



Rheology effects on cross-stream diffusion in a Y-shaped micromixer



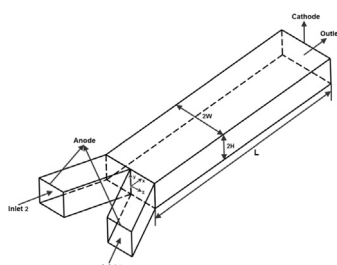
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HIGHLIGHTS

- Rheology effects on cross-stream diffusion in a Y-shaped micromixer are investigated.
- Non-linear rheology may result in significant alteration of species concentration field.
- Non-linear rheology effects are pronounced in the presence of thick EDLs.

GRAPHICAL ABSTRACT



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ABSTRACT

Micromixers are one of the essential components of modern bio-microfluidic devices. Since most bio-fluids are complex and their rheological behavior usually cannot be described by the Newton's law of viscosity, it is vital to take into account the non-linear behavior of the fluids being manipulated in these devices in the pertinent simulations. In this paper, the non-Newtonian rheology effects on mass transport in an electrokinetically driven Y-shaped micromixer of rectangular cross section are being investigated. The fluid rheological behavior is assumed to be efficiently described by the power-law viscosity model. The governing equations are solved in dimensionless form through a finite difference based numerical procedure for non-uniform grid. The results show that the deviations of the fluid rheological behavior from the predictions of the Newton's law of viscosity may result in significant alteration of the species concentration field, especially for thick EDLs. In this respect, a higher value of the flow behavior index gives rise to a thicker diffusion layer in the presence of a purely electroosmotic flow. Whereas the same is observed for a pressure assisted flow, the opposite is right in the presence of an adverse pressure gradient. Moreover, the diffusion layer extent is an increasing function of EDL thickness. The relevant functionality is pronounced by increasing the flow behavior index. In addition, the effect of decreasing both Péclet number and the rectangular geometry aspect ratio is to enhance the mixing efficiency.

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1. Introduction

Major advancements in microfabrication technology in the late 20th century led to the development of various microfluidic devices including lab-on-a-chip (LOC) systems. The lab-on-a-chip devices are microscale laboratories on a chip that can perform biochemical

diagnoses. The main advantages of these devices are ease of use, speed of analysis, low sample and reagent consumption, and high reproducibility due to standardization and automation [1].

With the advent of LOCs, electroosmosis has featured as a predominant mechanism for flow actuation. Electroosmotic micropumps have many advantages over the other types of micropumps. For example, unlike the classical pressure-driven micropumps involving moving components, the electroosmotic pumps have no moving parts and are simpler to be designed and fabricated [2,3]. Moreover, these pumps are bidirectional and

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Nomenclature

A	dimensionless function [Eq. (30)]
c	number concentration [kg m^{-3}]
c_0	inlet concentration [kg m^{-3}]
D	diffusivity [$\text{m}^2 \text{s}^{-1}$]
e	proton charge [C]
E	electric field [V m^{-1}]
E_x	electric field in the axial direction [V m^{-1}]
\mathbf{F}	body force vector [N m^{-3}]
H	half channel height [m]
I_{mix}	mixing index [Eq. (36)]
k	coefficient of discretized equations [Eqs. (32)–(34)]
k_B	Boltzmann constant [J K^{-1}]
L	channel length [m]
m	flow consistency index [Pas^n]
n	flow behavior index
n_0	ion density at neutral conditions [m^{-3}]
p	pressure [Pa]
Pe	Péclet number [$=u_{\text{HS}}/H/D$]
Q	dimensionless function [Eqs. (29)–(31)]
t	time [s]
T	absolute temperature [K]
\mathbf{u}	velocity vector [m s^{-1}]
u_{HS}	Helmholtz–Smoluchowski velocity [Eq. (12)]
u_{PD}	pressure driven velocity [Eq. (18)]
u_x	axial velocity [m s^{-1}]
W	half channel width [m]
x, y, z	coordinates [m]
Z	valence number of ions in solution

Greek symbols

α	channel aspect ratio [$=W/H$]
β, β_x	stretching parameters [Eqs. (26)–(28)]
Γ	velocity scale ratio [Eq. (17)]
δ	diffusion layer thickness [m]
ε	fluid permittivity [$\text{CV}^{-1} \text{m}^{-1}$]
ζ	zeta potential [V]
K	dimensionless Debye–Hückel parameter [$=H/\lambda_D$]
λ_D	Debye length [m]
ρ	fluid density [kg m^{-3}]
ρ_e	net electric charge density [C m^{-3}]
τ	stress tensor component [Pa]
$\boldsymbol{\tau}$	stress tensor [Pa]
φ	electrostatic potential [V]
Φ	externally imposed electrostatic potential [V]
ψ	EDL potential [V]
ω	scaling factor

Subscripts

av	average
c	relevant to concentration field
i, j, k	grid numbers in x, y, z directions
u	relevant to velocity field
ψ	relevant to electrical potential field

Superscripts

*	dimensionless variable
\wedge	transformed variable

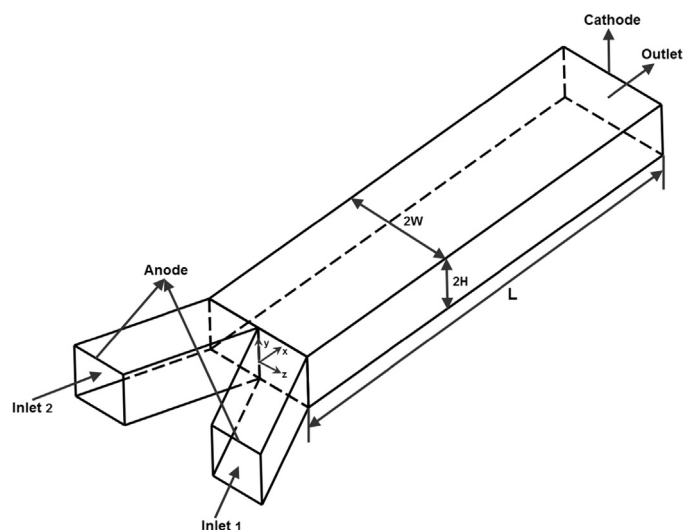


Fig. 1. Schematic of the Y-shaped microchannel, including dimensions and the coordinate system.

solution, it usually takes a net charge. Due to the electroneutrality principle, the liquid takes on an opposite charge in the electric double layer (EDL) near the surface. The electric double layer contains an immobile inner layer and an outer diffuse layer [5]. If an electric field is applied tangentially along the surface, a force will be exerted on the ions within the mobile diffuse electric layer, resulting in their motion [6]. Owing to viscous drag, the liquid is drawn by the ions and therefore flows tangential to the surface.

Mixing is a physical process with the goal of achieving a uniform distribution of different components in a mixture, usually within a short period of time. This definition includes the integration of two or more fluids into one phase, most often accompanied by volume contraction or expansion, or the inter-dispersion of solids [7]. Mixing is one of the essential functions in bio-microfluidic devices since it is vital in different processes such as cell activation, enzyme reaction, protein folding, sequencing or synthesis of nucleic acids, and so on [8]. Among various micromixers being developed is the Y/T-shaped micromixer, shown in Fig. 1. In most cases, this micromixer is used to bring two or more fluid streams into contact running side-by-side [9]. Although simple in design, such a device is a useful mixer, and, hence, has been applied in a number of cases [7].

Despite its macroscale counterpart, mixing in Y/T-shaped micromixer occurs primarily via molecular diffusion at the interface between the two fluids. This cross-stream diffusion, however, is a strong function of the velocity field. Kamholz et al. [10] were the first to realize that different residence time of the species due to the non-uniform velocity profile of a pressure driven flow results in a unique butterfly-shaped concentration profile. In their subsequent works [9,11], this research group reported the results of finite difference based numerical analyses of molecular diffusion in a pressure-driven flow T-sensor. They found that the resultant secondary concentration gradients yield variations in the scaling behavior between diffusive displacement and elapsed time in different regions of the channel. Ismagilov et al. [12] examined the scaling laws for transverse diffusive broadening in two-phase laminar flows in microchannels, both theoretically and experimentally. Shortly thereafter, Beard [13] investigated the Taylor dispersion of a solute in a microfluidic channel, by means of an approximate 2-D analytical solution. He showed that although diffusion of solute along the major axis is often neglected in constructing a governing transport equation, axial dispersion due to the laminar flow profile influences the distribution of solute in the channel. By means of computational fluid dynamics simulations of a

capable of generating constant and pulse free flows with flow rates well suited to LOC systems [4].

The fundamental origin of electroosmotic transport lies in the fact that when a surface is brought into contact with an electrolyte

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