmaceutical, biomedical engineering, food industry and in biotechnology. Böhme and Friedrich [1] addressed the peristaltic motion of viscoelastic fluid through a duct, wherein they particularly discussed the pressure-discharge features of peristaltic pumping as well as pumping efficiency. Haroun [2] analyzed the nonlinear peristaltic motion through an asymmetric channel and found that the maximum pressure rise increases when the fluid is non-Newtonian as compared to Newtonian fluid. Nadeem and Akram [3] studied the three-dimensional peristaltic flow through a rectangular duct and presented the exact solutions. Mekheimer et al. [4] explored the asymmetric peristaltic motion towards a rectangular duct and discussed the impact of lateral walls. Later on, Nadeem et al. [5] considered the similar problem [3] and addressed the effects of compliant walls. Hina et al. [6] examined the behavior of third-grade fluid induced by peristaltic

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Nomenclature

$\tilde{u}, \tilde{v}$	velocity components
C	particle volume fraction
$\tilde{p}$	pressure
E_c	Eckert number
$\tilde{a}$	half-width of the channel
k	thermal conductivity
$\tilde{x}, \tilde{y}$	Cartesian coordinate
P_r	Prandtl number
$\tilde{b}$	wave amplitude
$\tilde{c}$	wave velocity
$\mathbf{J}$	current density (A)
e	electron charge
n	number of electron density
c	specific heat
Re	Reynolds number
F	Forchheimer number
B_0	magnetic field
$\mathbf{E}$	electric field (V/m)
$\tilde{\mathbf{V}}$	velocity field (m/s)
M	Hartmann number
$\tilde{t}$	time
E_1	wall rigidity
$\bar{k}$	porous parameter
E_2	wall tension
E_3	mass characterization
$\tilde{T}$	temperature
b_1	Sisko fluid parameter
$\bar{S}$	drag force
$\mathcal{M}$	wall mass per unit area
$\mathcal{D}$	viscous damping
$\mathcal{T}$	elastic tension in the membrane
n	power law index
μ_s	viscosity of the fluid

Greek symbols

σ	electric conductivity of the fluid
r	stress tensor
β	heat/source-sink parameter
$\mathcal{C}_f$	Forchheimer coefficient
ϖ_T	thermal equilibrium time
ϖ_v	relaxation time of the particle
λ	wavelength
ϑ	stream function
μ_s	viscosity of the fluid
θ	dimensionless temperature
ϕ	amplitude ratio
ρ	fluid density

Subscripts

f	fluid phase
p	particulate phase

motion in the presence of slip condition. They observed that the axial velocity has higher magnitude due to the intensification of slip condition. Abbas et al. [7] studied the peristaltic flow of hyperbolic tangent fluid analytically by treating non-Newtonian fluid model in three-dimensional rectangular ducts with compliant walls.

The flow of particulate suspension is substantial because it is helpful in propagating biological fluids in a human body that occur due to peristaltic wave and acts like fluid-particle mixture. Using the continuum approach, the study of particle-fluid is especially applicable in the hydrodynamics of biological systems, because it is beneficial to explore multiple subjects such as capillary hemodynamic flow in vivo, fluidization, and sedimentation [8,9]. Particle-fluid suspension often observed in biological and physical sciences, and the collision between particles and fluid may cause a significant effect on the rheological behavior and viscosity of the suspension. It is also well-known that anisotropic particle microstructures and the clusters are the outcomes of particle movement that occurs due to wall-particle and particle-particle collision [10–13]. For instance, a collision of particle-fluid at mesoscopic level is a dynamics of erythrocytes. In microcirculation, the attitude of RBCs has a significant role in different pathological and physical mechanism. Moreover, randomly transverse rotation and propagation of RBCs in a shear flow play a significant role in thrombogenesis [14]. Such types of flows are strongly associated with RBC to RBC collision and also fluid plasma to RBC collision since a single RBC is interrupted by another coming from below or above. Hung and Brown [15] initially determined the peristaltic motion of small particles through a two-dimensional vertical channel and examined the dynamics and diverse geometric effects. Srivastava and Srivastava [16] discussed the two-phase blood flow using macroscopic model and found that apparent viscosity diminishes due to the magnitude of the blood vessel which complies with a Fahraeus–Lindqvist effect. Saxena and Srivastava [17] carried out the peristaltic motion of particle-fluid suspension through an asymmetric two-dimensional tube. They showed that due to an increment in particle concentration enhances the pressure but opposite reaction is observed for higher values of amplitude ratio. Akbar et al. [18] and Nayak et al. [19] analytically studied the magnetohydrodynamic flow of nanofluid and convective heat transfer by considering different sizes of nanoparticles with adopting two-phase nanoscale formulation.

Mass and bioheat transfer on the peristaltic motion have a wide range of applications in biomedical engineering. Heat transfer process is associated with the transaction of thermal energy between different components of physical systems. Heat transfer rate usually depends upon temperature difference of compartments and the physical features of a medium. When a fluid (either Newtonian or non-Newtonian) flow through a medium, then the flow is influenced by buoyancy force (external agency). During the convective heat transfer, the heat moves from one point to another point and from one particle to another particle by the flow of fluid. Moreover, heat transfer also involves conduction process of tissues, heat convection process that occurs due to the flow of blood from pores of tissues and hemodialysis, vasodilation and oxygenation. Of course, the mass transfer also involves in all these processes. Mass transfer is associated with the propagation of mass from one point to another location. The mass transfer also occurs in a wide area of engineering applications. In particular, mass transfer plays a vital role in chemical engineering and especially, in heat transfer engineering, reaction engineering, and process engineering. Due to a various number of applications in modern technology, several authors analyzed the mass and heat transfer on peristaltic flow through different media. For instance, Srinivas and Kothandapani [20] simultaneously examined the peristaltic flow with magnetic field effects in the presence of mass and heat transfer through a compliant porous channel. Nadeem and Akbar [21] considered