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Short communication

Hydromagnetic peristaltic transport of copper–water nanofluid with temperature-dependent effective viscosity

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ABSTRACT

The unique chemical, mechanical, and thermodynamic properties of nanofluids make them a subject of great interest for scientists from all domains. Such fluids are of particular significance in biomedical engineering owing to their vast and novel applications in modern drug delivery systems; for example, mixed convective peristaltic flow of water-based nanofluids under the influence of an externally applied magnetic field is of particular significance. Hence, a lot of research has focused on peristalsis in the presence of velocity and thermal slip effects. An empirical relation for the effective viscosity of the nanofluid is proposed here for the first time. The viscosity of the nanofluid varies with temperature and nanoparticle volume fraction. Numerical simulation of the resulting nonlinear system of equations is presented for different quantities of interest. The results indicate that the maximum velocity and temperature of the copper–water nanofluid increase for larger variable viscosity parameter. The pressure gradient in the wider part of the channel is also found to increase as a function of the variable viscosity parameter. The variable viscosity parameter also influences the size of the trapped bolus. An increase in the nanoparticle volume fraction reduces the reflux phenomenon in a peristaltic flow.

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Introduction

Motivated researchers across the globe have shown a keen interest in nanofluid mechanics over the past couple of decades. This is mainly because of the unique properties of nanofluids such as their chemical properties (e.g., colloids, nanoscale catalysts, nucleation phenomena, electrochemical reactivity, usefulness in nanoscale mass transport), mechanical properties (e.g., enhanced yield strength, superplasticity), magnetic, and thermal properties. Such remarkable properties make nanofluids very useful in modern cooling systems in the information technology and automobile industries, domestic and industrial cooling, solar energy collectors, energy storage systems, and in biomedical engineering. One of the major advantages of nanofluids is their role in the enhancement of thermal conductivity. Metallic nanoparticles with high thermal conductivity that are suspended in the base fluid with a low thermal conductivity remarkably increase the thermal conductivity of the base fluid. Several investigators have developed many models to predict the increase in the thermal conductivity of the base fluid after the addition of different types of nanoparticles. Many experimental investigations have also been performed for this purpose and the outcomes have been compared with the results predicted by the analytical models. However, further research is still required to develop a sophisticated theory to predict the thermal conductivity of nanofluids. Some empirical correlations are available to compute the effective thermal conductivity of two-phase mixtures. Maxwell’s study is the keystone in this regard (Maxwell, 1904). It analyzes the effective thermal conductivity of a two-phase heterogeneous mixture consisting of continuous and discontinuous phases. Spherical particles were used for the discontinuous phase. Hamilton and Crosser (1962) extended the work of Maxwell for non-spherical particles. These two models are largely used for the analysis of nanofluid flow to predict the thermal conductivity of nanofluids. Other models that can be used to predict the thermal conductivity of nanofluids have also been reported (Murshed, Leong, & Yang, 2005; Eastman, Phillpot, Choi, & Keblinski, 2004). Brinkman’s viscosity model (Brinkman, 1952) and Maı¨ga’s model (Maïga, Nguyen, Galanis, & Roy, 2004) are used to predict the effective viscosity of nanofluids. Although two-phase flow has been a subject of interest

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for scientists since Maxwell (1904), the term nanofluid was proposed for the first time by Choi (1995). In 2003, Khanafer, Vafai, and Lightstone (2003) studied the buoyancy-driven heat transfer enhancement in a two dimensional enclosure utilizing nanofluids. Buongiorno (2006) showed that thermophoresis and Brownian motion effects play a central role in the mechanical analysis of nanofluids. Turkyilmazoglu (2012) obtained exact analytical solutions for heat and mass transfer in magnetohydrodynamic (MHD) slip flow of nanofluids. Turkyilmazoglu and Pop (2013) studied heat and mass transfer effects in an unsteady natural convection flow of some nanofluids past a vertical infinite flat plate with radiation. The analysis of nanofluid flow owing to a rotating disk with heat transfer was performed by Turkyilmazoglu (2014). Sheikholeslami, Gorji-Bandpy, Ganji, and Soleimani (2014) examined the heat flux boundary condition for a nanofluid-filled enclosure in the presence of a magnetic field. Sheikholeslami and Ganji (2015) studied the flow of a nanofluid between parallel plates with heat transfer and Brownian motion. In their study the authors used the differential transform method (DTM) for the solution. The behavior of a nanofluid in a cubic cavity under the influence of an external applied magnetic field is studied by Sheikholeslami, Bandpy, and Ashorynejad (2015). In their study the authors used the lattice Boltzmann method for numerical simulations. Abbasi, Shehzad, Hayat, Alsaedi, and Obid (2015) examined the influence of heat and mass flux conditions in hydromagnetic flow of a Jeffrey nanofluid. Recently, Haq, Nadeem, Khan, and Akbar (2015) investigated the radiation and slip effects on MHD stagnation point flow of nanofluids over a stretching sheet. In another study Haq, Nadeem, Khan, and Noor (2015) studied the convective heat transfer in MHD slip flow over a stretching surface in the presence of carbon nanotubes.

Peristaltic transport of nanofluids is of central importance in the modern drug delivery systems. Such systems make use of an external magnetic field to guide the nanoparticle-based drugs up the flow stream to the tumor site. Hyperthermia and cryosurgery are two mechanisms normally used to kill the underside tissues during cancer therapy. Traditional anticancer agents are unable to breach into the damaged zones as they work by ceasing cell division and are not effective at treating tumors efficiently. Therefore, the use of magnetic nanoparticles as drug delivering agents under the influence of an external magnetic field is an excellent replacement of traditional cancer therapy methods. There is no doubt that drug delivery systems based on their simplicity, ease of execution, and ability to modify their properties for specific biological applications have received a lot of attention (Mody et al., 2014). In that regard, the analysis of peristaltic transport of nanofluids is exceptionally important and has received a lot of attention (Abbasi, Hayat, & Ahmad, 2015; Abbasi, Hayat, & Ahmad, 2015; Abbasi, Hayat, & Ahmad, 2015; Abbasi, Hayat, & Alsaedi, 2015). Our main objective here is to gain further understanding of this regime by investigating mixed convective peristalsis of copper–water nanofluids under the influence of an externally applied magnetic field. Hamilton–Crosser's (H–C) thermal conductivity model is used for the analysis (Hamilton & Crosser, 1962). A new model for the effective viscosity of a nanofluid is proposed by combining Brinkman's viscosity model (Brinkman, 1952) and the exponential model for temperature dependent viscosity. The relevant problems are formulated in the presence of Joule heating and viscous dissipation. The resulting nonlinear systems are solved numerically. Graphical analysis of the obtained results is performed in detail.

Mathematical modeling

Consider the flow of an incompressible nanofluid in a two-dimensional symmetric channel of width $2d$. The nanofluid comprises copper nanoparticles suspended in water. The nanoparticles and the water are assumed to be in thermal equilibrium. The fluid is conducting through a magnetic field of strength B_0 in the transverse direction, i.e., normal to the channel walls. The magnetic Reynolds number is assumed to be small. Thus the induced magnetic field is ignored. In addition, mixed convection, joule heating, and viscous dissipation effects are present. The effective density ρ_{eff}, effective heat capacity $(\rho C)_{\text{eff}}$, effective thermal expansion $\left(\rho\beta\right)_{\text{eff}}$, and effective electric conductivity (σ_{eff}) of the copper–water nanofluid are assumed to be of the following form (Abbasi, Hayat, & Ahmad, 2015a, 2015b, 2015c; Abbasi, Hayat, & Alsaedi, 2015d):

Table 1
Numerical values of physical properties of nanoparticles.

Phase	ρ (kg/m^3)	K (W/m K)	C (J/kg K)	β (1/k) $\times 10^{-6}$	σ (S/m)
Water	997.1	0.613	4179	210	0.05
Copper (Cu)	8933	400	385	16.65	5.96×10^{7}

$$\rho_{\text{eff}}=(1-\varphi)\rho_{\text{f}}+\varphi\rho_{\text{p}},\quad (\rho C)_{\text{eff}}=(1-\varphi)(\rho C)_{\text{f}}+\varphi(\rho C)_{\text{p}},$$
$$\left(\rho\beta\right)_{\text{eff}}=(1-\varphi)\rho_{\text{f}}\beta_{\text{f}}+\varphi\rho_{\text{p}}\beta_{\text{p}},\quad \frac{\sigma_{\text{eff}}}{\sigma_{\text{f}}}=1+\frac{3(\frac{\sigma_{\text{p}}}{\sigma_{\text{f}}}-1)\varphi}{(\frac{\sigma_{\text{p}}}{\sigma_{\text{f}}}+2)-(\frac{\sigma_{\text{p}}}{\sigma_{\text{f}}}-1)\varphi}. \tag{1}$$

Here, ρ, C, β, σ, and φ are the density, specific heat, thermal expansion coefficient, electric conductivity, and nanoparticle volume fraction, respectively. The subscripts p and f are used to indicate the nanoparticle and fluid phases, respectively. Numerical values of physical properties are given in Table 1. The H–C model for the effective thermal conductivity (K_{eff}) of nanofluids is used in the present analysis (Hamilton & Crosser, 1962). Hence the expression of effective thermal conductivity of nanofluids is given by

$$\frac{K_{\text{eff}}}{K_{\text{f}}}=\frac{K_{\text{p}}+(n-1)K_{\text{f}}-(n-1)\varphi(K_{\text{f}}-K_{\text{p}})}{K_{\text{p}}+(n-1)K_{\text{f}}+\varphi(K_{\text{f}}-K_{\text{p}})}, \tag{2}$$

where K is the thermal conductivity. In this model n denotes the shape factor of nanoparticles given by $3/\Psi$, where Ψ is the sphericity of the nanoparticles and it depends on the shape of the nanoparticles. For spherical nanoparticles $\Psi=1$ or $n=3$. For cylindrical nanoparticles $\Psi=0.5$ or $n=6$. For the analysis in this study we assume that the nanoparticles have a cylindrical shape, i.e., $n=6$. The effective viscosity of the nanofluid is predicted by combining Brinkman's model for the viscosity of two phase flow (Brinkman, 1952) with the exponential model for the temperature dependence of viscosity. Thus, Brinkman's viscosity model in mathematical form yields

$$\mu_{\text{eff}}=\frac{\mu_{\text{B}}}{(1-\varphi)^{2.5}}, \tag{3}$$

where μ_{B} is the viscosity of the base fluid. We further assume that the viscosity of the base fluid varies with temperature according to the following relation:

$$\mu_{\text{B}}=\mu_0\left(1-\alpha_1\left(T-T_0\right)\right). \tag{4}$$

Here μ_0 is the viscosity of water at a constant temperature, α_1 («1) is the dimensional variable viscosity parameter, T is the temperature of the fluid, and T_0 is the ambient temperature (constant wall temperature in this case). From Eqs. (3) and (4) the effective viscosity of the nanofluid is reduced as follows:

$$\mu_{\text{eff}}=\frac{\mu_0\left(1-\alpha_1\left(T-T_0\right)\right)}{(1-\varphi)^{2.5}}. \tag{5}$$

We note from the above equation that Brinkman's viscosity model (i.e., the effective viscosity independent of temperature) can be recovered for $\alpha_1=0$. The viscosity of the fluid independent of the

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