International Journal of Heat and Mass Transfer 55 (2012) 2926–2933

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Mixing enhancement in crisscross micromixer using aperiodic electrokinetic perturbing flows

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ARTICLE INFO

Article history:
Received 19 August 2011
Received in revised form 20 January 2012
Accepted 20 January 2012
Available online 22 March 2012

Keywords:
Active mixer
Micromixer
Mixing
Electroosmotic flow
Sprott system

ABSTRACT

A novel method is proposed for enhancing the mixing performance in a crisscross micromixer by means of aperiodic time-varying electrokinetic perturbing flows. In the proposed approach, the aperiodic oscillating source used to modulate the perturbing electric potential is derived using the Sprott system. The effects of the perturbation conditions and micromixer geometry parameters on the fluid flow characteristics and mixing performance are analyzed by means of numerical simulations. The results show that irregularly-alternating flow recirculation structures are induced within the lateral channels of the micromixer, which cause a repeated stretching and folding of the species streams in the main channel and enhance the mixing performance as a result. It is shown that an effective improvement in the mixing performance can be obtained through a suitable specification of the scaling factor in the Sprott system. Furthermore, it is shown that the mixing performance can be further enhanced by assigning suitable values to the micromixer geometry parameters or by reducing the ratio of the main channel flow velocity to the lateral channel flow velocity. Overall, the numerical results show that an average mixing efficiency of more than 90% can be obtained by specifying the scaling factor in the Sprott system as 7.5, the ratio of the main channel velocity to the lateral channel velocity as 0.25, the separation distance between the lateral channels as equal to half the width of the main channel, and the width of the lateral channels as equal to the width of the main channel.

1. Introduction

Mixing is a crucial process in many microfluidic systems, such as lab-on-a-chip (LOC) devices or micro-total analysis systems (μ-TAS). Mixing is most naturally achieved through turbulent flow. However, due to the very small characteristic scale of microfluidic devices, the fluid flow is confined to the low Reynolds number regime. As a result, the fluid flow is laminar rather than turbulent, and hence species mixing occurs primarily as the result of diffusion. Diffusion is an inherently slow process, and thus achieving a thorough species mixing requires both a long mixing time and a long mixing length. However, neither requirement is compatible with the overriding goal of microfluidic systems design, namely developing high throughput systems with a minimal device size. Consequently, a requirement exists for more efficient mixing schemes.

The literature contains many proposals for enhanced micromixing schemes. These schemes can be broadly classified as either passive or active, depending on the manner in which the species are mixed. In passive micromixers, the species are mixed via the flow effects induced by the geometric features of the microchannel itself. Typical mixers of this type include staggered herringbone mixers [1,2], three-dimensional serpentine mixers [3,4], split-and-recombine mixers [5,6], and waveform mixers [7,8]. In contrast to passive mixers, active mixers achieve species mixing by means of external perturbing forces. Typically, the species mixing is achieved by utilizing a periodic oscillating velocity/pressure perturbation to generate transverse flows within the microchannel. Glasgow and Aubry [9] showed that periodic velocity perturbations yield a significant improvement in the mixing performance of T-shaped micromixers at low Reynolds numbers. Niu and Lee [10] and Lee et al. [11] proposed a micromixer in which the species flows in the main channel were stirred by time-periodic velocity perturbations generated in a series of lateral channels distributed along the length of the mixing channel. It was shown that given appropriate amplitude and frequency of the perturbations, a chaotic mixing effect was induced, which caused a repeated stretching and folding of the species at the interface between them and enhanced their mixing as a result. Many similar mixing schemes based on periodic velocity/pressure perturbations have been proposed [12–14]. In each case, the results have shown that an enhanced mixing performance can be

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doi:10.1016/j.ijheatmasstransfer.2012.02.006

Nomenclature

C	species concentration [M]
C_0, C_∞	species concentration in completely-unmixed and completely-mixed conditions, respectively [M]
D	diffusion coefficient [$\mathrm{m^2\,s^{-1}}$]
E	electric field strength [$\mathrm{V\,m^{-1}}$]
E_m, E_l	electric field strength along main channel and lateral channel, respectively [$\mathrm{V\,m^{-1}}$]
$\vec{F}_E$	electrokinetic driving body force
k	Sprott system scaling factor
L	total length of main channel [m]
L_i	length of injection channel [m]
L_s	length of lateral channel [m]
p_1, p_2, p_3, p_4	Sprott system parameters
P	pressure [$\mathrm{N\,m^{-2}}$]
Pe	Peclet number
$\vec{r}$	location vector
R_v	ratio of velocity in main channel to velocity in lateral channel
Re	Reynolds number
t	time [s]
$\underline{u}$, v	velocity components [$\mathrm{m\,s^{-1}}$]
$\underline{V}$	velocity vector [$\mathrm{m\,s^{-1}}$]
V_{eo}	Helmholtz-Smoluchowski velocity [$\mathrm{m\,s^{-1}}$]
$\vec{V}_{eo,m}$, $\vec{V}_{eo,l}$	Helmholtz- Smoluchowski velocity in main channel and lateral channel, respectively [$\mathrm{m\,s^{-1}}$]
W	width of main channel [m]
W_b	distance between lateral channels [m]
W_s	width of lateral channel [m]
x, y	coordinates
x_1, x_2, x_3	oscillatory sources

Greek symbols

ε	dielectric constant
ε_0	permittivity of vacuum [$\mathrm{F\,m^{-1}}$]
ϕ	electric potential [V]
ϕ_P	electric potential applied to electrodes at end of lateral channels [V]
μ	viscosity of fluid [$\mathrm{Ns\,m^{-2}}$]
μ_{eo}	electroosmotic mobility [$\mathrm{m^2\,V^{-1}\,s^{-1}}$]
ρ	density of fluid [$\mathrm{kg\,m^{-3}}$]
ρ_e	net charge density [$\mathrm{C\,m^{-3}}$]
σ	electrical conductivity [$\mathrm{S\,m^{-1}}$]
η_m	mixing efficiency [%]
ζ	zeta potential [V]

obtained through an appropriate specification of the perturbation amplitude and frequency.

In recent years, electrokinetic schemes have emerged as the method of choice for species mixing in microfluidic systems. Compared to traditional pressure-driven mixing methods, electrokinetic mixing schemes have a number of significant advantages, including the ability to manipulate tiny volumes of sample with an extremely high degree of precision, a lack of moving parts, and a straightforward integration with other microfluidic devices. Tang et al. [15] and Coleman et al. [16] proposed T-shaped and cross-shaped electrokinetic micromixers, respectively, in which a periodically-varying electric field was applied to the side channels of the device such that the two species were injected alternately into the main microchannel. It was shown that an effective species mixing could be obtained given a suitable frequency of the alternating electric field. Oddy et al. [17] showed that the application of a periodic electric field to species with different conductivities induced an instability phenomenon at the species interface and improved the mixing efficiency as a result. Meisel and Ehrhard [18] used external periodic oscillatory electrical fields to excite secondary flows within fluids flowing through meandering microchannels or along microchannels containing internal obstacles. The results showed that the secondary flows led to a significant improvement in the mixing performance. Phelan et al. [19] proposed an electrokinetic mixer in which periodic electric fields with a 90-degree phase shift were applied to electrodes located at the ends of closed lateral channels. It was shown that the periodic electric field induced vortex structures within the lateral channels which created a chaotic mixing effect within the mixer. Chen and Cho [20] and Chen et al. [21] showed that the mixing efficiency of electrokinetically-driven flows can be improved by utilizing harmonic and chaotic electric fields to produce regular or irregular perturbation effects, respectively.

Most of the active mixing schemes presented in the literature achieve species mixing by means of periodic perturbation sources. By contrast, the use of aperiodic oscillating sources is far less common. However, aperiodic oscillating sources have a number of advantages, including the generation of a random-like oscillatory effect, an oscillatory characteristic comprising multiple oscillating frequencies, and so forth. Accordingly, the present study proposes an enhanced mixing scheme based on a crisscross micromixer in which the species are driven from the inlet to the outlet via a constant electric field and are perturbed by aperiodic time-varying electric potentials applied to electrodes embedded at the ends of closed lateral channels distributed along the length of the main channel. In order to enhance the mixing efficiency, the aperiodic time-varying electric potentials are modulated over time in accordance with the oscillatory behavior of the Sprott system [22]. The effects on the fluid flow characteristics and mixing performance of the perturbation conditions and the micromixer geometry parameters are systematically examined by means of numerical simulations.

2. Mathematical formulation

Fig. 1 presents a schematic illustration of the crisscross micromixer considered in the present study. As shown, the mixer comprises a single mixing channel and three pairs of lateral channels; each with an electrode at its closed end. The main microchannel has a

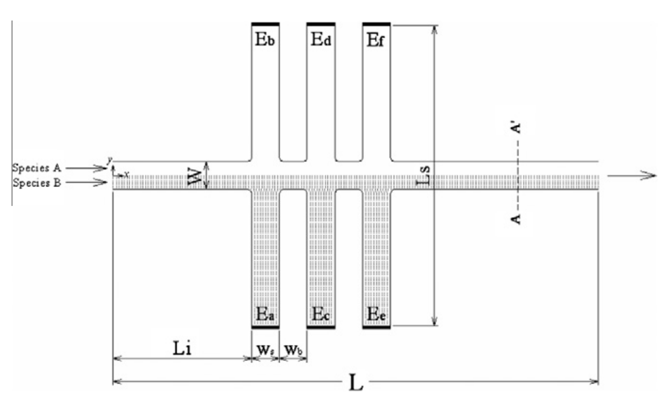

Fig. 1. Schematic illustration of crisscross micromixer comprising main channel and three pairs of lateral channels. Note that the ends of the lateral channels are closed and incorporate electrodes E_a–E_f, respectively.