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FLUID MIXING CONTROL INSIDE A Y-SHAPED MICROCHANNEL BY USING ELECTROKINETIC INSTABILITY

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ABSTRACT

An experimental study was conducted to further our understanding about the fundamental physics of electrokinetic instability (EKI) and to explore the effectiveness to enhance fluid mixing inside a Y-shaped microchannel by manipulating convective EKI waves. The dependence of the critical voltage of applied static electric field to trig EKI to generate convective EKI waves on the conductivity ratio of the two adjacent streams was quantified at first. The effect of the strength of the applied static electric field on the evolution of the convective EKI waves and fluid mixing process were assessed in terms of scalar concentration fields, shedding frequency of the convective EKI waves and scalar mixing efficiency. The effectiveness of manipulating the convective EKI waves by introducing alternative electric perturbations to the applied static electric fields was also explored for the further enhancement of the fluid mixing process inside the Y-shaped microchannel.

INTRODUCTION

Two-fluid mixing is an essential process for many microfluidic or “lab-on-a-chip” devices. Various biomedicial and biochemical processes, such as DNA purification, polymerase chain reaction (PCR), enzyme reaction, and protein folding, involve the mixing of two fluids. The performance of such processes depends heavily on the mixing effectiveness and rapidness of the samples and reagents. However, effective mixing of two fluids inside microchannels could be challenging since turbulence is usually absent due to the low Reynolds numbers of the microflows in nature. Therefore, the studies aimed to develop novel techniques and methodologies to enhance diffusion-dominated fluid mixing processes and to increase the interfacial contact surface area between the adjacent streams inside microchannels is very important and necessary for improved performances of microfluidic or “lab-on-a-chip” devices.

In recent years, extensive studies have been conducted to develop novel techniques and methodologies to enhance fluid mixing inside microchannels. Several innovative concepts of “micro-mixers” have been proposed through those studies. In general, the proposed “micro-mixers” can be categorized into two groups: passive mixers and active mixers [1]. Passive mixers do not require external energy; the enhanced mixing process relies entirely on the augmentation of diffusion or chaotic advection through special geometrical design of microchannels. In contrast, active mixers usually rely on adding external energy to introduce disturbances to enhance fluid mixing. Relying on generating external disturbances in terms of temperature [2], pressure [3, 4], electrohydrodynamics [5], dielectrophoretics [6], magnetohydrodynamics [7] as well as acoustics [8], several kinds of active micro-mixers have been proposed to effectively enhance fluid mixings in microchannels. In this study, we report an experimental study to explore the effectiveness of achieving fluid mixing control/enhancement inside a Y-shaped microchannel with an active control method of using electrokinetic instability.

Electrokinetic instability (EKI) occurs when two streams with different electric conductivities meet in a microchannel under a static electric field as shown schematically in Fig. 1. If the strength of the applied static electric field exceeds a certain threshold value, the flow instability of adjacent streams could be observed in a sinuous form along the downstream [9, 10]. The conductivity gradient subject to an external electric field has been suggested as a source of electrical charges and the Coulombic force acts to generate additional body force [11]. Relevant to the mechanism of electrokinetic instability, Hoberg & Melcher [11] showed that the interface of miscible fluids with conductivity gradient becomes unstable under a normal electric field in an unbounded domain. Baygents & Baldessari [12] suggested that the flow generated in isoelectric focusing devices is a consequence of the free charges generated by the electric field applied normally to the conductivity gradient.

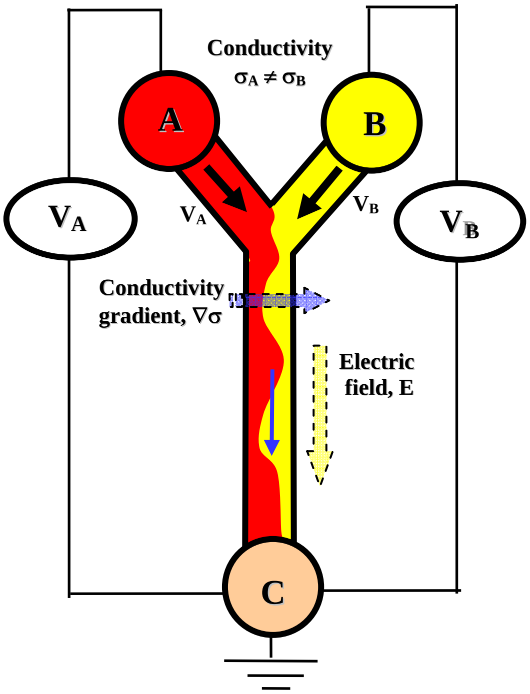


Fig.1. Schematic of electrokinetic instability

Several studies have already been conducted in recent years to try to enhance fluid mixing processes inside microchannel by using EKI. Applying a sinusoidally-alternating electric field at two ends of a microchannel, Oddy et al. [13] studied EKI in a rectangular microcahnnel. The changing of the flow structures induced by EKI was visualized from the images of the seeded tracer particles as well as measured fluorescent dye concentration fields. They proposed a concept of novel micro-mixing enhancement devices that using EKI as the mechanism for rapidly stirring of two fluid streams inside microchannels. Park et al. [14] studied the fluid mixing process enhanced by using EKI with different designs of T-shaped microchannels. They reported that microchannels with cavity structures at the walls could produce a repetitive vortex pattern which results in a higher mixing efficiency than that of a straight channel under the same electric field. Shin et al. [15] used an alternating electric field to manipulate EKI as a means of fluid mixing enhancement in a cross-shaped microchannel. Recently, Jonathan et al. [16] studied convective EKI in a cross-shaped microchannel using quantitative epi-fluorescence imaging technique. They reported that the required strength of the applied static electric field to trig EKI depends on both the centre-to-sheath conductivity ratio and the applied field ratio.

In this study, we report a parametric study to further our understanding about the fundamental physics of EKI and to explore the effectiveness to enhance fluid mixing inside a Y-shaped microchannel by manipulating convective EKI waves. Epi-fluorescence imaging technique is used to conduct qualitative flow visualization and quantitative scalar concentration distribution measurements to quantify the manipulated mixing process in terms of scalar concentration field, shedding frequency of the EKI waves and scalar mixing efficiency. The objectives of the present study is to provide detailed experimental results to further our understanding about the fundamental nature of EKI; to quantify the effects of the relevant parameters such as the conductivity ratio of adjacent streams, strength of the applied static electric field, and the frequency and amplitude of perturbing alternating electric fields on the effectiveness of EKI fluid mixing control/enhancement; and to explore/optimize design paradigms for the development of robust electrokinetic micromixers for various microfluidics or “lab-on-a-chip” applications.

EXPERIMENTAL DETALS

The Y-shaped channel used in the present study is made of poly-di-methyl-siloxane (PDMS) by using a rapid-prototyping “photolithography” technique [17]. The dimensions of the microchannel are given in Fig. 2. The cross section of the channel is rectangular with 320 µm in width and 130 µm in height. The length of the two inlet branches is 15.0mm, and the angle between the branches is 90.0^{0}. The length of the mixing channel is 40.0mm. Relatively large reservoirs at inlets and outlet of the Y-shaped channel are designed in order to minimize the induced pressure head differences between the inlets and outlet during the experiments.

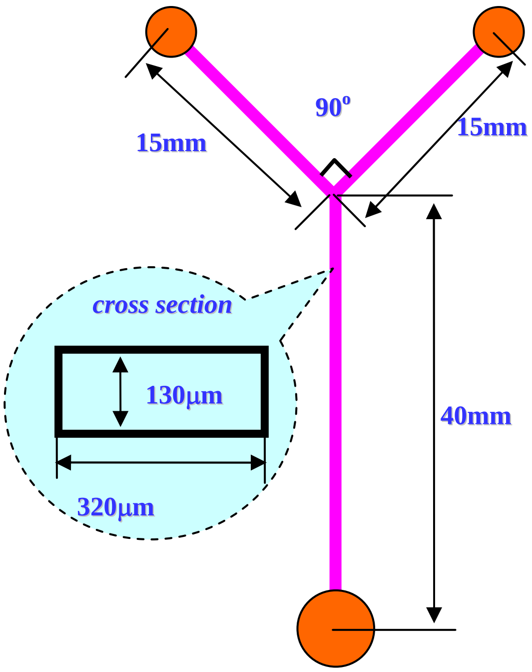


Fig. 2. The schematic of the Y-shaped microchannel

Deionized water was used as the working fluid in the present study. The DI water was filtered by using a syringe filter unit (Millipore millex-FG, Bedford, 0.2µm) before experiments. Borate buffers (Science Stuff Inc) were used to adjust the molecular conductivity of the two fluid streams from the inlet reservoirs R-A and R-B. Rhodamine B, which is reported to be neutral for pH values ranging 6.0 to 10.8 [18], is used as the fluorescent dye for qualitative flow visualization and quantitative scalar concentration measurements. Since the molar concentrations of the borate buffers (<1mM) and Rhodamine B (< 0.16 mM) are low, the changes in water physical properties such as the permittivity and viscosity due to adding the borate buffers and Rhodamine B are believed to be negligible. DI water was used to flush the channel several times prior to use for experiments.

Figure 3 shows the schematic of the experimental setup used in the present study. The microchip with the Y-shaped microchannel was placed on the test bed of an inverted fluorescent microscope (Leica DM-IL). A high-voltage DC power supply (Keithley, Model 247) was used to provide a static electric field between the reservoirs R-B and R-C. A function generator (Instek, Model GFG-8250A) and a high-voltage amplifier (Trek, Model 609-E) were used to apply static or a static electric field plus an alternating perturbation between the reservoir R-A and R-C. The electrodes installed in the reservoirs are made of platinum.

A mercury lamp was used as the illumination source. Passing through an epi-fluorescent prism (Excitation Filter of 532nm with 10nm BP, Dichroic 532nm RDC, Emitter of 610nm with 75 nm BP), the bright light from the mercury lamp is used to illuminate the Rhodmamine B molecules seed in the stream from the inlet reservoir R-A. Upon excitation, the seed fluorescent tracer, Rhodmine B molecules, will emit fluorescence with its emission peak at about 580nm. A 10X objective lens (NA=0.4) was used for the fluorescence imaging. The fluorescence light will pass through the Dichroic mirror and emitter filter to form images captured by a high-resolution CCD camera (SensiCam-QE, Cooke Corp). The CCD camera was connected to a workstation (host computer) via a digital delay generator (Berkeley Nucleonics, Model 565) for the image acquisition timing control, data storage and imaging processing. For the present study, the exposure time of the CCD camera was set as 7ms. 500 fluorescence images were recorded at a frame rate of 10 Hz for each case of the experiments.

It should be noted that the depth averaging along the optical axis is an artefact of epi-fluorescence imaging to study microflows. All the fluorescent molecules across the imaging depth of the 10X objective would contribute to the measured fluorescence intensity. Based on the formula suggested by Inoue&spring [19], the depth of focus for the 10X (NA=0.4) objective used in the present study is estimated to be about 5.0 µm. For all the experimental results reported at here, the focus plane of the objective was set in the middle plane of the 100 µm deep microchannel.

It is well known that the collected fluorescence intensity is proportional to the amount of the fluorescent molecules in the flow for diluted solution and unsaturated excitation. Quantitative scalar concentration distribution in the microflow can be derived from the acquired fluorescence images. The effects of the non-uniformity of the illumination intensity, background noise, the dark current of the CCD camera were corrected in the present study in order to minimize the measurement errors in the determination of scalar concentration distributions to quantify the scalar mixing process [16].

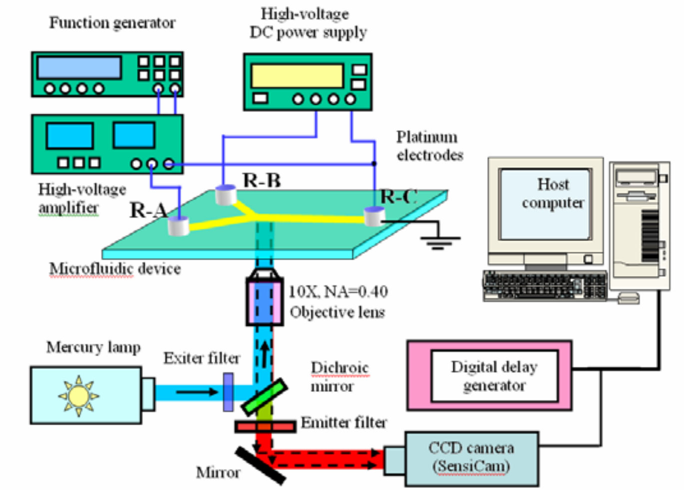


Fig. 3. Experimental setup

QUANTIFICATION OF MIXING EFFECTIVENESS

Following the work of Johnson et al. [20], a statistic approach was used in the present study to quantify the enhanced mixing process of the two adjacent streams induced by convective EKI waves under applied electric fields.

After a procedure to correct the effects of the non-uniformity of the illumination intensity, background noise and the dark current of the CCD camera, the acquired fluorescence images were used to calculate the fluid mixing efficiency, η, which is defined as:

$$\eta = 1 - \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(I_i - I_{ip})^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(I_{io} - I_{ip})^2}} ,$$

where N, I_i, I_{io} and I_{ip} represent the total number of pixels, fluorescence intensity at the i*th* pixel, the fluorescence intensity at the i*th* pixel without any mixing or diffusion, and the fluorescence intensity at the i*th* pixel for a homogenous mixtures, respectively.

When the two stream are perfectly mixed, every pixel should of course has the same intensity equals to averaged value of all partially mixed pixel intensities, i.e., $I_{ip} = \frac{1}{N}\sum_{i=1}^{N} I_i$. One the other hand, if the two streams do not mixed at all, half of the pixels that belongs to dark stream should have zero-intensity, while the other half in the fluorescent stream should have an intensity of I_{io}. Thus, I_{io} distribution was determined by setting the image intensity at bright half of the channel to $2I_{ip}$ and the opposite of the channel to zero. The mixing efficiency, η, ranges from 0 to 1 with η =1 indicating completely mixing, and η =0 no mixing.

EXPERIMENTAL RESULTS AND DISCUSSIONS

1. The effect conductivity ratio on the critical voltage of applied static electric field

Chen et al. [9] reported that convective EKI waves can be observed in forms of downstream propagating sinuous waves only when the voltage of the applied static electric field exceeds a certain threshold value, i.e., there exists a critical voltage of the applied static electric field in order to “trig” EKI to generated convective EKI waves. Jonathan et al. [16] reported that the critic voltage of the applied static electric field depends on both the centre-to-sheath conductivity ratio and the applied field ratio. We conducted a parametric study to quantify the effect of the conductivity ratio of the two adjacent streams on the critical applied static electric field to trig EKI. During the experiments, we kept the concentration of borate buffer in inlet reservoir R-B constant at 10mM, the concentration of the borate buffer in inlet reservoir R-A is changed from 0.1mM to 5mM to make the conductivity ratio between the two steams inside the microchannel, $\gamma = \sigma_B / \sigma_A$, being 2:1, 5:1, 10:1, 50:1 and 100:1. Rodamine B molecules were seeded in the stream of inlet reservoir R-A as the fluorescent tracer to visualize the evolution of the interface between the two adjacent streams.

In order to determine the critic voltage of the applied static electric field to trig EKI at a selected conductivity ratio, a small static voltage was applied between the inlets and outlet of the Y-shaped microchannel at first. Then, the voltage of the applied static electric field was increased in steps of every 25 volts until noticeable fluctuations of the interface between the two adjacent streams can be observed. During the experiments, same static voltage was applied to both inlet reservoirs R-A and R-A all the time, i.e., $V_A = V_B$. The required minimum voltage to induce observable fluctuations of the interface between the two adjacent streams is defined as the critical voltage of the applied electric field at that selected conductivity ratio.

Figure 4 shows the measured critical voltage of the applied static electric field as a function of the conductivity ratio between the two adjacent streams inside the Y-shaped microchannel. It can be seen that the critical voltage of the applied static electric field decreases rapidly with the increasing conductivity ratio of the two adjacent streams. The critical voltage was found to be about 900V as the conductivity ratio being 2. It drops to about 350V as the conductivity ratio increases to 100. This can be explained by that a larger conductivity ratio between the two adjacent streams would induce a higher free charge density, ρ_e, as suggested by Hoberge & Melcher [11] with a relationship of $\rho_e = -\frac{\varepsilon}{\sigma}\nabla\sigma \bullet E$, where σ the electrical conductivity of the fluid, ε the electrical permittivity of the fluid, and E the external electric field. The greater induced electric charges coupled with the applied external electric field would generate a stronger Coulombic force at the interface of the two adjacent streams to overcome the dissipative effects of the molecular diffusion to promote EKI. Therefore, critical voltage of the applied static electric field would decrease with the increasing conductivity ratio of the adjacent streams. Same trend was also reported by Jonathan et al. [16] when they studied the convective instability of electrokinetic flows in a cross-shaped micro-channel.

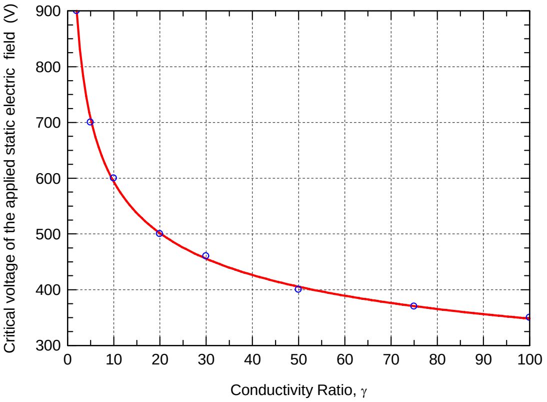


Fig. 4. The effect of conductivity ratio on the critical voltage of the applied static electric field

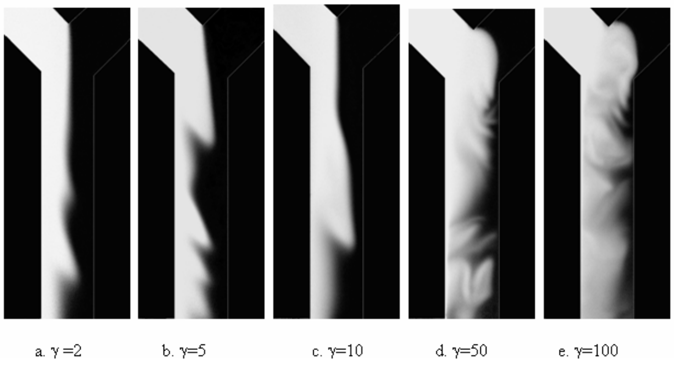
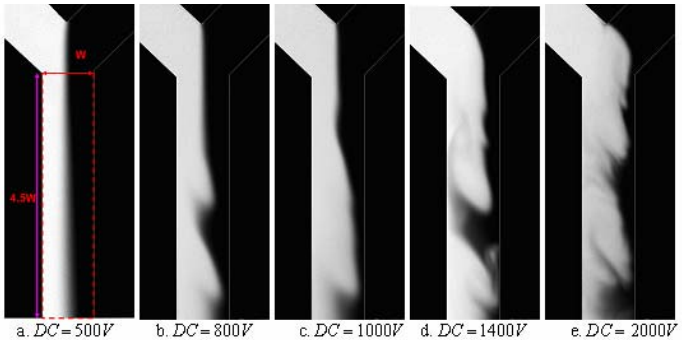

a. γ=2 b. γ=5 c. γ=10 d. γ=50 e. γ=100

Fig. 5. The effect of the conductivity ratio γ on the mixing process ($V_A = V_B = 1000V$).

Figure 5 shows the instantaneous fluorescence images of the mixing flows with different conductivity ratio but under same static electric field applied of $V_A = V_B = 1000V$. Even though the applied static electric field was kept as constant, the fluid mixing was found to become much more turbulent and intense as the conductivity ratio increases, i.e., the mixing process between the two adjacent streams was found to be enhanced as the conductivity ratio increases.

2. The effect of the applied static electric field on the evolution of the convective EKI waves

A systematical experimental study was conducted to investigate the effect of the strength of the applied static electric field on the evolution of the convective EKI waves and the mixing process inside the microchannel. During the experiment, the conductivity ratio between the two streams from the inlet reservoir R-A and R-B is kept as constant, i.e., $\gamma = 10$. Same static voltage was applied to both the inlet reservoirs R-A and R-B, i.e., $V_A = V_B$. The voltage was varied from 500V to 2000V.



a. $DC = 500V$ b. $DC = 800V$ c. $DC = 1000V$ d. $DC = 1400V$ e. $DC = 2000V$

Fig. 6. The effect of the voltage of the applied static electric field ($\gamma = 10$) on the evolution of the EKI waves.

Figure 6 shows typical fluorescence images with different strength of the applied static electric field. As visualized clearly in the images, the interface between the two adjacent streams was found to be straight and "clean" as the applied static voltage is relatively weak (i.e., less than 600V). No noticeable fluctuations or oscillations of the interface between the two adjacent streams can be observed. The fluid mixing was found to concentrate in a very thin layer along the straight interface, and the fluid mixing process was found to be conducted purely based on molecular diffusion. As the applied voltage becomes greater than 600V, the interface between the two adjacent streams was found to fluctuate and generate observable convective EKI waves propagating downstream. The generation of the convective waves was found to be periodic. Fluctuation amplitude of the interface and the size of the convective waves were found to increase rapidly with the increasing applied static voltage. When the applied static voltage is less than 1200V, the interface between the two adjacent streams was found to be still quite "clean" and "laminar" even though it was curved due to the periodic generation of the EKI waves. As the applied static voltage becomes higher than 1200V, smaller waves were observed in between big downstream propagating EKI waves. The smaller waves were found to grow up rapidly with the increasing applied static voltage. The generation of the EKI waves was found to become quite random, and the interface between the adjacent streams becomes much fussier. Some EKI waves were found to propagate upstream as the applied static voltage becomes higher than 1400V, and mixing process between the two adjacent streams was found to become much more turbulent and intensive.

In order to reveal the effect of the strength of the applied static electric field on the EKI mixing process inside the microchannel more quantitatively, the fluid mixing efficiency of the two streams under different applied static voltages were calculated. The interrogation area used for the fluid mixing efficiency calculation is shown in Fig 6 (a), and the results were given in Fig. 7. It can be seen clearly that the mixing efficiency increase monotonically with the increasing applied static voltage.

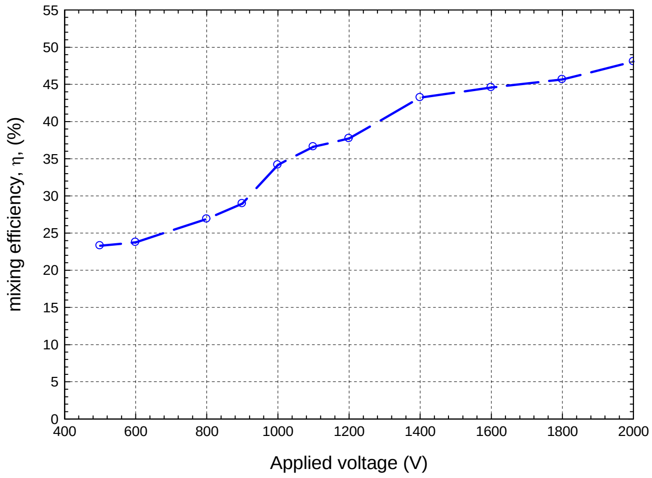


Fig. 7. The mixing efficiency VS the applied static voltage

3. Manipulating the convective EKI waves and mixing process with alternative electric perturbations

We conducted a comprehensive study to explore the effectiveness of using alternative electric perturbations to manipulate the evolution of the convective EKI waves to enhance fluid mixing between the two adjacent streams in the Y-shaped microchannel. During the experiments, while same static voltage of 1000V was applied between the inlets R-A, R-B and outlet R-C, an alternative voltage was used as the perturbations riding on the static electric field of 1000V applied between the inlet reservoir R-A and outlet R-C, i.e.: $V_A = V_{DC} + \tilde{V}_{AC} = V_{DC} + A_{AC}\sin(2\pi f_{AC})$; $V_B = V_{DC}$. By changing the frequency and amplitude of the alternative perturbations, the effects of the alternative electric perturbations on the evolution of the convective EKI waves and fluid mixing process in the microchannel were studied.

3a. The effect of the frequency of alternative electric perturbations

Based on the time sequence of the acquired fluorescence images, the shedding frequency of the convective EKI waves can be derived. The shedding frequency of the convective EKI waves under a static voltage of 1000V between the inlets and the outlet of the Y-shaped microchannel was found to be 0.60 Hz (i.e., $f_{natural} = 0.60$). We conducted a systematical study to investigate the effect of the frequency of alternative electric perturbations on the evolution of the convective EKI waves and the fluid mixing in the microchannel. During the experiment, the amplitude of the alternative electric perturbation was kept as constant, i.e., V_{AC} =250V. The frequency of the alternative electric perturbation changes from 0.1 Hz to 100 Hz.

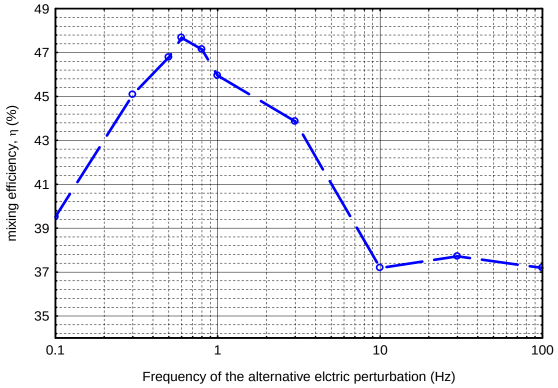


Fig. 8. The effect of the alternative electric perturbation frequency on the mixing efficiency

Figure 8 shows the profile of the fluid mixing efficiency as a function of the frequency of the applied alternative electric perturbation. It can be seen clearly that the mixing efficiency profile reaches its peak when the frequency of the applied alternative electric perturbation being about 0.6Hz, which equals to the natural shedding frequency of the convective EKI waves under a static voltage of 1000V without any alternative electric perturbations. The measurement results revealed that the mixing process can be most enhanced when the frequency of the applied alternative electric perturbation equates to the natural shedding frequency of the convective EKI waves. This fact may be explained based on the concept of hydrodynamic resonance, which has been widely employed in many active flow control studies [21, 22]. The existence of the optimal perturbation frequency is expected to provide a valuable guideline for the design of an efficient micro-mixer by using EKI.

It should be noted that Shin et al. [15] reported that the optimum frequency of the applied alternative electric field is close to double shedding frequency of the convective EKI waves when they studied EKI mixing process within a cross-shaped channel. For the study of Shin et al. [15], the fluid mixing inside the cross-shaped channel involves three streams with two interfaces (i.e., two high-conductivity-gradient layers) across the mixing channel. In the present study, two-stream mixing was studied with only one interface (i.e., one high-conductivity-gradient layer) across the microchannel. The inconsistency about the optimum frequency of the applied alternative electric field between the present study and Shin et al. [15] is believed to be closely related to the differences of the mixing type (two-stream mixing vs. three-stream mixing) and number of interfaces (one high-conductivity-gradient layer vs. two high-conductivity-gradient layers) involved in the two studies.

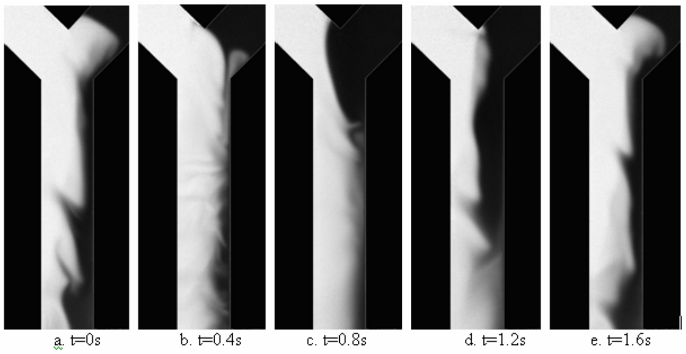

a. t=0s b. t=0.4s c. t=0.8s d. t=1.2s e. t=1.6s

Fig. 9. Instantaneous fluorescence images within one circle of the applied AC electric field (f_{AC} =0.6Hz)

Figure 9 shows the phase-resolved flow visualization images of the mixing process within one period of the applied alternative electric perturbation. The evolution of the convective EKI waves and the dynamics of the EKI mixing process under the excitation of the applied alternative electric perturbation were revealed clearly for the images.

3b. The effect of the amplitude of the alternative electric perturbation on the evolution of the EKI waves

As described above, the fludi mixing process was found to be mostly enhanced when the frequency of the alternative electric perturbation equates to the natural shedding frequency of the convective EKI waves. Therefore, the frequency of the applied alternative electric perturbation was set to equate to the natural shedding frequency of the convective EKI waves when we studied the effect of the amplitude of the applied alternative electric perturbation on the evolution of the EKI waves and the fluid mixing process. During the experiment, we chose parameters of V_{DC} =1000V, f_{AC} =0.60Hz. The amplitude of the alternative electric perturbation, A_{AC}, was changed from 50V to 500V.

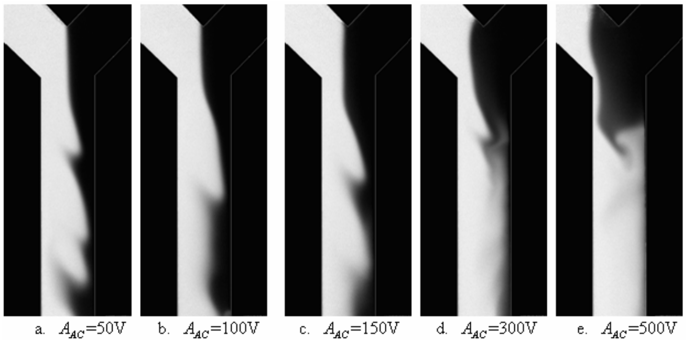

a. A_{AC}=50V b. A_{AC}=100V c. A_{AC}=150V d. A_{AC}=300V e. A_{AC}=500V

Fig.10. The effect of the amplitude of the alternative electric perturbation on the EKI mixing process

Fig. 10 shows some typical fluorescence images to visualize the effect of the amplitude of the alternative electric perturbation on the evolution of the EKI waves and the mixing process inside the microchannel. It was found that the applied alternative electric perturbation does not have any noticeable effects on the evolution of the convective EKI waves when the amplitude of the alternative electric perturbation is relatively small (A_{AC}<200V). When the amplitude of the alternative electric perturbation becomes relatively big (A_{AC}>200), the EKI mixing process was found to be affected greatly by the alternative electric perturbation.

In order to reveal the effect of the amplitude of the alternative electric perturbation on the fluid mixing process more quantitatively, fluid mixing efficiency with different amplitudes of the applied alternative electric perturbations were calculated, and the results were shown in Fig. 11. The mixing efficiency was found to increase slowly with the amplitude of the applied alternative electric perturbation when perturbation amplitude is relatively small (A_{AC}<200V). The mixing efficiency was found increase rapidly with the increasing perturbation amplitude when the amplitude of the alternative electric perturbation becomes relatively big (A_{AC} > 200V).

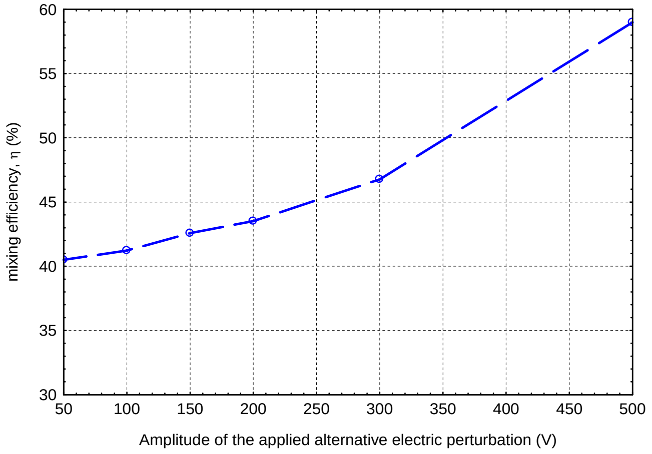


Fig.11. fluid mixing efficiency vs. the amplitude of the alternative electric perturbation

CONCLUSIONS

An experimental study was conducted to further our understanding about the fundamental nature of electrokinetic instability (EKI) and to explore the effectiveness of manipulating convective EKI waves to enhance fluid mixing inside a Y-shaped microchannel. Following conclusions were obtained as the outcomes of the present study:

1. There exists a threshold value for the applied static electric field, i.e., critical static electric field, to "trig" EKI to generate convective EKI waves at the interface of the adjacent streams. The critical static electric field was found to heavily depend on the conductivity ratio of the two adjacent streams.

2. The generated connective EKI waves were found to propagate downstream with their size growing rapidly as the increasing strength of the applied static field. Smaller waves were found to be generated between big EKI waves when the applied static electric field becomes relatively strong. The EKI waves were found to propagate upstream and downstream randomly as the applied static electric field becomes more significant, which makes the fluid mixing process between the two adjacent streams much more turbulent and intense.

3. The periodic shedding of the EKI waves and the fluid mixing process between the two adjacent streams can be manipulated effectively by adding alternative electric perturbations to the applied static electric field. The mixing process was found to be most enhanced when the frequency of the alternative perturbation equates to the natural shedding frequency of the convective EKI waves. This fact may be explained based on the concept of hydrodynamic resonance.

4. The enhanced EKI mixing process was found to be sensitive to the amplitudes to the applied alternative electric perturbations. The mixing efficiency was found to increase monotonically with the increasing amplitude of the applied alternative electric perturbation.

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