Journal of Magnetism and Magnetic Materials ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Influence of induced magnetic field and heat flux with the suspension of carbon nanotubes for the peristaltic flow in a permeable channel

Q1 Noreen Sher Akbar [a], M. Raza [b,*], R. Ellahi [b,c]

[a] DBS&H, CEME, National University of Sciences and Technology, Islamabad, Pakistan
[b] Department of Mathematics and Statistics, FBAS, IIU, Islamabad 44000, Pakistan
[c] Department of Mechanical Engineering, Bourns Hall A 373, University of California, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 15 November 2014
Received in revised form
9 December 2014
Accepted 18 December 2014

Keywords:
Induced MHD
Peristaltic flow
Carbon nanotubes
Permeable channel
Heat generation
Heat flux

ABSTRACT

This paper is intended for investigating the effects of heat flux and induced magnetic field for the peristaltic flow of two different nanoparticles with the base fluid water in a symmetric vertical permeable channel. A mathematical formulation is presented. Exact solutions have been evaluated from the resulting equations. The obtained expressions for pressure gradient, pressure rise, temperature, axial magnetic field, current density and velocity are described through graphs for various pertinent parameters. Streamlines are drawn for some physical quantities to discuss the trapping phenomenon.

1. Introduction

The prominent properties of carbon nanotubes (CNTs) make CNTs attractive in biological engineering applications. CNT based biomaterials for clinic use are expected in the near future. CNTs can be used to tune cellular fate through both extracellular pathway and intracellular pathway. CNT based biomaterials are applied to bone, nerves, and cardiovascular system. CNTs have also been used in controlling cellular alignment, to increase tissue regeneration, growth factor delivery and gene delivery. Q3

For the first time, carbon nanotubes (CNTs) were discovered by Iijima and Baughman [1,2]. A single CNT is one or multiple layers of graphene sheets which roll up. Depending on the number of the graphene sheets, CNTs are mainly classified into single wall carbon nanotubes (SWCNTs) and multi-wall carbon nanotubes (MWCNTs). SWCNTs have a diameter close to 1 nm with a varied length from nanometers to centimeters whereas the interlayer distance for MWCNTs is approximately 0.34 nm [3]. Owing to CNTs' extraordinary thermo-conductivity, electro-conductivity and mechanical property, CNTs find their applications as additives in structural materials such as golf stub, boat, aircraft, and bicycles. Other than these, CNTs are intensively attractive in composite materials [4,5], electrical devices [6–9], hydrogen storage [10,11], biomedical engineering [12–15], etc. All types of CNTs are good thermal conductors along tube direction as well. Measurement has shown that SWCNT had a thermal conductivity of 3500 W m^{-1} K^{-1} at room temperature. This was almost 10 times the thermal conductivity of copper (385 W m^{-1} K^{-1}) [16].

Peristaltic pumping is a sort of fluid transport in a tube when a progressive wave contraction or expansion propagates along its length. Peristalsis is an important mechanism known in many organisms and in various organs of a living body. Peristaltic flows also provide efficient ways for sanitary fluid transport and are thus in industrial exploited peristaltic pumping and medical devices. This mechanism is mainly used in the mechanical roller pumps using viscous fluids in the printing industry and for transporting blood in heart lung machines.

Several mathematical models are obtained to study the effects of a train of periodic sinusoidal waves on the walls of an infinitely long two dimensional channel or axisymmetric tubes containing a Newtonian or non-Newtonian fluid. Nicoll and Webb [17] and Nicoll [18] reported that peristalsis plays an important role in blood circulation. The investigation of peristaltic pumping from a mechanical view point was launched with an experiment by Latham [19], who evaluated the problem analytically. The results of that experiment were generally in good agreement with the theoretical investigations of Shapiro [20].

The study of fluid flow induced by unsteady motion of a wall is

* Corresponding author.
E-mail addresses: mohsin.phdma11@iiu.edu.pk, mohsinvirgo18@gmail.com (M. Raza).

http://dx.doi.org/10.1016/j.jmmm.2014.12.087
0304-8853/© 2015 Elsevier B.V. All rights reserved.

of great practical significance in the field of biomechanics. Nadeem and Akbar [21] studied the influence of radially varying MHD on the peristaltic flow in an annulus with heat and mass transfer. Mekheimer and Elmaboud [22] discussed the influence of heat transfer and magnetic field on the peristaltic flow of Newtonian fluid in a vertical annulus under a zero Reynolds number and long wavelength approximation. Ebaid [23] studied a new numerical solution for the MHD peristaltic flow of a biofluid with variable viscosity in a circular cylindrical tube by an Adomian decomposition method. Mekheimer [24] investigated the impacts of the induced magnetic field on the peristaltic flow of a couple stress fluid in a slit channel. Further important literature can be viewed via Refs. [25–39].

Motivated by the above discussion, we considered the peristaltic flow in a symmetric channel with permeable wall. We describe the effect of induced magnetic field and heat generation and heat flux on peristaltic flow of water and CNTs nanofluid. At the same time, an exact solution of dimensionless governing equations for water and CNTs nanofluid will be suggested and discussed through graphs.

2. Mathematical formulation

Consider the peristaltic transport of a CNTs water fluid in a symmetric channel with permeable wall of half-width '2a'. An external transverse uniform constant magnetic field H_0, an induced magnetic field $H(h_X(X, Y, t), H_0 + h_Y(X, Y, t), 0)$ and the total magnetic field $H^{+}\left(h_X(X, Y, t), H_0 + h_Y(X, Y, t), 0\right)$ are taken into account. Sinusoidal waves propagate beside the walls of the channel with continuous speed c. The wall deformation is given by

$$Y = \overline{H} = a + b\cos\left[\frac{2\pi}{\lambda}\left(\overline{X} - c\bar{t}\right)\right]. \tag{1}$$

In the above equations b denotes the wave amplitudes, λ is the wavelength, $\bar{t}$ is the time, $\overline{X}$ is the direction of wave propagation and Y is perpendicular to $\overline{X}$.

Equations governing the flow and temperature in the presence of heat source or heat sink and the equation which governs the MHD flow are given as follows:

(i) Maxwell's equations [24–26]:

$$\nabla\cdot\mathbf{H} = 0, \quad \nabla\cdot\mathbf{E} = \mathbf{0}, \tag{2}$$

$$\nabla\wedge\mathbf{H} = \mathbf{J}, \quad \mathbf{J} = \sigma\{\mathbf{E} + \mu_e(\mathbf{V}\wedge\mathbf{H})\}, \tag{3}$$

$$\nabla\wedge\mathbf{E} = -\mu_e\frac{\partial\mathbf{H}}{\partial\mathbf{t}}, \tag{4}$$

(ii) continuity equation:

$$\nabla\cdot\mathbf{V} = \mathbf{0}, \tag{5}$$

(iii) equations of motion

$$\rho_{nf}\left(\frac{\partial\mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = -\nabla p + \mu_{nf}\,\mathrm{div}\,\mathbf{V} + (\rho\beta)_{nf}g\alpha\left(T - T_0\right)$$

$$-\nabla\left(\frac{1}{2}\mu_e\left(H^{+}\right)^2\right) - \mu_e\left(H^{+}.\,\nabla\right)H \tag{6}$$

(iv) energy equation

$$(\rho c)_f\left(\frac{\partial\mathbf{T}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{T}\right) = \nabla\cdot k_{nf}\nabla T + Q_0 - \frac{\partial q}{\partial y}, \tag{7}$$

where ρ_{nf} is the effective density of the incompressible fluid, $(\rho c)_{nf}$ is the heat capacity of the fluid, $(\rho c)_p$ gives the effective heat capacity of the nanoparticle material, k_{nf} implies the effective thermal conductivity, g stands for constant of gravity, μ_{nf} is the effective viscosity of the fluid, d/dt gives the material time derivative, and p is the pressure. q is radiative heat flux and defined by [27]

Table 1
Thermal-physical properties of water and nanoparticles.

Physical properties	Water (H_2O)	SNCT	MNCT
ρ(kg m^{-3})	997.1	2600	1600
C_p	4179	425	796
$\beta\times10^5$ (K^{-1})	21	2.6	2.8
k (W m^{-1} K^{-1})	0.613	6600	3000

$$q = \frac{4\sigma^{*}}{3k^{*}}\frac{\partial T^4}{\partial y}, \tag{8}$$

where σ^{*} is the Stefan–Boltzmann constant and k^{*} is the mean absorption coefficient. It is assumed that the temperature differences within the flow are small, so that the term T^4 may be expressed as a linear function of temperature. Hence by expanding T^4 in a Taylor's series about T_∞ and neglecting higher-order terms

$$T^4 \approx 4T_\infty^3 T - 3T_\infty^4. \tag{9}$$

Combining Eqs. (2)–(4), we obtain the induction equation as follows:

$$\frac{\partial\mathbf{H}^{+}}{\partial t} = \nabla\wedge\left(\mathbf{V}\wedge\mathbf{H}^{+}\right) + \frac{1}{\xi}\nabla^2\mathbf{H}^{+}, \tag{10}$$

where $\zeta = \sigma\mu_e$ is the magnetic diffusively, σ is the electrical conductivity, μ_e is magnetic permeability ρ_{nf} is the effective density of the incompressible nanofluid, $(\rho c)_{nf}$ is the heat capacity of the nanofluid, $(\rho c)_p$ gives effective heat capacity of the nanoparticle material, k_{nf} implies effective thermal conductivity of nanofluid, g stands for constant of gravity, μ_{nf} is the effective viscosity of the fluid, d/dt gives the material time derivative, and p is the pressure. The appearance for static and wave structures are connected by the subsequent associations:

$$x = X - ct, \quad y = Y, \quad u = U - c, \quad v = V. \tag{11}$$

The dimensionless parameters used in the problem are defined as follows:

$$\bar{p} = \frac{a^2}{\mu_f c\lambda}p, \quad \bar{u} = \frac{\lambda}{ac}u, \quad \bar{v} = \frac{v}{c}, \quad \bar{y} = \frac{y}{\lambda}, \quad \bar{x} = \frac{x}{a}, \quad \bar{t} = \frac{c}{\lambda}t, \quad D\alpha = \frac{k}{a^2},$$
$$Re = \frac{\rho ca}{\mu_f}, \quad \delta = \frac{a}{\lambda}, \quad \bar{\theta} = \frac{T - T_0}{T_0}, \quad \bar{\Phi} = \frac{\Phi}{H_0 a}, \quad \bar{\Psi} = \frac{\Psi}{ca}, \quad R_m = \sigma\mu_e ac,$$
$$\overline{h}_x = \bar{\Phi}_{\bar{x}}, \quad \overline{h}_y = -\bar{\Phi}_{\bar{y}}, \quad G_r = \frac{\rho_f g\alpha a^2}{\mu_f c}\left(T_0\right), \quad S_1 = \frac{H_0}{c}. \tag{12}$$

After using the above non-dimensional parameters and transformation in Eq. (11) employing the assumptions of long wavelength ($\delta\to0$), the dimensionless governing equations (without using bars) for nanofluid in the wave frame take the final form

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{13}$$

$$\frac{dp}{dx} = \frac{\partial^3\Psi}{\partial y^3}\left(\frac{\mu_{nf}}{\mu_f}\right) + Re\,S_1^2\Phi_{yy} + \frac{(\rho\beta)_{nf}}{(\rho\beta)_f}G_r\theta, \tag{14}$$

$$\frac{dp}{dy} = 0, \tag{15}$$

Please cite this article as: N. Sher Akbar, et al., Journal of Magnetism and Magnetic Materials (2015), http://dx.doi.org/10.1016/j.jmmm.2014.12.087