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Steric-effect-induced alteration of thermal transport phenomenon for mixed electroosmotic and pressure driven flows through narrow confinements

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ABSTRACT

The present paper addresses, for the first time, the thermal transport process for mixed electroosmotic and pressure-drive flows of electrolyte solutions, through nanoscopic confinements with step-change in the wall temperature, by going beyond the prevalent simplifying assumption of non-interacting, point charge behaviour of the ions in the electrolyte solution. An attempt is made here to delineate the alterations in the heat transfer characteristics induced by the inclusion of the finite ionic size effect or the 'steric effect', in the electrokinetic framework, which becomes very significant for electro-hydrodynamic flows through narrow-confinements with high surface charge density. Under such situations the finite size of the ions cannot be trivially precluded from the analysis, thereby rendering the point charge assumption erroneous. The distinctive influence of the 'steric' effect of ions on the heat transfer characteristics is numerically investigated by delineating the variations in the local liquid temperature, local Nusselt number and the thermal entrance length for the thermally developing regime. The observed significant influences of the bulk volume fraction of ions, as represented by the steric factor, on the thermal transport phenomenon are physically explained by simultaneously highlighting their intrinsic differences with the effects of other existing parameters, like Joule heating and viscous dissipation. The utilitarian scope of the work lies in the fact that it proposes a more comprehensive methodology for analyzing the heat transfer characteristics in state-of-the-art nanoscale electromechanical devices.

1. Introduction

Applications of micro/nano-scale transport processes spread across the broad spectrum of fields from mechanical, chemical and biochemical engineering, micro-electro-mechanical-systems (MEMS) to material processing, bio-medicine, drug delivery and thermal management of miniaturized electronic devices [1–5]. Initially, attempts were made to implement the conventional and simplistic pressure-driven flow actuation mechanism for triggering liquid flows through micro/nano conduits constituting the micro-scale devices pertinent for the above mentioned applications [6–8]. However, over such reduced length-scales, the pressure-driven actuation methodology was analyzed to have certain inherent disadvantages like, greater power requirement due to frictional losses, restricted control over the flow, and poor configurability with miniaturized devices. The advent of electrically actuated flows, or electrokinetic flows (especially the electroosmotic flow), provided a novel alternative for circumventing these issues related to pressure-driven flows [9–11]. From an application-oriented perspective, the superiority of the electroosmotic flow actuation technique stems from its compact yet simple design requirement, minimized sample dispersion, and efficient reconfigurability with electrical circuitry. However, electroosmotic flows are often associated with uncontrolled heating of thermally labile biological samples. Hence, as an optimum approach, both pressure-driven and electroosmotic flow actuation mechanisms are usually implemented in tandem in majority of the state-of-the-art microfluidic applications.

The global trend towards miniaturization brought into focus various applications, both biological and non-biological in nature like polymerase chain reaction (PCR) for DNA amplification, micro-scale heat exchangers, and cooling of miniaturized electronic devices, which necessitated in-depth understanding of thermal transport processes through micro/nano confinements. In order to address this issue, initially various studies were conducted to delineate the thermally fully-developed heat transfer characteristics of combined pressure-driven and electroosmotic flows through micro-confinements, by simultaneously taking into consideration the effects of volumetric heat generation due to Joule heating and viscous dissipation [12–20]. It is important to note here that due to the reduced length-scale of micro-systems, the role of viscous dissipation in altering the thermal transport phenomenon becomes significant, and hence can no longer be trivially excluded

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Nomenclature

a	activity of the ionic species
a_M	mean electrolytic activity
c_p	specific heat capacity at constant pressure
D	ionic diffusion co-efficient
E_x	externally applied electric field
e	electronic charge
G_1	non-dimensional Joule heating parameter
G_2	non-dimensional viscous dissipation parameter or the Brinkman number
H	half channel height
h	convective heat transfer co-efficient
J	ionic flux density
k	thermal conductivity of the fluid
k_B	Boltzmann constant
Nu	Nusselt number based on half channel height
Nu_{TFD}	thermally fully developed value of the Nusselt number
n	ionic species concentration
n_0	average number of positive or negative ions in the electrolytic solution or the buffer solution
n_r	reference ionic number density
P_x	externally applied pressure gradient
Pe	thermal Peclet number
q''_W	channel wall heat flux
S	volumetric heat generation due to Joule heating
T	local temperature of the electrolyte
T_i	liquid inlet temperature/channel wall temperature in the region upstream of the entrance section
T_W	channel wall temperature
T_M	Bulk mean temperature or the mixing cup temperature
u	combined electroosmotic and pressure-driven flow velocity
$\bar{u}$	non-dimensional flow velocity
u_{HS}	Helmholtz–Smoluchowski velocity
W	Width of the channel
z	valency of the ions in the electrolyte
ν	steric factor
α	thermal diffusivity
ε	permittivity of the medium
ε_0	permittivity of free space
ζ	zeta potential
η	non-dimensional transverse co-ordinate
θ	non-dimensional temperature profile
θ_M	non-dimensional bulk mean temperature
κ	half channel height to Debye length ratio
λ_D	Debye length
μ	viscosity of the electrolyte
ρ	density of the medium
ρ_c	net charge density per unit volume in the diffuse layer
σ	conductivity of the electrolyte
ψ	electrokinetic potential
Ω	relative strengths of pressure-driven and electroosmotic actuations
ω	Debye–Hückel parameter
ξ	non-dimensional axial co-ordinate

from the analysis, as is usually done within the classical macroscale framework [21–24]. Moreover, in order to conclusively comprehend the underlying physics of microscale thermal transport processes, it is imperative to also analyse the heat transfer characteristics in the thermally developing or the entrance regime, as classically addressed in the Graetz problem [25,26] or the extended Graetz problem [27]. In this regard, semi-analytical solutions for the heat transfer problem were evaluated for thermally developing but hydrodynamically fully-developed electroosmotic flows [28,29], and combined pressure-driven and electroosmotic flows [30], by considering isothermal and constant heat flux boundary conditions at the microchannel walls. In these endeavours, the physical problem was modelled by considering an arbitrary uniform liquid temperature at the channel inlet, which greatly compromised the practical feasibility of the analysis. The concerned anomaly stemmed from the fact that the assumption of uniform inlet liquid temperature fails to capture the effects of the internal heat generation sources, like Joule heating and viscous dissipation, on the liquid temperature in the thermal entrance section, while simultaneously considering the flow to be hydrodynamically full-developed throughout the domain. This conceptual problem was circumvented by considering an adiabatic preparation zone for the fluid upstream of the thermal entrance section, which ensured a non-uniform liquid temperature profile at the entrance consistent with the effects of the volumetric heat generation sources [31,32]. In accordance with this approach, the heat transfer characteristics in the thermally developing regime, for mixed electroosmotic and pressure-driven flows, were delineated by considering an adiabatic fluid preparation zone, implemented through a step-change in the wall temperature, and the simultaneous interplay of thermal axial conduction, Joule heating and viscous dissipation [33,34]. It is to be noted here that in majority of the above mentioned works the electrokinetic effects were considered to be restricted to a very small region, in the vicinity of the micro-channel walls, as necessitated by the ‘thin’ electric double layer (EDL) approximation. Under the thin EDL approximation, the details of charge distribution can be neglected for almost over the entire channel cross-section, except for the very small region adjacent to the walls (thin EDL). Hence, this approximation fails to address the electro-hydrodynamics existing in narrow confinements, where the EDL thickness is comparable to the characteristic channel dimensions. Very recently, the influence of ‘thick’ EDL (the scenario in which the ionic charge distribution percolates to majority of the channel cross-section) on the thermally developing heat transfer mechanism for mixed electroosmotic and pressure-driven flows through narrow-slits, with a step-change in the wall temperature, was addressed in a very comprehensive manner [35]. It was further observed that on considering non-trivial EDL effects, the viscous dissipation played a more significant role in altering the heat transfer characteristics, and its effects were intrinsically different from that of Joule heating under the existing physical situation.

It is imperative to mention in the context of above-mentioned developments in the reported literature that so far, in the existing literature pertaining to the thermal transport of combined electroosmotic and pressure-driven flows, the electrokinetic effects, stemming from the development of the EDL, have always been modelled on the basis of the assumption that the dissociated ions of the electrolytic solution behave as non-interacting point charges. However, in case of electro-hydrodynamic flows through nano-scopic fluidic confinements involving the development of high interfacial electrical potential, the simplifying assumption of the point-sized ionic charges leads to anomalous/aphysical description of the ionic distribution near the walls, if one resorts to the classical Boltzmann distribution. This anomaly culminates in a grossly erroneous understanding of the involved transport phenomena, including the thermal transport. Under such physical situations, the conceptual contradictions in the EDL description can