



Assessment of mixing problem on the EOF with thermal effects

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ABSTRACT

A potential of mixing applications on an electroosmotic flow (EOF) with thermal effects is examined. For the thermal conditions, we apply the sinusoidal temperature boundary conditions on the walls. We exemplify two cases: (1) the mixing of laminar flows and (2) Taylor–Aris dispersion model. In the first case, we consider to mix two different samples that flow in parallel along the channel. In addition, by scaling analysis, we qualitatively examined the mixing result. The mixing efficiency is proportional to the temperature difference. Through the Taylor–Aris dispersion model, we found that the temperature gives rise to an increase of the $D_{\text{eff}}(T)$ at the low Peclet number where the diffusion and convection effect coexist.

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1. Introduction

Miniaturization realizes a Lab-On-a-Chip (referred to as LOC) device that integrates many laboratory functions on a single chip of the size of a coin. The LOC has a small channel size less than 1 mm. As the LOC is a reactor, to mix or separate different samples is important. Under the viscous dominant environment, the electroosmosis is an outstanding way to control the flow in microfluidic devices. To control and mix the samples, many researches are performed [1–5]. However, there is not enough researches on thermal effects for mixing or separating the samples.

Most previous researches are the spontaneously thermal phenomena like a joule heating and viscous dissipation [6–10], not further mentioned in this paper. Ross and Locascio [11] first attempted the temperature gradient focusing (TGF) technique by heating and cooling block apparatus in microchannels. In addition, Edwards et al. [12] demonstrated a micro-scale thermal flow-field fractionation (ThFFF) system under the pressure driven (PDF) flow to separate the samples. On the other hand, Nguyen and Wu [13] simply slightly introduced somewhat a potentiality of the thermal energy for the mixing enhancement, not in detail. They exemplified that the use of thermal sensitive fluorescent dyes and thermal bubbles by heating means [14,15]. Actually, through temperature dependent physicochemical properties, Kwak et al. [16]

showed that the thermal effects generate a shear flow and even a wavy flow, so-called the thermally driven electroosmotic Couette flow.

Here, we assess the mixing efficiency in the EOF with thermal effects, viz., the thermally driven electroosmotic Couette flow. Practically, all variables of the electroosmotic mobility ($\eta = \epsilon \zeta / \mu$) are a function of temperature. The diffusion coefficient is also a function of temperature, which is estimated by the Stokes–Einstein model. We apply the spatially induced sinusoidal temperature boundary conditions to generate the wavy flow. Two examples are considered: (a) the mixing model on the laminar flows and (b) Taylor–Aris dispersion model. We take into account the enhancement of the mixing efficiency by thermal effects and the effective diffusion coefficient by varying Peclet numbers and temperature differences.

2. Statement of the problem

To assess the potential of mixing applications in EOF with thermal effects we consider the 2D microchannel with the thermal effects as shown in Fig. 1. First, two different laminar samples flow in parallel while applying the spatially arbitrary thermal boundary. By varying temperature difference, we examine the enhancement of the mixing efficiency at the end of the microchannel. Second, to understand the mass transport mechanism we determine the effective diffusion coefficient as considering the Taylor–Aris dispersion model. We obtain the effective diffusion coefficient by measuring the propagated band thicknesses within the given traveling time.

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Nomenclature

c	concentration of a species
C_p	specific heat capacity [kJ/kg K]
D	diffusion coefficient of species [m^2/s]
\vec{E}	electric field strength (E_x, E_y) [V/m]
e	absolute charge of electron (1.602×10^{-19} C)
F	Faraday constant
h	channel height [m]
k_B	Boltzmann constant (1.381×10^{-23} J/K)
n_0	ionic concentration of electrolyte solution [M]
l	length of the channel [m]
p	pressure [N/m^2]
R_0	mean particle diameter [m]
R	ideal gas constant
t	time [s]
T	temperature [K]
U	thermally driven electroosmotic flow velocity [m/s]
\vec{u}	velocity vector (u, v)
x, y	longitudinal/transverse coordinate
w	characteristic length scale of diffused layer [m]
EDL	electric double layer
EOF	electroosmotic flow
Z	valence

Greek symbols

ρ	density [kg/m^3]
ρ_e	net charge density [Cm^{-3}]
ϵ	permittivity [CV/m]
ϵ_0	vacuum permittivity [CV/m]
η	electroosmotic mobility [m^2/Vs]
ζ	zeta potential [V]
μ	dynamic viscosity [Pas]
ϕ	electric potential [V]
ψ	intrinsic electric potential created in EDL [V]
κ	thermal conductivity [W/mK]
γ	electrical conductivity [$\text{m}^2\text{S}/\text{mol}$]
λ	Debye layer thickness [m]
σ	mixing efficiency [%]
τ	residence time of fluid [s]
∇	($\partial/\partial x, \partial/\partial y$)

Subscripts

I	initial state
∞	complete state
0	reference physical property
L	lower wall of the channel
U	upper wall of the channel
t	$\partial/\partial t$

For this research, the EOF is the uniform flow due to much small electric double layer (referred to as EDL) compared with the channel height, $\lambda/h \ll 1$. The horizontal walls contacting liquid are charged with a zeta potential, ζ . An external electric field $\vec{E} = (E, 0)$ is applied to drive electroosmosis. For the sake of the simplicity, the assumptions to be imposed are: an (1:1) symmetric electrolyte (almost pure water) is only in the channel; the brownian motion of molecules is excluded; in the diffusion mechanism, we assumed that the particles are spherical and the solute size is larger than the molecule of the solution. Under the mild or weak electric field the joule heating can be negligible. And, the viscous dissipation is excluded because this only becomes a significant as the very thin channel (the channel height h less than 10 nm) [8].

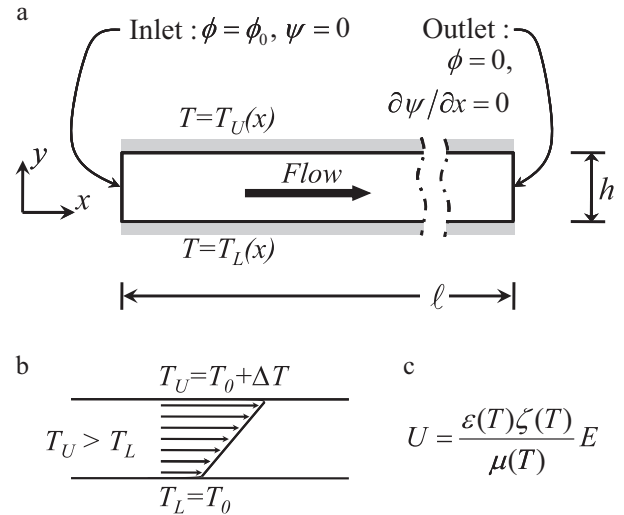


Fig. 1. Schematic of the thermally driven electroosmotic Couette flow in the two-dimensional microchannel where U is a thermally driven electroosmotic Couette flow, h is the channel height, l is the channel length, ΔT is the temperature difference between two walls, and the subscripts L and U denote the lower and the upper plate, respectively. In case of the thin EDL ($\lambda/h \ll 1$) assumption, we could apply the slip boundary conditions at each wall. (a) Geometry and boundary conditions, (b) the cartoon of the thermally driven electroosmotic Couette flow, and (c) the temperature-dependent Helmholtz-Smoluchowski equation.

2.1. Governing equations

To interpret electroosmosis the Gouy–Chapman continuum model is employed. The governing equations are the two dimensional unsteady Navier–Stokes (NS) equations for an incompressible newtonian fluid. Furthermore, the NS equations are coupled with the electric potential, heat and mass transport equations:

$$\nabla \cdot \vec{u} = 0; \quad (1)$$

$$\rho (\vec{u}_t + \vec{u} \cdot \nabla \vec{u}) = -\nabla p - \rho_e \vec{E} + \nabla \cdot (\mu \nabla \vec{u}); \quad (2)$$

$$\rho C_p (T_t + \vec{u} \cdot \nabla T) = \nabla \cdot (\kappa \nabla T); \quad (3)$$

$$(c_t + \vec{u} \cdot \nabla c) = \nabla \cdot (D \nabla c); \quad (4)$$

where $\vec{u} = (u, v)$ is the velocity vector; p , the pressure; ρ_e , the net charge density; T , the absolute temperature; $\vec{E} = (E_x, E_y)$, the external electric potential; ρ , the density of the fluid property; μ , the dynamics viscosity; κ , the thermal conductivity; C_p , the heat capacity; c , the concentration of a species; D , the diffusion coefficient of the species. ∇ is the gradient operator, $\nabla = (\partial/\partial x, \partial/\partial y)$ and the subscript t is $\partial/\partial t$. All temperature-dependent physical properties will be mentioned in Section 2.2 later. The distributions of these electric potentials are governed by the Poisson equation:

$$\nabla \cdot (\epsilon \nabla \Psi) = -\rho_e, \quad (5)$$

where ϵ is the permittivity of electrolyte (assumed as the water) is discussed in Section 2.2 as well. The Boltzmann distribution assumed as follow;

$$\rho_e = -2eZn_0 \sinh \left(\frac{eZ\Psi}{k_B T} \right). \quad (6)$$

where e is the absolute charge of electron (1.602×10^{-19} C), n_0 the ionic concentration of electrolyte solution, k_B the Boltzmann constant (1.381×10^{-23} J/K), Z the ionic valence, and Ψ the intrinsic electric potential created in the EDL. Combining Eqs. (5) and (6), we can obtain the Poisson–Boltzmann equation.

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