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Electrothermal transport of nanofluids via peristaltic pumping in a finite micro-channel: *Effects of Joule heating and Helmholtz-Smoluchowski velocity*

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ABSTRACT

The present article studies theoretically the electrokinetic pumping of nanofluids with heat and mass transfer in a micro-channel under peristaltic waves, a topic of some interest in medical nano-scale electro-osmotic devices. The microchannel walls are deformable and transmit periodic waves. The Chakraborty-Roy nanofluid electrokinetic formulation is adopted in which Joule heating effects are incorporated. Soret and Dufour cross-diffusion effects are also considered. Under low Reynolds number (negligible inertial effects), long wavelength and Debye linearization approximations, the governing partial differential equations for mass, momentum, energy and solute concentration conservation are derived with appropriate boundary conditions at the micro-channel walls. The merging model features a number of important thermo-physical, electrical and nanoscale parameter, namely thermal and solutal Grashof numbers, the Helmholtz-Smoluchowski velocity (maximum electro-osmotic velocity) and Joule heating to surface heat flux ratio. Closed-form solutions are derived for the solute concentration, temperature, axial velocity, averaged volumetric flow rate, pressure difference across one wavelength, and stream function distribution in the wave frame. Additionally expressions are presented for the surface shear stress function at the wall (skin friction coefficient), wall heat transfer rate (Nusselt number) and wall solute mass transfer rate (Sherwood number). The influence of selected parameters on these flow variables is studied with the aid of graphs. Bolus formation is also visualized and analyzed in detail.

1. Introduction

Nanoscale engineering has emerged as a substantial development in the 21st century. Such systems can achieve performance that is not possible at the macroscale. Nanotechnology includes nanomaterial developments and an important sub-category in this regard is *nanofluids*. Introduced by Choi [1] these fluids achieve higher thermal conductivities and convective heat transfer coefficients as compared with conventional base fluids (e.g. air and water). Nanofluids are synthesized by suspending nanoparticles which may be metallic/non-metallic and are generically 1–100 nm in dimension, in base fluids and have been deployed in an extensive range of technologies many of which have been reviewed lucidly by Taylor et al. [2]. These include lubrication systems where heat can be dissipated more effectively with nanofluids [3], heat exchangers in solar power plants [4], anti-bacterial agents in biotechnological sterlization [5], nano-bioconvection microbial fuel cells (MFCs) using combined silver nanoparticles and gyrotactic micro-organisms [6], hyperthermia medications [7] and nano-coated drug delivery systems [8]. Although for the first decade most research in nanofluids was focused on laboratory and property-based experimentation, in recent years mathematical modelling has emerged as an important new area. Numerous geometrical systems have been explored and both steady and unsteady flows analyzed. Yadav et al. [9] investigated the Rayleigh-Benard problem for nanofluids, using a linear hydrodynamic stability approach. Basir et al. [10] examined the enrobing hydrodynamics, heat and mass transfer in transient axisymmetric boundary layer flow of bioconvective nanofluids from an extending cylindrical body using Maple software. Zaimi et al. [11] used a homotopy method to study the stagnation flow of nanofluids with bioconvection from a contracting or extending

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two-dimensional sheet. These studies all confirmed the marked influence of nano-particles on Nusselt and Sherwood numbers.

In parallel with the above developments, modern microfluidic systems are also being continuously investigated. In such systems electro-kinetics (or electro-osmosis) plays a significant role. Although first identified over two centuries ago by Reuss [12], electro-osmosis has more recently infiltrated into many sophisticated microscale designs including bio-chip systems for drug delivery, biomedical diagnostics and bio-micro-electro-mechanical-systems (bioMEMS). Electrokinetics involves the dynamics of electrolytes (ionic solutions) and is generated by the imposition of an external electric field in an electrolyte-filled conduit with electric double layers on its wetted surfaces. The microscopic (or smaller) scale of bioMEMS amplifies the effect of the Coulomb electrical forces and this in turn greatly modifies micro-channel transport processes. The multi-physical nature of electrokinetic phenomena also makes this area particularly attractive to interdisciplinary engineering sciences since mathematical models must describe accurately the interplay between electrical, viscous and other body forces (buoyancy, magnetic, rotational) and complex geometric features. Electro-osmotic flow provides enhanced flow control at lower volumetric flow rates compared with conventional pressure-driven flows. Interesting developments in electrokinetic engineering sciences include separation of emulsions in microchannel-membrane systems, valve designs for pharmacological delivery [13] in which the flow rate is regulated by electrical current passing through the membrane, skin iontophoresis systems [14], soap film manipulation [15] with electrohydrodynamic induction and electro-kinetic DNA concentrators [16]. Mathematical studies of electrokinetic transport have featured many analytical and also numerical methods. Dejam et al. [17] studied analytically the shear dispersion a neutral non-reacting chemical species within a channel with porous walls, under the dual effects of pressure-driven and electro-osmotic flow, and computed the dispersion coefficient as a function of the Debye–Hückel parameter, Poiseuille contribution fraction, and Péclet number. Moreau et al. [18] explored both computationally and experimentally the use of electro-osmosis in removing contaminants in geomaterials. Jian et al. [19] employed a Laplace transform method to derive closed-form solutions for time-dependent electro-kinetic viscoelastic flow in a micro-channel, describing the influence of viscosity ratio, density ratio, dielectric constant ratio, relaxation time, interface charge density jump, and interface zeta potential difference on velocity evolution. Liang et al. [20] used a computational flow code to investigate the electro-osmotic flow (EOF) perturbations generated close to a membrane surface within an unobstructed empty membrane channel aimed at elevating wall shear and thereby delaying the onset of fouling for nanofiltration and reverse osmosis processes. Iverson et al. [21] studied analytically the influence of duct aspect ratio and volumetric heat generation and Peclet number on heat transfer in electro-osmotic rectangular ducts with isothermal boundary conditions and vanishing Debye layer thickness. They showed that fully developed Nusselt number is reduced from a maximum for the parallel plate configuration to a minimum for the square duct scenario and furthermore that electro-kinetically generated flow achieves significantly longer thermal entry zones compared with pressure-driven flow. A similar study has been communicated by Broderick et al. [22] but for larger values of electrical double layer thickness. Schit et al. [23] considered the electro-osmotic flow and heat transfer of power-law bio-fluids in a micro-channel with Joule electro-thermal heating effects, with thermal radiation and velocity slip condition. They considered the scenario wherein the channel depth is substantially greater than the thickness of electrical double layer comprising both the Stern and diffuse layers, and showed that increasing Joule heating parameter depresses Nusselt number for both pseudo-plastic and dilatant fluids.

An important possible development in micro-systems is the combination of nanofluids and electro-osmotic flow. The important potential significance of such systems i.e. nano-electro-kinetic devices has been described by Murshed et al. [24]. Dutta [25] has investigated the nanofluidic separation of non-neutral analytes using a pressure-gradient in combination with a counteracting electroosmotic flow field. Safarna et al. [26] studied the influence of an external electrical field on iron-oxide-water nanofluid flow and heat transfer in micro-channels using the finite volume method and the Maxwell-Garnetts (MG) and Brinkman models for thermal conductivity and viscosity. They found that Nusselt number is strongly influenced by Reynolds number and applied voltage. Choi et al. [27] examined the electrokinetic flow of charged nanoparticles in microfluidic aqueous NaCl solution Couette flow, noting for the first time, a strong deviation of the velocity profile from the classical linear Couette flow case. Rokni et al. [28] used numerical shooting quadrature to study electrokinetic and magnetohydrodynamic body force effects on rotating nanofluid flows. They found that there is a strong elevation in Nusselt number with magnetic and electrical field parameters and also Reynolds number and a substantial depression with increasing rotation effect.

Peristaltic pumping is a biological process which efficiently transfers fluids via flexible conduits under progressive waves of contraction or expansion from a zone of lower pressure to higher pressure [29,30]. Peristalsis in living organisms is an involuntary mechanism and features in numerous aspects of physiology including intestinal dynamics, swallowing, blood flow, embryology, etc. However in biomimetic engineered designs, actuators can be deployed to achieve this transport. When combined with electro-osmotics and/or magnetohydrodynamics, very elegant and versatile microscale and nanoscale pumps can be designed, as elucidated by Chang and Yossifon [31], Takamura et al. [32] and Reichmuth et al. [33]. These designs maximize the use of external electrical fields for microfluidic manipulation and enhanced directional control and also capitalize on valveless miniaturized configurations for eliminating tribological wear and leakage. Modern progress in hyperthermia, cryosurgery and laser diagnosis systems have also made heat transfer in electro-osmotic peristaltic pumps of great interest to engineers. Many sophisticated systems in this regard have been manufactured and tested in medicine and excellent works reporting such developments include Berg et al. [34] (two-stage peristaltic micropumps). Analysis of such systems was conducted for thermo-magnetic peristaltic pumps by Tripathi and Bég [35]. Other significant investigations include Mao et al. [36] who reported on the synthesis of a dielectric elastomeric peristaltic micro-pump and Loumes [37] who reported in a novel peristaltic multi-stage impedance pump utilizing a periodic asymmetrical compression on a segment of the transport vessel (elastic tube). Studies of peristaltic nanofluid pumping have also emerged in recent years, inspired by breakthroughs in nanoscale fabrication techniques and the desire to enhance thermal as well as hydrodynamic performance. Hayat et al. [38] considered double-diffusive peristaltic convection in tubes with wall slip and magnetic Joule effects. Abbasi et al. [39] studied rheological nanofluid pumping via peristalsis. Bég and Tripathi [40] considered dual thermal and species buoyancy effects in axisymmetric peristaltic nanofluid transport. Prasad et al. [41] derived analytical solutions for velocity profile, pressure drop, time averaged flux and frictional force in peristaltic flow through inclined tubes, for a range of wave forms, observing that a much larger bolus (trapped fluid zone) is achieved for single sinusoidal waves as compared with multi sinusoidal waves. Further studies