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Entropy generation analysis for peristaltic flow of nanoparticles in a rotating frame

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ABSTRACT

The present article is intended to analyze the effect of entropy generation on peristaltic flow of nanoparticles in a rotating frame. The flow is influenced by an external magnetic field. Viscous dissipation and thermal radiation effects are considered for modeling energy equation. The nonlinearity of resulting problem is simplified by adopting lubrication approach. Exact solutions for streamlines, velocity and temperature are calculated. Effective heat transfer is also studied via graphs. Moreover, It is noticed that temperature decays for larger radiation. An increase in internal heat generation enhances the temperature. Entropy generation N_S is an increasing function of radiation.

1. Introduction

One of the most important phenomena that is encountered in engineering and industrial processes is heat transfer. In many industrial facilities heat must be efficiently managed by adding, removing or moving into the different sectors. For this purpose, conventional heat transfer fluids like water, ethylene glycol (EG), pumping oil, etc. have shown poor performance due to their low thermal conductivity. Hence highly efficient heat transfer fluid development is the most important priority of the scientists and engineers. Due to this fact nanoscience and nanotechnology has introduced the new type of liquids termed as nanofluid. It can be prepared by dispersing nanostructures of size ranging between 1 and 100 nm in conventional base liquid. Nanoparticles could be metallic/intermetallic compounds (like Ag, Cu, Ni, Fe, etc.), ceramic compounds such as oxides, carbides and sulfides. Al_2O_3, Fe_3O_4, CuO, ZnO, mesoporous SiO_2, etc. are some nanostructured ceramic materials available in literature. Carbon based compounds, such as carbon nanotubes, graphene, graphene oxide, etc. can also be used as nanoparticles. Nanofluids have wide range of application in biomedical, lubrication, surface coating and petroleum industry. Experimental studies have shown that some NFs are formulated and used in enhanced oil recovery (EOR) process [1,2], wettability alternation, anticorrosive coatings and drilling technology [3]. Dispersion of nanoparticles as MoS_2, TiO_2 and CuO, in conventional lubrication oil have shown enhancement in friction reduction [4]. Other applications include surface coatings [5], environmental remediation [6], inkjet printing [7] and as fuel additives [8]. Recent developments in nanofluid are mentioned in the Refs. [9–15].

Transport of various Newtonian and non-Newtonian fluids from region of lower pressure to a high pressure region is the result peristalsis. It is the naturally inherited mechanism of various biological systems. The content within the hollow muscular structures is propelled and mixed by the successive contraction and relaxation of muscular fibers. Most of the biological fluids such as urine in the ureter, lymph transport in lymphatic vessels, chyme in gastrointestinal tract, ovum in the fallopian tube and blood pump in heart-lung machine, etc. are transported by the mechanism of peristalsis. After the seminal work of Latham [16], analysis of peristalsis in laboratory frame of reference was done by Fung and Yih [17] whereas Shapiro et al. [18] presented the study using wave frame of reference. The magnetohydrodynamic (MHD) peristaltic flow in a channel is of great interest while dealing with the problems involving movement of a conductive physiological fluids e.g. the blood. Being magnetic in nature, blood is very helpful in modern drug delivery system. These systems in the presence of external magnetic field guide the drug containing nanoparticles to the tumor site. Hyperthermia and cryosurgery are the main mechanisms used for the destruction of undesired tissues in cancer ther-

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apy. Traditional anticancer agents cease the division of cells which is not as efficient as modern processes. Therefore involvement of nanoparticles in modern drug delivery systems under the effect of externally applied magnetic field is a valuable replacement of traditional cancer therapy methods. Due to such important properties, peristaltic flow of nanofluid has received enormous attention (see Refs. [19–30]).

The process of heat transfer and fluid flow pervades in all aspects of life. Interest of researchers and scientists in heat transfer processes is especially in biological fluid flows involving transport of physiological fluid is growing fast. In connection with peristalsis heat transfer plays vital role in oxygenation and hemodialysis (see Refs. [31–39]). Recently, heat transfer effects are presented with the consideration of entropy generation. Bejan [40,41] was the first to perform the analysis of entropy generation and found various applications such as two phase flows [42], MHD pumps and electric generators [43]. Various factors like viscosity, chemical reactions, frictional forces, etc. cause energy loss within the thermodynamical system resulting in entropy generation. To improve the working of many thermal engineering devices and systems, minimization of entropy generation is achieved by including electronic cooling designs, chemical vapor deposition instruments and solar collectors. Presence of temperature gradient involves some irreversibility in almost all thermal processes i.e. effecting efficiency of the system and reduce the quality of energy. The current researches in thermal engineering have shown that the second law of thermodynamics is more efficient in optimizing the system when compared with first law since it does not determine the variations in energy and only manipulates the accounting of energy. Investigators have carried out the irreversibility analysis of various systems and proved that entropy production analysis is helpful in determining the efficiency of system [44]. Few recent researches in connection with peristalsis are mentioned in Refs. [45–48]. Heat transfer through thermal radiation has influence in many industrial processes and technological devices. Rocket propulsion [49], solar collector rendering [50], combustion systems [51], plume dynamics [52] and materials processing [53] are main areas where heat transfer through thermal radiation is prominent. Recent developments in analytical and computational tools have directed the attention towards thermal convection flows with significant radiative flux. The rate of energy transfer between two points in numerous conductive and convective processes strongly depend on temperature difference at the location. However, the transfer rate of energy due to thermal radiation between two bodies is dependent upon the absolute temperature difference. It is well established that the importance of radiation is intensified when the absolute temperature is very high. Some studies on peristalsis involving thermal radiation effects can be seen through Refs. [54–60].

Many cosmic and geophysical flows are based on the phenomenon of rotation. Rotation helps in studying and understanding the behavior of ocean circulation and galaxies formation. Rotational diffusion plays vital role in nanoparticle orientation in fluid system [61–63]. Rotation also helps in the measurement of the energies of transitions between quantized rotational states of molecules in the gas phase (rotational spectroscopy) [64]. There is scarce literature when both channel and fluid are in rigid body rotation [65–68]. Moreover, rotational flows generate heat due to an increase in frictional forces. Therefore, studying entropy generation in rotating system is of great importance. The present study is carried out to analyze the thermodynamic irreversibility in MHD nanofluid. Both fluid and channel are in rigid body rotation. In addition, channel walls are taken to be of compliant nature. Energy equation is modeled in the presence of thermal radiation. Nonlinear system is simplified via lubrication approach. Exact solution is calculated for the velocities (u, v) and temperature θ. Influence of pertinent parameters on entropy generation N_S and Bejan number Be is also discussed.

2. Modeling

The peristaltic flow of nanofluid comprising of nanoparticles (Al_2O_3 and CuO) in a symmetric channel of width 2d is studied. Water is used as a base fluid. Both the fluid and nanoparticles are in thermodynamical equilibrium. Thermophysical properties of nanofluid are mentioned in Table 1. A magnetic field of strength B_0 in normal direction to flow is applied. Coordinates are selected in such a manner that x-axis is along the flow direction and z-axis is at right angle to it. The channel is rotating about z-axis with angular velocity Ω. Wall properties make the channel walls flexible. The fluid motion is caused by sinusoidal waves along the channel walls (see Fig. 1). Therefore the wall geometry can be expressed mathematically as

$$z = \pm\eta(x,t) = \pm\left[d + a\sin\frac{2\pi}{\lambda}(x - ct)\right], \tag{1}$$

where a stands for amplitude, λ wavelength, c wave speed and $t$the time. Here $+\eta$ and $-\eta$ are the upper and lower position of channel boundaries respectively. Velocity field for the considered flow analysis is taken in the form $\mathbf{V} = [u(x,z,t), v(x,z,t), w(x,z,t)]$.

The heat transfer analysis of nanofluid with considered nanoparticles is carried out by taking temperature T_1 and T_0 at the upper and lower walls respectively. Viscous dissipation and radiation effects are also employed in energy equation. The radiative heat flux q_r is defined as [13]:

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{\partial T^4}{\partial z}, \tag{2}$$

where σ^* denotes the Stefan-Boltzman constant and k^* is the Rosseland's mean absorption coefficient. Temperature difference within the flow field is considered small which allows the expansion of T^4 as linear function of T. Hence expanding Taylors series of T^4 about T_m and ignoring higher-order terms we can write q_r as

$$T^4 \approxeq 4T_m^3 T - 3T_m^4. \tag{3}$$

The Maxwell-Garnet model for effective thermal conductivity (K_{eff}) used in the present flow problem is defined as [31]:

$$\frac{K_{eff}}{K_f} = \frac{K_p + 2K_f - 2\phi(K_f - K_p)}{K_p + 2K_f + \phi(K_f - K_p)}. \tag{4}$$

The effective density (ρ_{eff}), effective heat capacity $(\rho C)_{eff}$ and effective electric conductivity (σ_{eff}) of considered nanoparticles for two phase flow model is [9,31]:

$$\rho_{eff} = (1-\phi)\rho_f + \phi\rho_p, (\rho C)_{eff} = (1-\phi)(\rho C)_f + \phi(\rho C)_p,$$
$$\frac{\sigma_{eff}}{\sigma_f} = 1 + \frac{3\left(\frac{\sigma_p}{\sigma_f} - 1\right)\phi}{\left(\frac{\sigma_p}{\sigma_f} + 2\right) - \left(\frac{\sigma_p}{\sigma_f} - 1\right)\phi}. \tag{5}$$

The effective viscosity due Brinkman is mathematically written as [39]:

$$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}}. \tag{6}$$

In the above expressions ρ, C, σ and ϕ define the density, specific heat, electric conductivity and nanoparticle volume fraction, respectively. The subscripts p and f denote the nanoparticle and fluid phases, respectively.

The relevant flow equations are