Generating efficient chaos effect in micro channel using electrohydrodynamic theory

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AC electro-osmotic flow is a promising technique in microfluidic manipulation. AC electroosmotic force has been generated inside a novel twisted micro channel in order to overcome the low Reynolds number fluid. The behavior of concentration distribution has been investigated by solving the transient electric field, fluid mechanic and convection-diffusion theory inside the channel. Two particles have been released inside the channel to investigate the efficiency of generated chaotic regime. Velocity streamlines and perturbation of species concentration reveal high performance stirring process which above 95% mixing efficiency achieved for 210 μm channel length. The efficiency increases by increasing the applied voltage amplitude. Geometrical and exciting parameters have been optimized in order to maximize the efficiency of mixing process and avoid electrolysis and sample damage.

Keywords: MEMS-based mixer, Microfluidic, Chaotic regime, Electro-hydrodynamic force, Electro-kinetic flow

1 Introduction

In last two decades, advances in micro engineering have been applied in biological laboratories and chemical testing applications[1,2]. Micro-total-analysis-systems (μTAS) and Laboratory-On-a-Chip (LOC) devices integrate the microfluidic components (such as micro mixers, micro valves, micro pumps, micro separators, micro reactors and detectors) in a single electronic chip (the chip is made by silicon or glass or polymer) and done the entire testing process in short time, cheap cost, with small sample volume and eases portability of microfluidic devices. In micro engineering Lab-On-a-Chip processes we need to mix multiple fluids. For example, in many applications the blood solution must be completely mixed with biomarkers/particles in small space and very short time. So, in such devices, the mixing time, efficiency, and controlling the process is very important. The stirring process can be completely troublesome in micro scale, due to low Reynolds number in such scale (Eq. (1)):

$$Re = \frac{\rho \, U \, d}{\mu} \qquad \qquad \dots (1)$$

where, Re is the Reynolds number, ρ is the fluid density, U is the average net flow velocity, μ is the dynamic viscosity of the fluid and d is the hydraulic diameter of the micro channel[3]. Without any external and secondary flow, molecular diffusion is the main transport phenomenon in micro channel. Under such conditions, the stirring performance is very poor. Generally, MEMS-based mixers can be classified into passive and active types. The passive micro stirrers such as parallel and serial laminations[4,5], herringbone mixer[6], the passive mixers contain irregular or asymmetric micro channel geometry to perturb flow streamlines. In contrast to the passive, the active micro mixers achieve a complete stirring effect by inducing external secondary flow to enhance the stirring process. Various techniques are used for active micro mixers such as; acoustic vibration[7], pressure disturbance[8], electro-kinetic instability mixer[9], magneto hydrodynamic[10] and so on. High performance stirring in low Reynolds number fluid can be achieved by the chaotic advection (or the so-called Lagrangian chaos mechanism). Chaotic regime associated with stretching, folding and breaking the fluid up, obtains an effective increase in the interfacial contact area between the two fluids, as proven by[11]. EHD or Electro-Kinetics (EK) theory is the study of the motions of ionized particles or molecules and their interactions with electric field and the surrounding fluid[12].Induced time-dependent electro-kinetic flow indicates considerable promise for application in micro-scale transport processes. In AC-electro-kinetic (ACEK)

case, ionized liquid moves relative to the stationary charged surface by action of the applied time-dependent electric field[13]. In order to offer the ability of smaller fluid/sample volumes and high performance more miniaturization is necessary. The mixing problem is compounded by the fact that we face to creeping flow (very low Reynolds number fluid, $Re < 0.1$) in micro-channels. Generation of chaos effect is more efficient to increase the fluids interfacial contact area and overcome the viscous resistance of the highly laminar fluid flow. In last decade, the chaos mechanism combined with stretching, folding and breaking up the fluid is used to stir low Reynolds number liquids. EHD forces, specially the ACEK force showed a valuable ability for micro engineering application in Lab-On-a-Chip devices. The concept of electro-kinetic theory is based on electrical double layer (EDL) or Debye layer. Due to the electrochemical equilibrium between a solid surface and an electrolyte solution typically leads to the interface acquiring a net fixed electrical charge, a layer of mobile ions, known as an electrical double layer, forms in the region near the interface[13]. The formation of EDL is electrochemical process which is schematically plotted in Fig. 1.

If a tangential electric field is applied to an electrolyte solution, the charges in the electrical double layer at the interface of electrolyte solution and surface, experience a considerable force. Therefore, these EDL charges move and as a result pull the bulk fluid along the actuation path. The generated flow called as AC electro-osmotic (ACEO) flow[13]. An ACEO micro mixer was investigated by Chen et al.[14], they designed a ring-shaped micro chamber with four integrated electrodes and create chaos effect associated with stretching and folding of the fluid. Other chaotic micro stirring process was achieved by using a 2 Hz periodic switching field to induce instability EK flows[15], their results demonstrated the mixing efficiency of 95% within a mixing length of 1000 μm. Another chaotic oscillating electric field is derived for mixing process by Deval et al[16]. From fabrication point of view, the ring-shaped mixer fabricated by silicon on isolator (SOI) wafer (for electrically isolated from the substrate). Vafaie et al[17] proposed a biocompatible and novel fabrication process for highly miniaturized microfluidic devices in. This paper investigates stirring process by chaotic regime in a highly miniaturized micro channel.

2 Design

In this research, we use the twisted micro channel for enhancing the chaos effect. The volume amount of testing liquid (such as biological fluid, buffer solution, chemical reagents and so on) is reduced to nano-liter scale by using highly miniaturized micro channel. In fact, we have already designed a novel four phase AC electro-osmotic (ACEO) micro pump for Lab-On-a-Chip applications[18]. Therefore, it assumes that the initial pumping process occurred by ACEO micro pump with the net flow velocity of U_{in} and we will disturb the initial pumped liquid by generating a time-varying chaos effect. The two fluids (fluid A and B) inter the micro channel and the high throughput stirring process will be done by appropriate exciting the electrodes. The model and the geometrical parameters are displayed in Fig. 2. Four semi-circular obstacles are considered within the micro channel and two electrodes are embedded on each one of obstacles. The size and positions of the electrodes are shown in Fig. 2. The curvature of obstacles and also
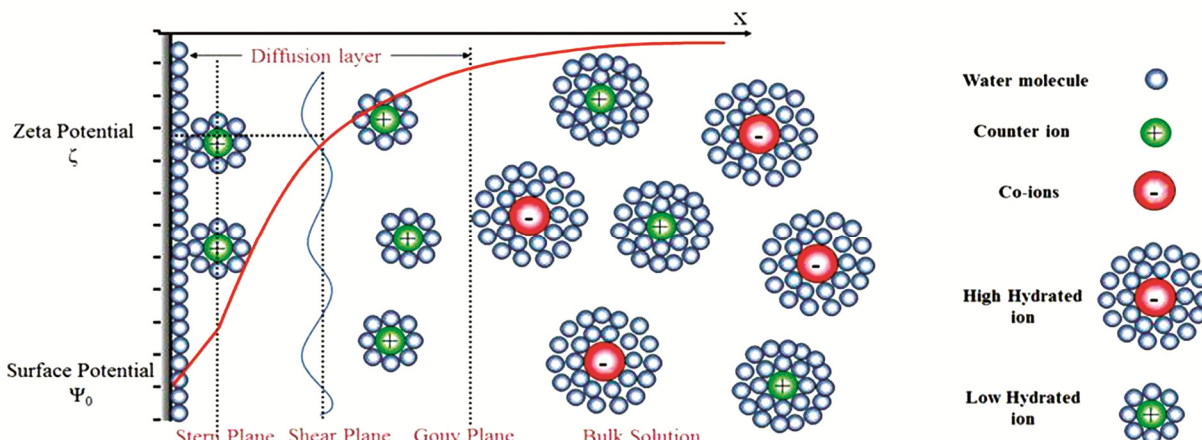

Fig. 1 — Debye layer formation; a thin layer charged by counter-ions, at interface between the solid wall and electrolyte.
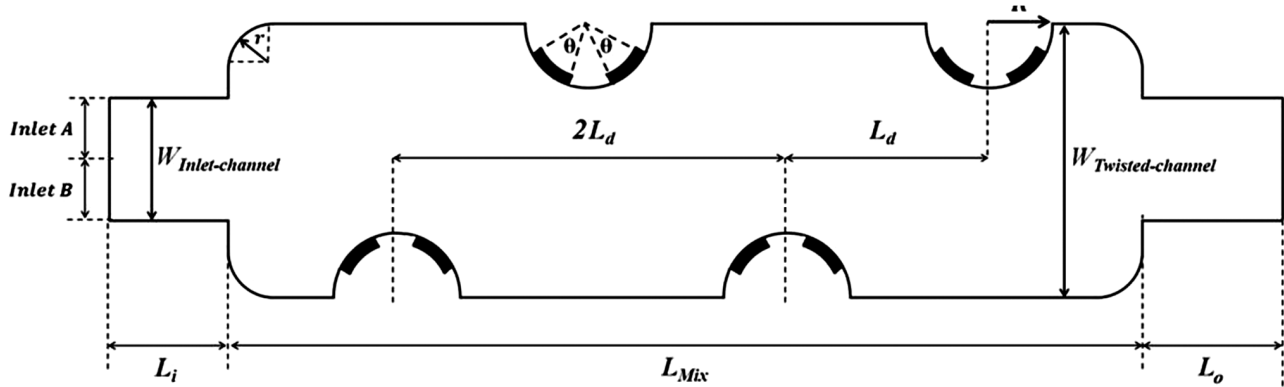
Fig. 2 — Micro mixer schematic design; the view of micro channel, inlets, outlet and micro-electrodes.

Table 1 — Geometrical parameters of the design

Symbol	Description	Value
$W_{\text{Inlet-Chamber}}$	Width of the inlet channel	20 (μm)
$W_{\text{Twisted-Channel}}$	Width of the twisted channel	40 (μm)
L_i	Entrance length	30 (μm)
L_{Mix}	Total length of the twisted channel	160 (μm)
L_o	Outlet length	30 (μm)
L_d	Distance between the two adjacent obstacles	35 (μm)
R	Radious of the semi-circular obstacles	30 (μm)
θ	Related to size of the electrodes, (electrode size = $\pi {R\theta}/{180°}$)	60 (deg)
r	Curvature radius in the twisted microchannle	5 (μm)

the curvature of micro channel (with radius r) enhance the chaotic regime by utilizing the Coanda effect[19]. Broadly specking the Coanda effect is the tendency of a fluid to be attracted to a nearby surface and this effect is the most noticeable near a curved surface. Geometrical size and the parameters used for designing the ACEK micro stirrer model are assigned in accordance with Table 1.

3 Theory and Physics

As mentioned previously, the initial stirring operation essentially relies on molecular diffusion which is a very poor transport mechanism. However, we improve it by ACEK force. As mentioned earlier, when an electric field is applied to the fluid (via electrodes), the net charge in the EDL is induced to move by the resulting Coulomb force. The generated flow is termed ACEK flow. From physical point of view, we must analysis a multi-physics problem that involves fluid mechanics, EK field and convection-diffusion theory. For analyzing the stirring operation

we solve the fluidic incompressible Navier-Stokes equation (Eq. (2)) and continuity equation[20] (Eq. (3)):

$$\rho\left[\frac{\partial \overline{u}}{\partial t} + \vec{u}\nabla\overline{u}\right] = -\nabla p + \mu\nabla^2\vec{u} + \rho_e\vec{E} \qquad ...(2)$$

$$\nabla\overline{u} = 0 \qquad \ldots(3)$$

where, ρ is the fluid density, u is the net flow velocity of the ACEO micro pump, p is the pressure in the micro channel, μ is the fluid viscosity, ρ_e is the electric charge density, and E is the generated electric field in micro channel. The interaction between electrical double layer (EDL) and excess ions indicates the electrical driving force which can be expressed by Eq. (4):

$$\overline{E} = -\nabla V \qquad \ldots(4)$$

where, V is the applied electric potential. The counter-ions in the EDL will experience an effective force by imposing a time-variable electric field (caused by the tangential component of electric field). As a result of generated force, the charges move, pulling the fluid inside the fluid along the excitation path and generating secondary flow well known as electro-kinetic flow. The EK velocity (u) is approximated by Helmholts-Smoluchowski equation (Eq. (5)). This approximation is valid only for thin double layer[21] (about 10 nm). The effect of EK flow is considered as slip flow velocity at the edge of electric double layer. Therefore, the slip flow velocity boundary conditions can be considered by incompressible Navier-Stokes for fluid motion inside the micro channel.

$$u = -\varepsilon_0\varepsilon_r\zeta\vec{E}\Big/\mu \qquad \ldots (5)$$

where, ε_0 is the dielectric permittivity of vacuum, ε_r is the relative permittivity of the fluid, ξ is the electro-kinetic zeta potential, μ is the fluid dynamic viscosity and E is the electric field. We also need to obtain the concentration field inside the micro channel, so we solve it by the Convection-Diffusion equation (Eq. (6)):

$$\frac{\partial C}{\partial t} + (\bar{u}_{eo} + \bar{u}_{ep})\overline{\nabla}C - D\nabla^2 C = 0. \qquad \ldots (6)$$

where, C is the concentration of species inside the channel, u_{eo} is the electro-kinetic (or electro-osmotic) mobility and u_{ep} is the electrophoretic mobility of the fluids, D is the diffusion coefficient between the two fluid (fluid A and B) which is to mixed with each other. Electrophoretic mobility is very poor in comparison with EK mobility[17], so it is neglected in this study. As indicated in Fig. 3 the two fluids with different concentrations of 1 and 0 mol.m^{-3} entered to the channel by the ACEO micro pump. Eight electrodes are located at surface of the obstacles and they excited by very low electric potential of $V_1(t)$ and $V_2(t)$, which it ensure the

whole portable applications. Initial and boundary conditions for solving the multi-physics micro stirring problem are shown in Fig. 3, and the material properties of the structure were assigned in accordance with Table 2. As mentioned, the study considers the creeping flow due to the characteristics of micro scale, and also the two fluids taken into the channel with initial net flow velocity[18] of U. The zero pressure $P=0$ were selected for inlets and outlet and also zero pressure gradient were set at the micro channel walls (considering no flux across the wall $n\nabla P = 0$). We appropriately assume that the applying secondary EK force and variation in the fluid concentration do not alter the mechanical properties[22] of the solution (such as dynamic viscosity, fluid temperature and density). Two groups of electrodes are actuated by the voltages of $V_1(t)$ and $V_2(t)$, and electrical insulation conditions were applied to the black walls which all of them are shown in Fig. 3. Under these boundary conditions, the electric potential can be solved by the Laplace equation (Eq. (7)):

$$\nabla^2 V = 0 \qquad \ldots(7)$$

In accordance the electric field is obtained by Eq. (4) and the ξ potential effect determines by slip wall
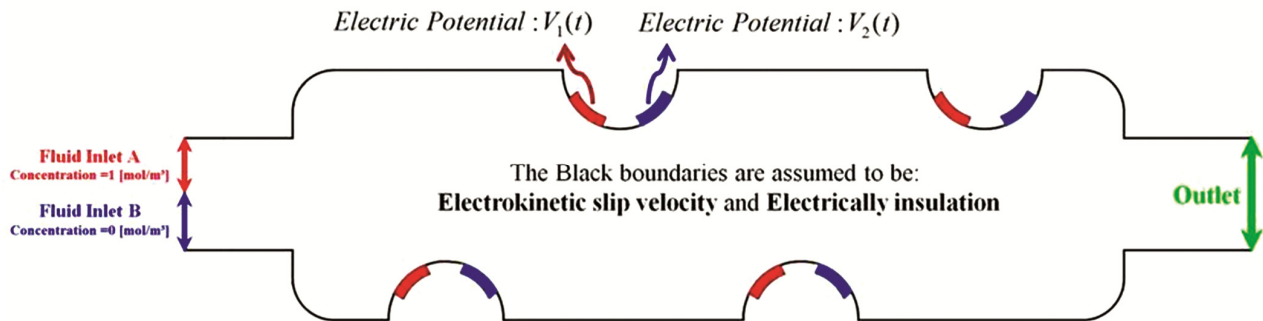

Fig. 3 — Boundary conditions for fluid mechanic, electrostatic and convection-diffusion equations.

Table 2 — Material properties, electric actuation and related diffusion parameters of the stirring process[14]

Symbol	Description	Value
ρ	Water density	1×10^3 (kg.m^{-3})
μ	Water viscosity	1×10^{-3} (N.s.m^{-2})
ε_r	Dielectric constant of water	80.2
U	Net flow input velocity	0.15 (mm.s^{-1})
ζ	Zeta potential for wall of micro channel (silicon or glass)	-75 (mV)
V_0	Amplitude of electric potential $V_1(t)$ and $V_2(t)$	100 (mV)
f	Actuation frequency of $V_1(t)$ and $V_2(t)$	2.5 (Hz)
D	Diffusion coefficient	1×10^{-11} (m^2.s^{-1})
C_A	Concentration of fluid A	1 (mol.m^{-3})
C_B	Concentration of fluid B	0 (mol.m^{-3})

boundary conditions. The no-slip boundary conditions applied to inlet and outlet of the micro-channel and also the slip boundary conditions applied to the walls of micro channel (in accordance with Eq. (8)):

$$\frac{\partial u_x}{\partial x} = 0 \quad \text{and} \quad \frac{\partial u_y}{\partial y} = 0 \quad \text{at inlets and outlet}$$

$$u_x = -\frac{\varepsilon \zeta E_x}{\mu} \text{ and } u_y = -\frac{\varepsilon \zeta E_y}{\mu} \text{ at walls}$$

$$\dots(8)$$

From the concentration process point of view, we analysis the convection-diffusion equation (Eq. (6)) for species concentration process subject to the conditions as follows; In order to design a high performance micro stirrer and overcome to the high lamination we chose a very low diffusion coefficient ($D=1\times10^{-11}$ m^2.s^{-1}) for species. Under this condition, there is a poor tendency for stirring process between the two species. Liquids A and B take into the micro channel with concentrations of 1 and 0 mol.m^{-3}, respectively, and the concentration will be disturbed by generated chaos effect into the micro channel.

4 Results and Discussion

A set of simulations were done by coupling the fluid mechanic, electric field and convection-diffusion physics to investigate the high throughput chaotic effect generation inside the micro channel. By applying oscillatory voltages to the embedded electrodes, more efficient tangential force generates near the twisted obstacles (at the EDL). The interaction between the secondary ACEO flow and primary pumping flow perturbs the fluid. As a result, sufficient AC electro-osmotic flow manipulates the fluid inside the channel (called as chaos effect, Fig. 4). As shown in Fig. 4(a, e), when the electric potential and corresponding electric field is zero, there is no secondary EK flow and resulting the velocity field streamlines are very smooth. The chaotic effect arises from the electrodes by the interaction of AC electric fields with the electric double layer charges. The pattern of induced secondary flow alters with oscillating of the electric field (Fig. 4). We release two adjacent particles inside the micro channel (particle A coordination: $x = 0$, $y = 9.5e - 6$; particle B coordination: $x = 0$, $y = 10.5e-6$) and trace the particle trajectories. Fig. 5(a, b) compares the trajectories of particles in two different case, (a) without any electric field and (b) by applying time-dependent electric field (with a frequency of f). Analysis revealed that the two adjacent particles move in together when there is no secondary flow but the particles experience time-dependent electro kinetic force when the electrodes are excited. As a result, the particles are stretched and folded. Therefore, the particles finally travel in individual routs. In our proposed system, the interaction between the AC electro-osmotic flow and the twisted obstacles cause to break the fluid up and eases the final step of mixing process. These stretching and folding actions are a proof of chaos effect in micro channel and lead to enhancing the stirring process[23].
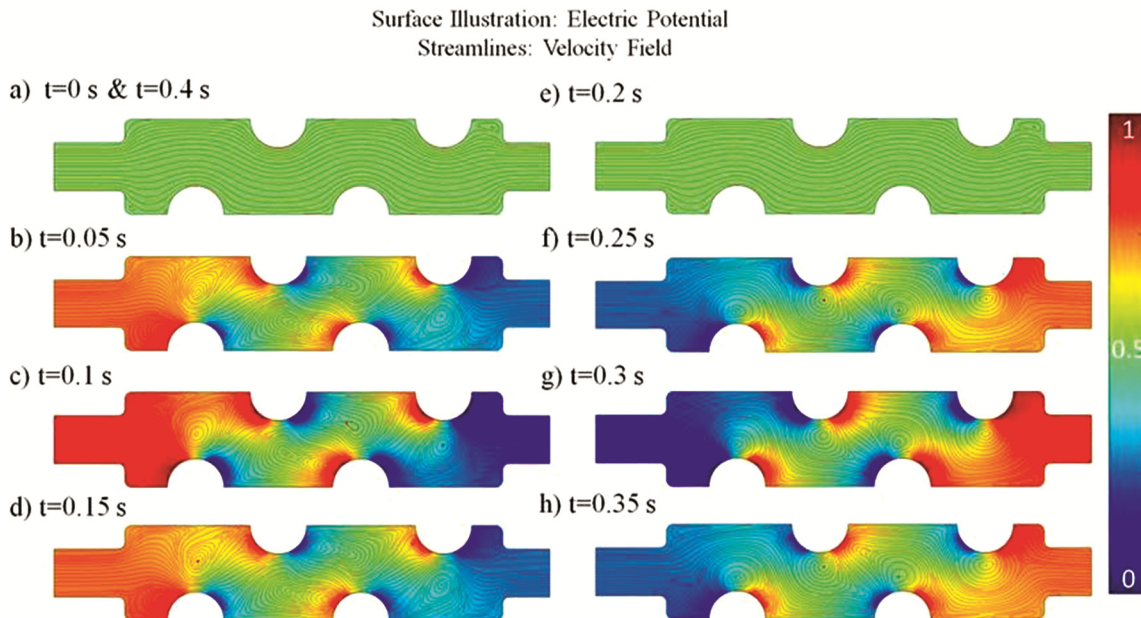

Fig. 4 — Electric potential surface illustration and fluid velocity streamlines during a period of E ($t = 0.25$ s).
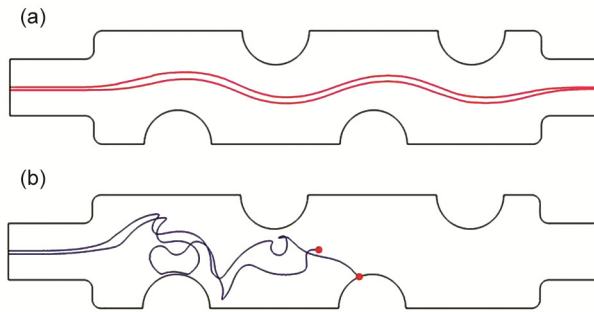
(a)

(b)

Fig. 5 — Particle trajectories (a) without electric field, the two close particles move side by side and (b) with alternate electric field, particles are stretched and folded by the electrokinetically-driven force.

As discussed above, a time-varying chaos effect generated by the interaction between the primary net flow velocity and oscillatory external electric field. It should be noted that the curvature of semi-circular obstacles improve the chaos regime by using Coanda effect. This regime increases the interfacial contact area between the liquids A and B and as a result enhances the molecular diffusion transport mechanism between the two liquids. The generated stretching and folding patterns lead to sufficiently breaking the fluid up. In order to examine the influence of chaos effect on stirring process, we analyze the transient fully coupled physical model including fluid mechanic, EK flow and species convection-diffusion process. As illustrated in Fig. 6 the ACEO rotation actions associated with the fluid breaking up arise near the electrodes (at twisted obstacles).

Fluids A and B are taken into the micro channel with different concentration of C_A and C_B. As a result

of charge and discharge of the EDL, the rotation effects generated and the two species concentration perturbed inside the twisted micro channel which leads to high throughput stirring process. It should be noted that, in this case the species concentration of 0.5 $mol.m^{-3}$ means that the two fluids are completely mixed. As plotted in Fig. 6(a), without any electric field the mixing process is mainly based on poor molecular diffusion. In contrast when an efficient electric field applied, species concentration distribution reaches to 0.5 $mol.m^{-3}$ in a small period of time (Fig. 5(b-j)). Diagram of species concentration is plotted in Fig. 7(b) for different times, as shown in figure legend. In this case the $t = 0$ s means that the electrodes are not excited and the stirring process is only based on molecular diffusion.

4.1 Mixing efficiency

In order to investigate the stirring performance of proposed twisted micro channel, the stirring efficiency η at the outlet cross section can be evaluated by the following equation[24]:

$$\eta = [1 - \frac{\int_A |C - C_\infty| \, dA}{\int_A |C_0 - C_\infty| \, dA}] \times 100 \ \%. \qquad \ldots(9)$$

where, C is the species concentration at the output cross section of channel, C_∞ is the species concentration in the fully stirred point ($C_\infty = 0.5$ $mol.m^{-3}$), and

a) t=0 s   f) t=0.5 s

b) t=0.15 s   g) t=0.7 s

c) t=0.25 s   h) t=0.9 s

d) t=0.3 s   i) t=1 s
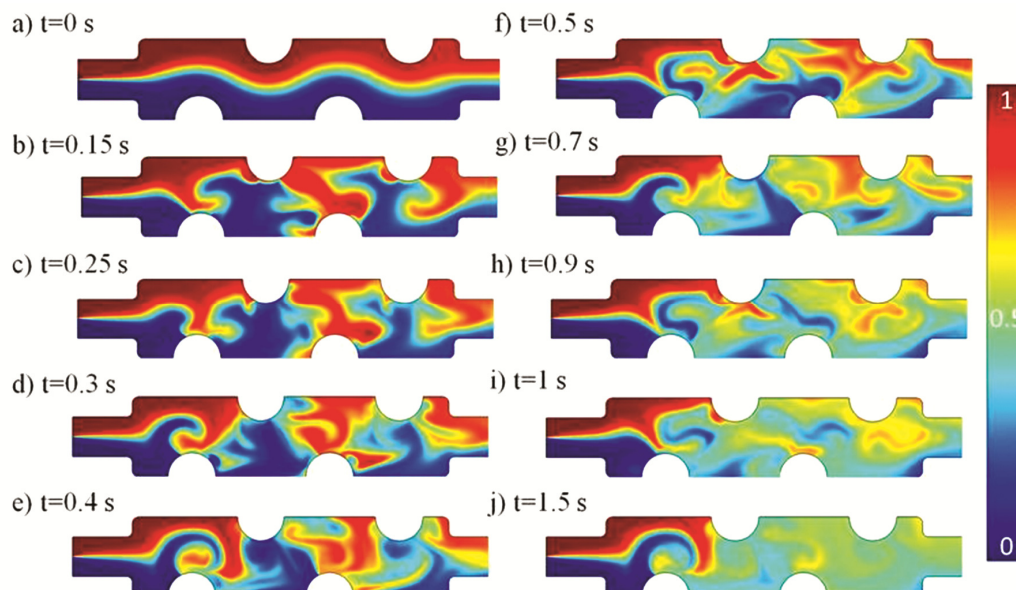
e) t=0.4 s   j) t=1.5 s
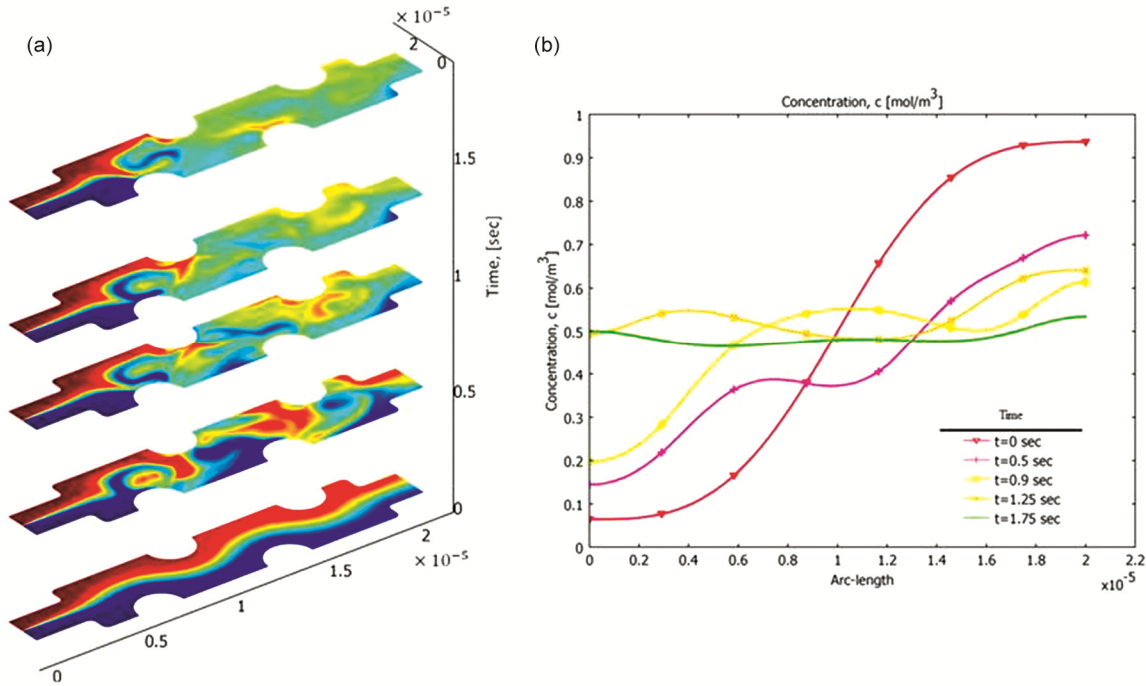

Fig. 6 — Species concentration distribution.

Fig. 7 — Concentration perturbation (a) surface plot and (b) line plot at outlet cross-section.
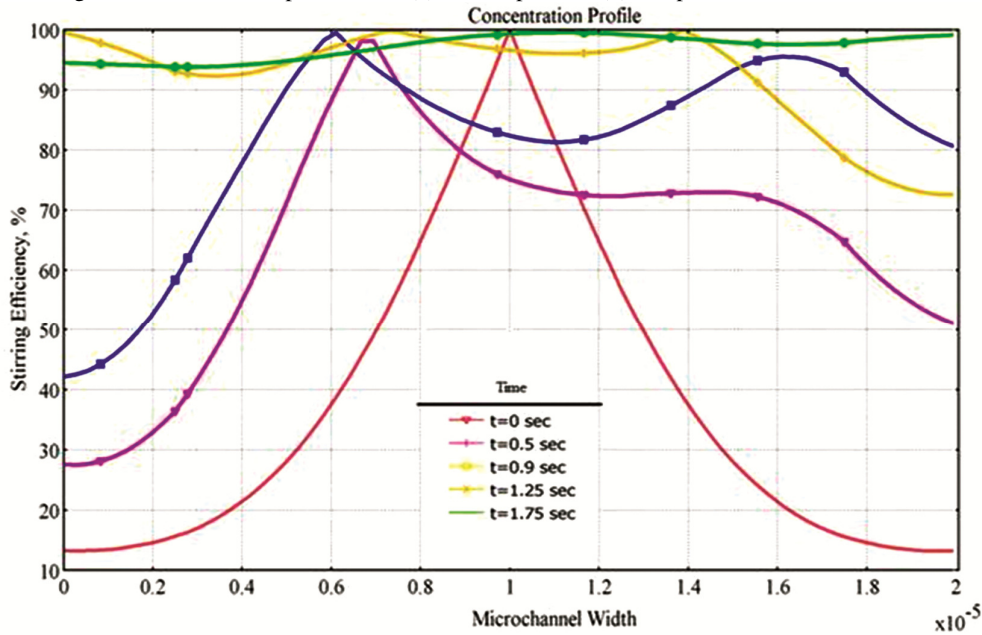

Fig. 8 — Stirring efficiency; the efficiency over the channel width in different times as shown in the figure legend.

C_0 is species concentration in the completely unstirred point ($C_0 = 0$ or 1 mol.m^{-3}). Figure 8 visualizes mixing quality at outlet cross-section of the miniaturized micro channel with applying the voltage of $V_1(t) = 0.1\sin$ (2π × 2.5 Hz × t) and $V_2(t) = -0.1\sin$ (2π × 2.5 Hz × t) to the electrodes. As shown in figure legend, after a time of 1.25 s the average mixing efficiency is over 90% and it reaches above 95% after a

time of 1.75 s. Our proposed semi-circular obstacles are responsible to generate high efficient ac electro-osmotic flow and the corresponding high performance mixing effect.

4.2 Optimization parameters

The performance of generated chaos effect in the twisted micro channel is mainly affected by amplitude and frequency of actuation system, channel geometry,
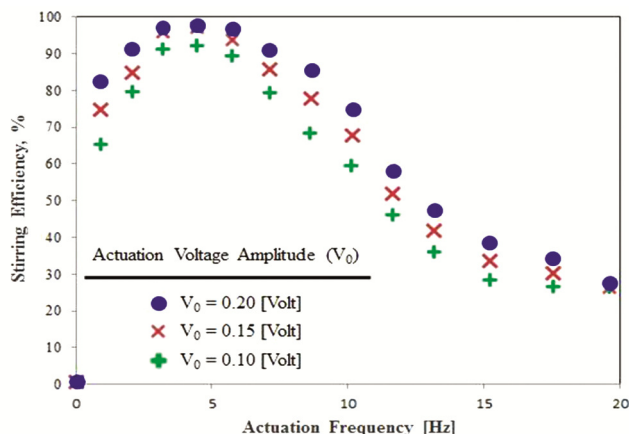
Fig. 9 — Actuation frequency and voltage amplitude effect on stirring efficiency; the profile are plotted for a small frequency range and three different cases of voltages, as shown in legend.

net flow velocity amplitude and size of the electrodes. In order to low sample consumption, highly integrated system, low energy consumption and high throughput mixing performance, we miniaturized the micro mixer structure. It should be noted that using small net flow velocity, in the range 0.1 mol.m^{-3} to 0.3 mol.m^{-3} is common in most of the integrated Lab-On-a-Chip applications. When the fluid medium charging (τq-1=σ/ε) the frequency of the applied electric field is in the same range, the counter ions do not have enough time to entirely screen the electrodes at the twisted wall. Therefore, a part of electric field is consumed for screening process and the other part is dropped over the fluid medium. The inner portions of EDL on the electrodes charge more rapidly than the outer portions. Therefore, the electrode structures are screened partially and a sufficient tangential force causes to generate an efficient ACEO flow near the twisted obstacles (from the screened portion towards the unscreened portion). It should be noted that the

generated ACEO flow is independent of the sign of the applied electric signal. At higher actuation frequencies, there is not enough time for the ions to do electrode screening and all of the electric field is dropped over the fluid medium. In this case the AC electroosmotic effect is completely inefficient for fluid manipulation and mixing purpose. A set of simulations were done to improve the chaos effect, inside the twisted micro channel. Actuation frequency is optimized in frequency range of 2 Hz to 6 Hz, while this low range of frequency has been proven to capable of electrolysis and corresponding bubble generation inside the channel[25].

In order to avoid probably electrolysis, we use a very low voltage amplitude actuation, in the range of 0.1 V to 0.2 V. In addition to suppressing the electrolysis, low voltages cover all the portable applications by Lab-On-a-Chip devices. As indicated in Fig. 9 the yield of chaos effect enhanced by increasing the voltage from 0.1 V to 0.2 V and corresponding stirring efficiency improve to about 98%, but the corresponding generated higher electric field inside the micro channel, will probably leads to damage the solution and samples.

5 Conclusions

This study investigates numerically the generation of chaos effect inside a novel twisted micro channel by employing EK flow. We enhanced the chaos effect by using Coanda effect, for this purpose the twisted micro channel with four semi-circular obstacles were considered and the electrodes were embedded at the channel wall. As a result we drive an ACEK flow by interaction between the initial pumped fluid flow and a time-dependent electric field. The combination of ACEO force and Coanda effect enhanced the

Table 3 — Comparison table

Reference	Stirring type	Channel width (µm)	Velociy (mm/s)	Frequency (Hz)	Stirring efficiency	Materials
4	Passive-parallel	85	0.7	passive	-	Silicon-glass
26	Patterned wall	200	0.1	passive	-	PDMS
27	Electro-kinetic	200	0.5	1	-	-
28	2D Tesla	200	5	passive	-	Cyclic Olefin Copolymer (COC)
29	Chaotic-patterned wall	200	0.01-0.09	passive	90 %	PDMS
16	Dielectrophoretic	50	0.5	1	-	Si–SU8-glass
14	AC Electro-osmotic	10	0.1	8	75 %	SOI
30	AC Electrothermal	60	0.1	100 (kHz)	90%	Si-SiO$_2$
This research	Electrokinetic (ACEO)	40	0.15	2.5	above 95 %	Si

generated chaos regime inside the channel. We study stirring process by solving fully coupled multi-physics system (including fluid mechanic, electro-kinetic effect and convection-diffusion process). The results revealed a time-dependent chaos effects associated with stretching and folding effects. As a result, the proposed system is able to break the fluid up at micro scale. From mixing point of view, two fluids are taken into the channel and a high efficient stirring process produced affected by chaos regime. We also optimize the structure and actuation system for highly integrated mixing applications, low power portable devices and avoid electrolysis. The yield of above 95% achieved for stirring process in about 1.75 s. The system is compared with other chaotic-based micro mixers in accordance with Table 3. In comparison with the earlier works, our proposed low-voltage ACEO flow near the twisted obstacles is more efficient to generate chaotic regime and on-chip stirring applications

Acknowledgement

References

1 Poorreza E, Vafaie R H, Mehdipoor M, Pourmand A, & Ghavifekr H B, *Indian J Pure Appl Phys*, 51 (2013) 506.
2 Mehdipour M, Vafaie R H, Pourmand A & Ghavifekr H B, *A new miniaturized traveling-wave electro-osmotic micro-pump by low velocity of fluid for lab-on-a-chip application*, 20th IEEE International Conference on Electrical Engineering (ICEE), 2012.
3 Squires T M, & Quake S R, *Rev Mod Phys*, 77 (2005) 977.
4 Koch M, Witt H, Evans A G R & Brunnschweiler A, *J Micromech Microeng*, 9 (1999) 156.
5 Branebjerg J, Gravesen P, Krog J P & Nielsen C R, *Fast mixing by lamination*, The ninth annual international workshop on micro electro mechanical systems (An investigation of micro structures, sensors, actuators, machines and systems), 1996.
6 Stroock A D, Dertinger S K, Ajdari A, Mezić I, Stone H A & Whitesides G M, *Science*, 295 (2002) 647.
7 Nguyen N T & Wu Z, *J Micromech Microeng*, 15 (2004) R1.
8 Deshmukh A A, Liepmann D & Pisano A P, *Continuous micromixer with pulsatile micropumps*, Technical digest of the IEEE solid state sensor and actuator workshop, 2000.
9 Oddy M H, Santiago J G & Mikkelsen J C, *Anal Chem*, 73 (2001) 5822.
10 Bau H H, Zhong J & Yi M, *Sens Actuators B*, 79 (2001) 207.
11 Ottino J M, *The kinematics of mixing: stretching, chaos, and transport*, (University press: Cambridge), 1989.
12 Castellanos A, Ramos A, Gonzalez A, Green N G & Morgan M, *J Phys D: Appl Phys*, 36 (2003) 2584 .
13 Vafaie R H, Mehdipour M, Pourmand A, & Ghavifekr H B, *A novel miniaturized electroosmotically-driven micromixer modified by surface channel technology*. In electrical engineering (ICEE), 20th Iranian conference on IEEE, 2012.
14 Chen H, Zhang Y, Mezic I, Meinhart C & Petzold L, *Numerical simulation of an electroosmotic micromixer*, ASME 2003 International Mechanical Engineering Congress and Exposition, 2003.
15 Fu L M, Yang R J, Lin C H & Chien Y S, *Electrophoresis*, 26 (2005) 1814.
16 Deval J, Tabeling P & Ho C M, *A dielectrophoretic chaotic mixer*, The Fifteenth IEEE International Conference on Micro Electro Mechanical Systems, 2002.
17 Vafaie R H, Mehdipoor M, Pourmand A, Poorreza E & Ghavifekr H B, *Biotechnol Bioprocess Eng*, 18 (2013) 594.
18 Mehdipoor M, Vafaie R H, Pourmand A, Poorreza E & Ghavifekr H B, *A novel four phase AC electroosmotic micropump for lab-on-a-chip applications,* 8th IEEE International Symposium on Mechatronics and its Applications (ISMA) 2012.
19 Hashimoto M, *Generation and applications of bubbles and droplets in microfluidic systems*, Harvard University, 2009.
20 Vafaie R H & Ghavifekr H B, *Microsys Technol*, 23 (2017) 1393.
21 Ramos A, Morgan H, Green N G, & Castellanos A, *J Phys D: Appl Phys*, 31 (1998) 2338.
22 Chen J K & Yang R J, *Electrophoresis*, 28 (2007) 975.
23 Cho C C, *Microfluid Nanofluidics*, 5 (2008) 785.
24 Erickson D & Li D, *Langmuir*, 18 (2002) 1883.
25 Studer V, Pépin A, Chen Y & Ajdari A, *Analyst*, 129 (2004) 944.
26 Wang H, Iovenitti P, Harvey E & Masood S, *J Micromech Microeng*, 13 (2003) 801.
27 Lee Y K, Deval J, Tabeling P & Ho C M, *Chaotic mixing in electrokinetically and pressure driven micro flows*, The 14th IEEE International Conference on Micro Electro Mechanical Systems (MEMS), 2001.
28 Hong C C, Choi J W & Ahn C H, *Lab Chip*, 4 (2004) 109.
29 Biddiss E, Erickson D & Li D, *Anal Chem*, 76 (2004) 3208.
30 Ghandchi M & Vafaie R H, *Microsys Technol*, 23 (2017) 1495.