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Model and comparative study for peristaltic transport of water based nanofluids

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ABSTRACT

With every passing day the nanofluids are proving more and more useful in several industrial and biomedical processes. Such utility of nanofluids grasped attention of the researchers from all over the world. At present, several theoretical models are available to predict the effective thermal conductivity of nanofluids. On the other hand it still remains to examine the effects of different thermal conductivity models on the outcomes of the analysis. Mixed convective peristaltic transport of water based nanofluids with viscous dissipation and heat generation/absorption is examined here using two different models of the effective thermal conductivity of nanofluids. Analysis is performed using the Titanium oxide or titania (TiO_2), Aluminum oxide or Alumina (Al_2O_3), Copper oxide (CuO), Copper (Cu) and Silver (Ag) nanoparticles. Water is treated as the base fluid. The two cases of Maxwell's and Hamilton–Crosser's thermal conductivity models are used in the analysis. Numerical solutions for the axial velocity, temperature and heat transfer rate at the boundary are obtained and analyzed. Results show that for higher nanoparticle volume fraction and for nanoparticles with higher thermal conductivity the gap between the results predicted by the Hamilton–Crosser's and the Maxwell's model widens.

1. Introduction

Heat transfer plays a key role in countless industrial and engineering processes as energy input in several complex systems or in a form of energy output produced by the system itself, which needs to be removed by the cooling systems. Usually the heat transfer takes place through flow of appropriate heat transfer fluids i.e. air, water, mineral oil etc. Low thermal conductivities of such fluids proved to be one major constraint in their use as heat transfer fluids. It is well established now that the addition of nano-meter sized particles enhances the thermal conductivity of conventional heat transfer fluids. The mixture obtained by adding nanoparticles to the base fluids is known as nanofluid, a term introduced by Choi [1]. Commonly used nanoparticles are metallic oxides (CuO, TiO_2, $Al2O_3$, ZnO), metals (Cu, Ag, and Au), nitride/carbide ceramics (AlN, SiN, SiC, TiC), single/multi-walled CNTs and composite materials such as alloyed nanoparticles Al70Cu30. Water, ethylene glycol, and oil are generally used as base fluids. Nanofluids find extensive applications in modern heating and cooling systems, in solar collector, evacuated solar collectors, photovoltaic thermal systems, thermal energy storage, solar thermoelectric devices, solar cells, biomedical engineering, detection of radiation, modern drug delivery system etc.

Subject to such wide utility of nanofluids, several investigations analyzing different aspects of nanofluids are made in the near past, some of which can be seen through refs. [2–10].

Recent developments in biomedical engineering have increased the efficiency of drug delivery systems. Colloidal drug delivery systems have been established in order to advance the efficiency and the specificity of drug action. The unique characteristics of nanoparticles interact with complex cellular functions in new ways. Peristalsis of nanofluids is of considerable importance in biomedical engineering particularly in modern drug delivery systems, in hyperthermia and cryosurgery as means to destroy the undesired tissues in cancer therapy. Despite its utility and applications, not much has been said about the peristalsis of nanofluids. Some of the available studies analyzing the peristaltic transport of nanofluids can be seen through refs. [13–15]. In these studies the authors have used the Bongiorno's model taking into account the thermophoresis and Brownian motion effects. This model does not deal with the effective density/thermal conductivity/viscosity of the nanofluid. Yet fewer studies discuss the peristalsis of nanofluid using the phase flow consideration (see refs. [16–19]).

Mixed convective peristaltic transport of water based nanofluids is studied here. Analysis is performed using the Hamilton–Crosser's model for thermal conductivity of nanofluids [12]. This model has an advantage over the Maxwell's thermal conductivity model [11] as it takes into account the shape of the nanoparticles in the flow analysis. The

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basic aim of this study is to examine the peristalsis of water based nanofluids using both the Maxwell's and Hamilton–Crosser's thermal conductivity models. The viscous dissipation and heat generation/absorption are also taken into account. Problem is formulated using the long wavelength and low Reynolds number approximations. Numerical solutions are computed for the velocity, temperature and heat transfer rates at the boundary. Comparison between the results obtained by the two thermal conductivity models is also presented. Key findings of present analysis are summarized at the end.

2. Formulation

We consider an incompressible nanofluid flowing through a channel of width $2d$. The nanofluid is composed of nanoparticles and water. Different nanoparticles namely Titanium oxide or titania (TiO_2), Aluminum oxide or Alumina (Al_2O_3), Copper oxide (CuO), Copper and Silver are used for the analysis. Study is performed using the two thermal conductivity models namely the Maxwell's model for thermal conductivity of nanofluids given by [11]:

$$\frac{K_{eff}}{K_f}=\frac{K_p+2K_f-2\phi(K_f-K_p)}{K_p+2K_f+\phi(K_f-K_p)}. \tag{1}$$

The Hamilton–Crosser's (H–C) model of thermal conductivity of nanofluids is [12]:

$$\frac{K_{eff}}{K_f}=\frac{K_p+(n-1)K_f-(n-1)\phi(K_f-K_p)}{K_p+(n-1)K_f+\phi(K_f-K_p)}. \tag{2}$$

Here K_{eff} denotes the effective thermal conductivity of the nanofluid, K_f the thermal conductivity of the continuous phase (i.e. water in this case), K_p the thermal conductivity of the discontinuous phase (i.e. nanoparticles) and ϕ the nanoparticle volume fraction. In the Hamilton–Crosser's model n denotes the shape factor of nanoparticles given by $3/\Psi$ where Ψ is the sphericity of the nanoparticles and depends on the shape of the nanoparticles. For spherical nanoparticles $\Psi=1$ or $n=3$. In this case the H–C model reduces to the Maxwell's model. For cylindrical nanoparticles $\Psi=0.5$ or $n=6$. The prime aim throughout this analysis will remain to analyze the impact of these two thermal conductivity models on the peristaltic transport of water based nanofluids and to investigate variations in the results brought by the two models. The channel walls are maintained at a constant temperature T_0. Coordinate system is chosen in a way that the $\overline{X}$-axis lies along the length of the channel and the $\overline{Y}$-axis lies normal to the $\overline{X}$-axis. Flow within the channel is induced due to the propagation of sinusoidal waves traveling at the channel walls with constant speed c. The wavelength and the amplitude of these waves are denoted by λ and a_1 respectively. Hence the geometry of peristaltic walls is given by expression [15,16]

$$\pm\overline{H}(\overline{X},\overline{t})=\pm d\pm a_1\cos\frac{2\pi}{\lambda}(\overline{X}-c\overline{t}). \tag{3}$$

Here $+$ and $-$ signs denote the walls in the positive and negative $\overline{Y}$ directions respectively. If $\overline{P}(\overline{X},\overline{Y},\overline{t})$ denotes the pressure, $\overline{U}(\overline{X},\overline{Y},\overline{t})$ and $\overline{V}(\overline{X},\overline{Y},\overline{t})$ the $\overline{X}$ and $\overline{Y}$ components of velocity then the laws of conservation of mass and linear momentum taking into account the mixed convection, viscous dissipation and heat generation/absorption yield

$$\frac{\partial\overline{U}}{\partial\overline{X}}+\frac{\partial\overline{V}}{\partial\overline{Y}}=0, \tag{4}$$

$$\rho_{eff}\left(\frac{\partial}{\partial\overline{t}}+\overline{U}\frac{\partial}{\partial\overline{X}}+\overline{V}\frac{\partial}{\partial\overline{Y}}\right)\overline{U}=-\frac{\partial\overline{P}}{\partial\overline{X}}+\mu_{eff}\left(\frac{\partial^2\overline{U}}{\partial\overline{X}^2}+\frac{\partial^2\overline{U}}{\partial\overline{Y}^2}\right)+g(\rho\beta)_{eff}(T-T_0), \tag{5}$$

$$\rho_{eff}\left(\frac{\partial}{\partial\overline{t}}+\overline{U}\frac{\partial}{\partial\overline{X}}+\overline{V}\frac{\partial}{\partial\overline{Y}}\right)\overline{V}=-\frac{\partial\overline{P}}{\partial\overline{Y}}+\mu_{eff}\left(\frac{\partial^2\overline{V}}{\partial\overline{X}^2}+\frac{\partial^2\overline{V}}{\partial\overline{Y}^2}\right), \tag{6}$$

$$(\rho C)_{eff}\left(\frac{\partial}{\partial\overline{t}}+\overline{U}\frac{\partial}{\partial\overline{X}}+\overline{V}\frac{\partial}{\partial\overline{Y}}\right)T=K_{eff}\left(\frac{\partial^2 T}{\partial\overline{X}^2}+\frac{\partial^2 T}{\partial\overline{Y}^2}\right)+\Phi$$
$$+\mu_{eff}\left[2\left(\left(\frac{\partial\overline{U}}{\partial\overline{X}}\right)^2+\left(\frac{\partial\overline{V}}{\partial\overline{Y}}\right)^2\right)+\left(\frac{\partial\overline{U}}{\partial\overline{Y}}+\frac{\partial\overline{V}}{\partial\overline{X}}\right)^2\right]. \tag{7}$$

In the above equations g denotes the acceleration due to gravity and Φ the dimensional heat generation/absorption parameter. The effective density ρ_{eff}, effective viscosity μ_{eff}, effective heat capacity $(\rho C)_{eff}$ and effective thermal expansion $(\rho\beta)_{eff}$ of the nanofluid for the two phase model are given as follows [4,16–18]:

$$\rho_{eff}=(1-\phi)\rho_f+\phi\rho_p,\ \ (\rho C)_{eff}=(1-\phi)(\rho C)_f+\phi(\rho C)_p,$$
$$(\rho\beta)_{eff}=(1-\phi)\rho_f\beta_f+\phi\rho_p\beta_p,\ \mu_{eff}=\frac{\mu_f}{(1-\phi)^{2.5}}, \tag{8}$$

in which ρ, C, β and μ are the density, specific heat, thermal expansion coefficient and viscosity, respectively. The subscripts p and f denote the nanoparticles and fluid phase respectively. Numerical values of the thermo-physical properties of water and nanoparticles are given through Table 1 [4].

Since the flow in channel is symmetric therefore the analysis is performed only for the upper half of the channel. The transformations between fixed and moving frames are [17,18]

$$\overline{x}=\overline{X}-c\overline{t},\ \overline{y}=\overline{Y},\ \overline{u}(\overline{x},\overline{y})=\overline{U}(\overline{X},\overline{Y},\overline{t})-c,$$
$$\overline{v}(\overline{x},\overline{y})=\overline{V}(\overline{X},\overline{Y},\overline{t}),\ \overline{p}(\overline{x},\overline{y})=\overline{P}(\overline{X},\overline{Y},\overline{t}), \tag{9}$$

where the lower case letters denote the quantities in the moving frame. Making use of the abovementioned transformations into Eqs. (4)–(7) we have

$$\frac{\partial\overline{u}}{\partial\overline{x}}+\frac{\partial\overline{v}}{\partial\overline{y}}=0, \tag{10}$$

$$\left((1-\phi)\rho_f+\phi\rho_p\right)\left((\overline{u}+c)\frac{\partial}{\partial\overline{x}}+\overline{v}\frac{\partial}{\partial\overline{y}}\right)(\overline{u}+c)$$
$$=-\frac{\partial\overline{p}}{\partial\overline{x}}+\frac{\mu_f}{(1-\phi)^{2.5}}\left(\frac{\partial^2\overline{u}}{\partial\overline{x}^2}+\frac{\partial^2\overline{u}}{\partial\overline{y}^2}\right)+g\left((1-\phi)\rho_f\beta_f+\phi\rho_p\beta_p\right)(T-T_0), \tag{11}$$

$$\left((1-\phi)\rho_f+\phi\rho_p\right)\left((\overline{u}+c)\frac{\partial}{\partial\overline{x}}+\overline{v}\frac{\partial}{\partial\overline{y}}\right)\overline{v}=-\frac{\partial\overline{p}}{\partial\overline{y}}+\frac{\mu_f}{(1-\phi)^{2.5}}\left(\frac{\partial^2\overline{v}}{\partial\overline{x}^2}+\frac{\partial^2\overline{v}}{\partial\overline{y}^2}\right), \tag{12}$$

Table 1
Thermophysical properties of water and nanoparticles.

	ρ (kg m^{-3})	C_p (J kg^{-1} K^{-1})	K (W m^{-1} K^{-1})	$\beta(l/k)\times10^{-6}$
H_2O	997.1	4179	0.613	210
TiO_2	4250	686.2	8.9538	9.0
Al_2O_3	3970	765	40	8.5
CuO	6320	531.8	76.5	18.0
Cu	8933	385	401	16.7
Ag	10,500	235	429	18.9