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Analytical and numerical investigation of nanoparticle effect on peristaltic fluid flow in drug delivery systems

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ABSTRACT

In this paper the peristaltic flow of nanofluids in drug delivery systems is studied analytically and numerically. The flow is considered under low Reynolds number with long wavelength approximation. Least squares method (LSM), Galerkin method (GM) and fourth-order Runge–Kutta numerical method (NUM) are used to solve the present problem. The results are presented to study temperature, velocity, nanoparticle fraction field and pressure gradient. The effects of some physical parameters such as Brownian motion parameter, thermophoresis parameter, thermal Grashof number and basic-density Grashof number on non-dimensional velocity, nanoparticle fraction distribution and temperature profiles are considered. Early results implied that increasing thermal Grashof number reduces the axial velocity profile, while increasing species Grashof number has conversed treatment.

1. Introduction

Peristalsis is a form of fluid transport induced by wave traveling on the walls of a tube. The peristaltic transport of fluids occurs in many bioscience and engineering applications. In live systems, it has been found to be involved in many biological systems such as movement of food through alimentary canal, movement of ovum in the fallopian tubes, blood flow in the arteries and male reproductive tract. Also, as industrial applications, it involves the transport of sanitary fluid, corrosive fluid and drug delivery systems.

In the review of its importance, the peristaltic flow of Newtonian and non-Newtonian fluids has been investigated by numerous authors. Fung and Yih [1] presented the first theoretical work on the peristaltic pumping which involves inertia-free Newtonian flows driven by sinusoidal transverse waves of small amplitude. Mittra and Prasad [2] extended their study including an elastic or viscoelastic wall, and a Poiseuille flow. Srivastava and Srivastava [3] investigated the peristaltic flow of blood transport assuming a single layered Casson fluid and ignoring the presence of a peripheral layer. Mekheimer [4] examined the peristaltic flow of blood in a non-uniform channel with the presence of magnetic field. The flow is considered under zero Reynolds number with long wavelength approximation.

Ali et al. [5] analyzed the peristaltic flow of couple stress fluid in an asymmetric channel under long wavelength and low Reynolds number approximations. Wang et al. [6] investigated the peristaltic motion of Johnson–Segalman fluid as physiological fluid in a tube with a sinusoidal wave traveling the walls. Reddy et al. [7] studied the flow of a power-law fluid in an asymmetric channel caused by the movement of peristaltic waves with the same speed but with different amplitudes.

Many authors [8–11] have studied the influence of heat transfer on peristaltic flow of Newtonian and non-Newtonian fluids with or without considering magnetic field through channels or vertical annulus. They discussed the effects of physical parameters on flow behavior. Srinivas and Kothandapani [12] investigated the problem of heat transfer for the motion of a viscous fluid induced by traveling sinusoidal waves in a channel. Radhakrishnamacharya and Srinivasulu [13] studied the effect of elasticity and mass characterizing parameters of the flexible walls on peristaltic transport of a viscous fluid with heat transfer in a uniform channel. The effect of heat transfer and magnetic field on the peristaltic flow of Newtonian fluid in a vertical annulus was examined by Mekheimer and Abd elmaboud [14].

In recent decades with the rapid development of micro-electromechanical system (MEMS) technologies and increasing demands of biological and medical fields, the application of MEMS in biology has made a great progress. The drug delivery system has become an encouraging topic in BioMEMS, due to its commercial and research interests in health care. A nano-drug supply system and a bio-MEMS were introduced by Kleinstreuer et al. [15]. Their main concern was the conditions for delivering uniform concentrations at the exit of microchannel of the supplied nano-drugs. A heat flux which depends on the levels of nano-fluid and purging fluid velocity was

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Nomenclature

a	half width of the channel
b	wave amplitude
c	velocity of the wave
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
F	nanoparticle volume fraction
Gr_F	species Grashof number
Gr_T	thermal Grashof number
N_b	Brownian motion parameter
N_t	thermophoresis parameter
Q	volume flow rate
k	thermal conductivity
k_1	reaction rate constant
Re	Reynolds number
Pr	Prandtl number
g	gravitational acceleration
$\tilde{u}, \tilde{v}$	axial velocity and transverse velocity

Greek symbols

β	volumetric volume expansion coefficient
ϕ	amplitude ratio
μ	dynamic viscosity of the fluid
ν	kinetic viscosity of the fluid
δ	wave number
ρ_f	fluid density
ρ_p	density of nanoparticle mass
Φ	dimensionless nanoparticle volume fraction
λ	wavelength

added to ascertain that drug delivery to the living cells occurs at an optimal temperature. The added wall heat flux had also a positive influence on drug-concentration uniformity. In general, the nano-drug concentration uniformity is influenced by channel length, particle diameter and the Reynolds number of both the nanofluid supply and main microchannels. Since the transport mechanisms are dependent on convection–diffusion, longer channels, smaller particle diameters as well as lower Reynolds numbers are desirable for best; that is uniform drug delivery [16]. Despite the importance of application of peristaltic flow in medical systems, there are a few studies of peristaltic transport of nanofluids in such systems. Akbar et al. [17] studied the peristaltic flow of a nanofluid in a diverging tube which was the first research on the peristaltic flow in nanofluids. Tripathi and Bég [18] examined the peristaltic flow of nanofluids through a two-dimensional channel. The results of this study demonstrated that the pressure gradient is reduced by increasing thermophoresis parameter.

Influence of applied magnetic field on the peristaltic transport of copper–water nanofluid in the presence of Halland Ohmic heating effects was studied by Abbasi et al. [19]. Their results depicted that the addition of copper nanoparticles reduces the velocity and temperature of fluid.

Shehzad et al. [20] examined MHD mixed convective peristaltic transport of viscous nanofluid in a channel with thermophoresis at the boundaries. They studied the effects of sundry parameters on the velocity, temperature, concentration of nanoparticles, and heat and mass transfer rates at the wall. Mixed convection peristaltic transport of nanofluid in the presence of applied magnetic field is analyzed by Hayat et al. [21]. The impacts of Joule heating and Soret and Dufour effects were also outlined in their study. They used long wavelength and low Reynolds number approximations in the modeling of nonlinear problem. Peristaltic transport of silver–water nanofluid in the presence of viscous dissipation, heat generation/absorption, Ohmic heating and slip effects was developed by Abbasi et al. [22]. Results show that the addition of 5% silver nanoparticles reduces the velocity of base fluid by almost 10% and its temperature by 16%.

Shehzad et al. [23] examined mixed convective peristaltic transport of water based nanofluids with viscous dissipation and heat generation/absorption using two different models of the effective thermal conductivity of nanofluids. The two cases of Maxwell's and Hamilton–Crosser's thermal conductivity models were used in their analysis. Their results indicated that when the thermal conductivity of discontinuous phase (nanoparticles) is relatively higher than that of the continuous phase (water) then the results predicted by the Maxwell's and the Hamilton–Crosser's model differ by a large amount.

Mathematical modeling is a vantage point to reach a solution in an engineering problem, so the accurate modeling of nonlinear engineering problems is an important step to obtain accurate solutions [24–28]. Most technical problems in fluid mechanics and heat transfer problems are inherently nonlinear. These problems and phenomena can be modeled by ordinary or partial nonlinear differential equations to find their behavior in the environment. Therefore, some different methods have been introduced to solve these equations, such as the Variational Iteration Method (VIM) [29,30], Homotopy Perturbation Method (HPM) [31–33], Differential Transformation Method (DTM) [34–36], Homotopy Analysis Method (HAM) [37,38], Adomian Decomposition Method [39], Modified Homotopy Perturbation Method (MHPM) [40] and Optimal Homotopy Asymptotic Method (OHAM) [41]. Also, there are some simple and accurate approximation techniques for solving differential equations called the Weighted Residual Methods (WRMs). Least squares method (LSM), Galerkin method (GM), Collocation Method (CM) and Method of Moments (MM) are examples of the WRMs [42]. Ghasemi et al. [43] used Collocation Method (CM) for third grade non-Newtonian blood flow in porous arteries in the presence of magnetic field. Electrohydrodynamic flow (EHD flow) in a circular cylindrical conduit was studied using the Least-Squares Method (LSM) by Ghasemi et al. [44]. They concluded that LSM is in an excellent agreement with the numerical solution. The motion of a spherical particle released in a swirling fluid flow was studied employing the Least-Squares Method (LSM) and the Method of Moments (MM) by Ghasemi et al. [45]. Darzi et al. [46] applied Least-Squares Method (LSM) to investigate the effect of thermal radiation on velocity and temperature fields of a thin liquid film over a stretching sheet in a porous medium. Hatami et al. [47] and Atouei et al. [48] used LSM for thermal analysis of semi-spherical fins. Also, other applications of Weighted Residual Methods (WRMs) in different engineering problems can be found in Refs. [49–52]. Also, very recently a novel computational technique called Parameterized Perturbation Method (PPM) was used to obtain the solutions of nonlinear fundamental heat transfer equations by Ghasemi et al. [53].

The aim of this study is to obtain the approximate solution of the peristaltic flow of nanofluid in a channel which has application in drug delivery systems. The expressions for velocity, temperature and nanoparticle fraction distribution are obtained under the assumptions of long wavelength and low Reynolds number. The Least squares, Galerkin and numerical methods are used to solve the governing equations of the problem. Also the effects of some parameters such as Brownian motion and thermophoresis parameters, thermal, and basic-density Grashof number on velocity and nanoparticle fraction profiles are investigated.

2. Description of the problem

Consider the peristaltic pumping of a conducting fluid through a channel. A longitudinal train of progressive sinusoidal waves takes place on the upper and lower walls of the channel. We have restricted our problem to the half-width of the channel as shown in Fig. 1. The geometry of the channel wall is given by [54]:

$$\tilde{h}\left(\tilde{\xi}, \tilde{t}\right) = a + b \sin \frac{2\pi}{\lambda}\left(\tilde{\xi} - c\tilde{t}\right) \tag{1}$$