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Transportation of ionic liquids in a porous micro-channel induced by peristaltic wave with Joule heating and wall-slip conditions

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HIGHLIGHTS

- A mathematical model is developed for ionic liquids induced by peristaltic wave.
- Slip velocity and Joule heating effects are employed in a porous medium micro-channel.
- Analytically solved under low Reynolds number and long wave length assumptions.
- Temperature enhances with a rise in the Joule heating parameter and Brinkman number.
- EOF increases the size of the trapping bolus, while decreases with porous permeability.

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ABSTRACT

This article presents a mathematical model for studying peristaltic mechanism of combine pressure and electro-osmotically driven flow of ionic liquids through a micro-channel having electrokinetic effects. The velocity slip and the thermal slip conditions at the channel wall are taken into account for investigating the thermomechanical interactions. The micro-channel is assumed to have porous structure. The governing equations for fluid flow and heat transfer in the electrical double layer (EDL) together with the Poisson-Boltzmann equation are considered. The analytical solutions have been obtained under low Reynolds number and long wave length assumptions. It is also assumed that the channel height is much greater than the thickness of the electrical double layer (EDL). The essential features of electro-osmotically driven flow and associated heat transfer characteristics in a micro-channel are clearly demonstrated by varying dimensionless parameters for velocity profile, temperature profile, pressure distribution, stream function, wall shear stress and the Nusselt number. The pressure drop exhibits a linear dependence on the flow rate. The study reveals that the electro-osmotic parameter has an enhancing effect on the size of the trapping bolus while the reducing effect on porous permeability of the channel. The temperature distribution is significantly influenced by Joule heating parameter and Brinkman number. The study bears the potential applications in biomedical engineering for the development of microfluidic devices in particular microfluidic pump to transport small volume of ionic liquids by maintaining temperature distribution.

1. Introduction

Micro-fluidic devices are growingly becoming an alternative to the conventional flow systems because of their compactness and enormous surface to volume ratio. These micro-scale devices are used for separation and analysis of chemicals and biological samples, micro-electronics, material processing, biotechnology, micro-electro-mechanical systems (MEMS) and heat transfer augmentation (Becker and Gartner, 2000; Nandy et al., 2008; Ehrfeld, 2003; Hadd et al., 1997). Fluid flow in microscale environment has some advantages in comparison to macroscale environment. Fluid flow in a micro-channel is a low Reynolds number flow, because it is proportional to the dimension of the channel, which is small in the case of microfluidic devises. Utilization of electrokinetic body forces in microfluidic design can reorganize various fluid handling applications in order to build flow control elements with non-moving components. In micro-technological devices like lab-on-chip and MEMS, the micro-channel constitute the basic structure. Some producer design their syringe pumps especially for microfluidic applications. The effect of the surface potential on liquid transport across ultrafine capillary slits under an imposed electric field

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Nomenclature

$(\xi\prime, \eta\prime)$	cartesian coordinates [m]
$(u\prime, v\prime)$	velocity components [m/s]
c	wave speed [m/s]
P_r	Prandtl number
Br	Brinkman number
$p\prime$	fluid pressure [Pa]
Re	Reynolds number $(\frac{cd_1\rho}{\mu})$
E_x	electric field [V/m]
F	dimensionless flow rate [m^3/s]
Nu	Nusselt number
m	electroosmotic parameter
k_1	thermal conductivity
k	permeability parameter
c_p	specific heat at constant pressure

Greek symbols

μ	co-efficient of viscosity [Pa.s]
λ	wave length [m]
ζ	zeta potential at the wall
σ	electrical conductivity [S/m]
ρ	density of fluid [kg/m^3]
δ	wave number $(\frac{d}{\lambda})$
θ	dimensionless temperature
β_1	velocity slip parameter at the wall
β	mobility parameter
λ_D	Debye length
ϕ	electric potential distribution
ψ	non-dimensional stream function

was studied by Burgreen and Nakache (1964). Chung et al. (2008) proposed some electro-osmotic microfluidic devices for rapid mixing and low power drug delivery, which are acceptable for autonomous microsystems. They indicated that insulin and hormones are separated by body in a pulsatile manner. An analytic solution for electro-osmotic flow in a cylindrical capillary was presented by Kang et al. (2002) by solving the complete Poisson-Boltzmann equation with arbitrary zeta-potentials. Maynes and Webb (2003) have analyzed the electro-osmotic flow in parallel plate micro-channel as well as in circular microtube with imposed constant wall heat flux and constant boundary conditions. Wang et al. (2014) critically reviewed on the transport properties of ionic liquids including the viscosity, thermal conductivity of heat transfer and diffusion coefficient of mass transfer, wherein they observed a good correlation between those properties of ILs. Sharma and Chakraborty (2008) and Chakraborty (2006) investigated analytical solutions for the extended Gratez problem in combined electro-osmotically and pressure driven micro-channel flow under simultaneous consideration of the effects of stream wise condition, viscous dissipation and Joule heating. Sheikholeslami and Ganji (2016) have examined the Joule heating effects on magnetohydrodynamic nanofluid flow between two parallel vertical permeable sheets via differential transform method. Ellahi et al. (2014) investigated the influence of heat and mass transfer on peristaltic flow in a non-uniform rectangular duct by considering long wavelength and low Reynolds number. Bhatti et al. (2017) analyzed the effects of heat transfer on peristaltically induced motion of small particles under a uniform inclined magnetic field. Their results revealed that the influence of particle volume fraction and magnetic field oppose the fluid velocity. Shit et al. (2016) developed a mathematical model for peristaltic transport of magnetohydrodynamic flow of biofluids through a micro channel with rhythmically contracting and expanding walls under the influence of an applied electric field. Their results depicted that the flow is appreciably influenced by the sufficient strength of externally applied magnetic field and electro-osmotic parameter. Chakraborty (2006) pointed out that in practice, most of the researchers have concentrated only on the combination of pressure driven and electroosmotically driven flow in a microfluidic device. However, peristaltic mechanism can provide faster rate of microfluidic transport and is happens to propel biofluids through the circulatory system of human beings. Interestingly, he has first established the employment of an axial electric field and studied theoretically the rate of microfluidic transport in the peristaltic microtubes.

The transport of ionic liquids in a flexible tube by peristaltic motion as a fundamental physiological process has found many applications in medicine and biology. The peristaltic mechanism mainly involved in urine transport from kidney to bladder, through the ureter, moment of chyme in the gastrointestinal tract, transport of spermatozoa in ductus efferentes of the male reproductive tracts, transport of lymph in the lymphatic vessels and in the vasomotion of the arteries, venules and capillaries. Shit and Ranjit (2016) investigated the peristaltic transport of a couple stress fluid in an asymmetric and non-uniform channel under the effect of an externally applied magnetic field. In the context of the present study, peristaltic mechanism could be useful tool for the design of microfluidic-based lab-on-a-chip devices to analyze blood samples more accurately and quickly. Tripathi and Beg (2014) studied the peristaltic flow of nanofluids through a channel having applications in drug delivery system and heat transfer enhancement using nanoparticles. Shit et al. (2014) have investigated the effect of induced magnetic field on peristaltic transport of a micropolar fluid in the presence of slip velocity. The study puts forward an important observation that the flow is appreciably influenced by the presence of a magnetic field and slip velocity. Shit et al. (2017) also examined the application of Adomian decomposition technique to blood flow through an asymmetric non-uniform channel induced by peristaltic wave in the presence of magnetic field and velocity slip at the wall. Tripathi et al. (2016) examined out the influence of transverse magnetic field on time-dependent peristaltic transport of electrically-conducting fluids with an applied external electric field under induced electric field through a microchannel. Pandey et al. (2011) have investigated the multi-layered peristaltic flow of power-law fluids with different viscosity. Mekheimer (2004) investigated the effect of magnetic field on peristaltic transport of couple stress fluid in a non-uniform two dimensional channel, wherein he reported that the pressure rise for a couple stress is greater than that for a Newtonian fluid and it is smaller for a magnetohydrodynamic fluid than for a fluid without an effect of a magnetic field. Bhatti et al. (2016); Bhatti et al. (2016); Bhatti and Zeeshan (2016) endoscopically analyzed the peristaltic flow of blood obyeing sisko fluid model. Bhatti et al. (2016) also examined the effects of variable magnetic field on peristaltic flow of Jeffrey fluid in a non-uniform rectangular duct having compliant walls, wherein they mentioned the important effects of magnetic field through velocity profiles. Tripathi (2013) have developed analytical as well as computational technique on transient peristaltic heat flow through a finite length porous channel. The combined effects of heat and mass transfer on the magnetohydrodynamics (MHD) peristaltic transport with porous medium and compliant wall have been discussed by Srinivas and Kothandapani (2009). Sheikholeslami (2017); Sheikholeslami (2017); Sheikholeslami