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REGULAR PAPER

Zheyan Jin · Hui Hu

# Mixing enhancement by utilizing electrokinetic instability in different Y-shaped microchannels

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**Abstract** An experimental study was conducted to assess the effectiveness of manipulating convective electrokinetic instability (EKI) waves to control/enhance fluid mixing inside three Y-shaped microchannels, which includes a conventional straight channel, a channel with micro-cavities, and a channel with micro-steps. Epi-fluoresence imaging technique was used to conduct qualitative flow visualization and quantitative scalar concentration field measurements inside the microchannels. The effects of the applied static and alternating electric fields on the evolution of the convective EKI waves and the resultant fluid mixing process were quantified in terms of scalar concentration distributions, shedding frequency of the EKI waves, fluid mixing efficiency and mixing augmentation factor. While the fluid mixing efficiency was found to increase monotonically with the increasing strength of the applied static electric fields for all the studied microchannels, the channel with micro-cavities was found to have the best overall mixing enhancement performance among the three studied microchannels. It was found that fluid mixing processes in the microchannels would be further enhanced by adding alternating electric perturbations to the applied static electric fields, regardless the frequency and magnitude of the alternating electric perturbations. The fluid mixing process would be most enhanced when the frequency of the alternating electric perturbations is close to the "natural frequency" of the EKI waves (i.e., the shedding frequency of the EKI waves with the applied static electric fields only).

**Keywords** Electrokinetic instability · Fluid mixing enhancement · Microfluidics · Epi-fluorescence imaging technique

## 1 Introduction

Two-fluid mixing is an essential process in many microfluidic or "Lab-on-a-Chip" devices. For example, various biomedical and biochemical processes, including DNA purification, polymerase chain reaction, enzyme reaction and protein folding, involve the mixing of two fluids. The performance of such processes relies on effective and rapid mixing of samples and reagents. However, effective mixing of two fluids inside microchannels could be very challenging since turbulence is usually absent due to the nature of low Reynolds numbers of the microflows. Therefore, development of novel techniques and methodologies to enhance the diffusion-dominated fluid mixing processes inside microchannels is very important and

Z. Jin (✉)
School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 20092, China
E-mail: zheyanjin@tongji.edu.cn

H. Hu
Department of Aerospace Engineering, Iowa State University, Ames, IA 50011, USA
E-mail: huhui@iastate.edu

necessary in order to improve the performance of such microfluidic devices (Campbell and Grzybowski 2004; Nguyan and Wu 2005).

In recent years, more and more attentions have been drawn to use electrokinetic instability (EKI) as an active flow control method to enhance fluid mixing in microchannels. EKI occurs when two streams with different electric conductivities meet in a microchannel under an applied 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 interface of the mixing streams. Oddy et al. (2001) is the first to use EKI to manipulate fluid mixing process in a microchannel. Chen et al. (2005) conducted a pioneer study to elucidate the underlying fundamental physics of EKI and associated flow phenomena in a T-shaped microchannel. They reported that EKI can be observed as convective waves propagating downstream as the strength of the applied static electric field exceeds a threshold value (i.e., the critical strength of the applied electric field), which corresponds to the convectively unstable mode of the EKI. When the strength of the applied electric field becomes relatively high, upstream propagating waves were observed, indicating the mode of absolute instability. Posner and Santiago (2006) studied the behavior of EKI waves in a cross-shaped microchannel under a wide range of the applied static electric fields and conductivity ratios of the center-to-sheath streams. They found that the required critical strength of the applied static electric field depends on both the center-to-sheath conductivity ratio and the ratio of the static voltages applied to different branches of the cross-shaped microchannel. Shin et al. (2005) demonstrated for the first time that adding an alternating electric perturbation to the applied static electric field could manipulate convective EKI waves to either enhance or suppress the fluid mixing process in a cross-shaped microchannel depending on the frequency of the alternating perturbation. Park et al. (2005) investigated the mixing enhancement in T-shaped microchannels by using static electric field to generate the EKI. Cavity structures on the wall were found to produce a repetitive vortex pattern yielding a higher mixing efficiency than that of a straight channel. Tai et al. (2006) studied a T-shaped micromixer featuring 45° parallelogram barriers (PBs) within the mixing channel and reported that the height of PBs has obvious effects on both required critical electric field strength and mixing efficiency. Huang et al. (2006) studied a cross-shaped microfluidic mixer featuring embedded a pair barrier and presented the effects of a pair barrier on the critical electric field. More recently, with the consideration of wide applications of two-stream mixing systems in Y-shaped microchannels, Jin et al. (2008) and Hu et al. (2008) conducted experimental studies to explore the effectiveness of manipulating convective EKI waves to control/enhance fluid mixing inside straight Y-shaped microchannels.

As far as two-fluid mixing in microfluidic devices (i.e., using EKI as an active mixer) is concerned, although many important results have already been obtained through those previous studies, much work is still needed for the development of effective and robust EKI micro-mixers for various microfluidics or

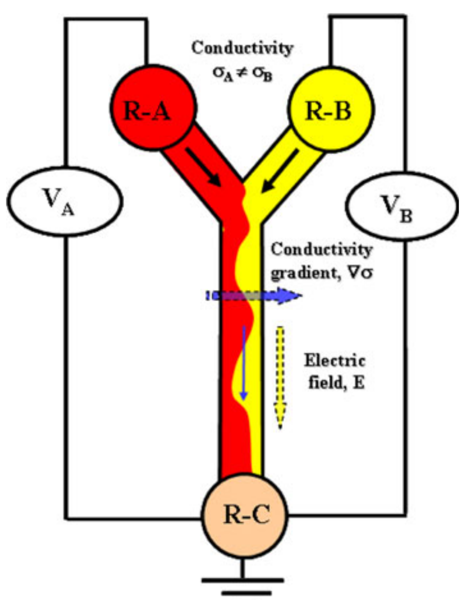


**Fig. 1** Schematic of EKI

"Lab-on-a-Chip" applications. For examples, so far, only Park et al. (2005) and Tai et al. (2006) have studied the effects of different geometries of T-shaped microchannels on mixing enhancement performance, and they both applied static electric fields only to produce convective EKI waves. To the authors' best knowledge, no studies have ever been explored to quantify the effects of different geometries of micro-structures inside Y-shaped microchannels on the fluid mixing enhancement/control by applying both static and alternating electric field to manipulate convective EKI waves. With this in mind, we carried out the present study to further our understanding about EKI and to explore/optimize design paradigms for the development of robust EKI micro-mixers for various microfluidics applications.

In the present work, an experimental study was conducted to assess the effectiveness of manipulating EKI waves to control/enhance fluid mixing inside three Y-shaped microchannels, which includes a conventional straight channel, a channel with micro-cavities, and a channel with micro-steps. Epi-fluoresence imaging technique was used to conduct qualitative flow visualization and quantitative scalar concentration field measurements inside the microchannels. The effects of the relevant parameters, such as the strength of the applied static electric fields and the frequency and amplitude of the applied alternating perturbations, on the evolution of the EKI waves and the resultant fluid mixing in the microchannels were examined quantitatively in terms of scalar concentration distributions, shedding frequency of the EKI waves, fluid mixing efficiency and mixing augmentation factor (MAF).

## 2 Experimental details

By using the rapid-prototyping "photolithography" micro-fabrication technique, the Y-shaped microchannels used in the present study are made of poly-di-methyl-siloxane and glass. The dimensions of the three studied microchannels are given in Fig. 2. The channels are 320 μm in width and 130 μm in height. The two upper branches are 15.0 mm in length, which form an angle of 90.0°, while the length of the mixing channel is 40.0 mm. The specific micro-structures near the conjunctions for the three studied microchannels are enlarged and shown in Fig. 2 as well. Relatively large reservoirs at the inlets and outlets of the Y-shaped microchannels are designed in order to minimize the effects of the pressure head differences between the inlets and outlets during the experiments.

Deionized (DI) water was used as the working fluid in the present study. The DI water was filtered by a syringe filter unit (Millipore millex-FG, Bedford, 0.2 μm) before experiments. Borate buffers (Science Stuff Inc.) were used to adjust the molecular conductivity of the two fluid streams. Rhodamine B, which is reported to be neutral for pH values ranging 6.0–10.8 (Schrum et al. 2000), was used as the fluorescent dye for qualitative flow visualization and quantitative scalar concentration measurements. Since the molar concentrations of borate buffers ($\leq$10 mM) and Rhodamine B (0.16 mM) are quite low, the changes in water physical properties such as the permittivity and viscosity are negligible. DI water was used to flush the microchannels several times prior to use for experiments. For all the tests, Rhodamine B was dissolved in 10 mM Sodium borate solution to a final concentration of 0.16 mM and the mixture was put into reservoir

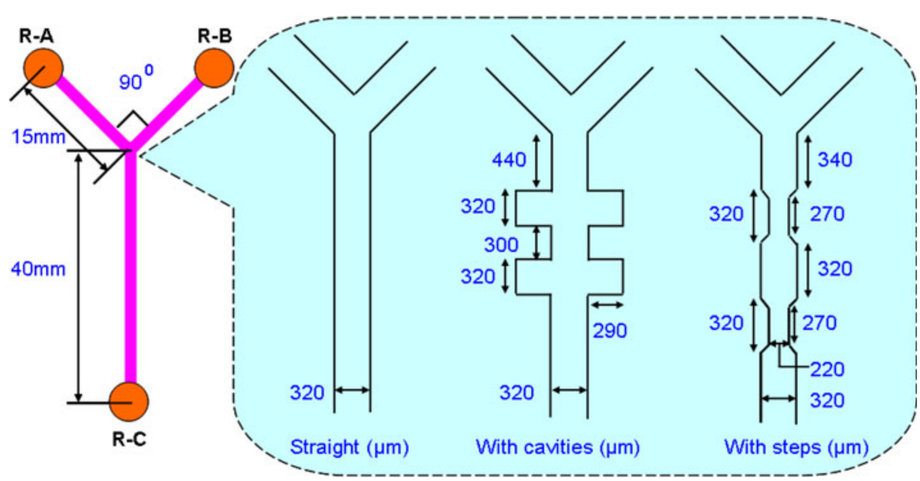


**Fig. 2** Schematic of the three studied Y-shaped microchannels

R-A, while reservoir R-B contains Sodium borate solution (1 mM) only. Thus, the conductivity ratio of the two adjacent streams in the microchannels was 10 for the present study.

Figure 3 shows the schematic of the experimental setup used in the present study. A 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 combined to produce an alternating electric field to inlet reservoir R-A, which can be expressed as

$$V = V_{DC} + V_{AC}\sin(2\pi ft), \quad (1)$$

where $V_{DC}$ is the magnitude of the static electric potential applied to reservoir R-B, $V_{AC}$ the magnitude of the alternating electric perturbation imposed on the static electric potential and $f$ the frequency of the alternating electric perturbation. The electrodes put into the reservoirs are made of platinum.

A mercury lamp was used as the illumination source in the present study. Passing through an epi-fluorescent prism (Excitation Filter of 532 nm with 10 nm BP, Dichromic 532 nm RDC, Emitter of 610 nm with 75 nm BP), the bright light from the mercury lamp was used to excite the Rhodamine B molecules seeded in the stream from reservoir R-A. The excited Rhodamine B molecules would emit fluorescence with its emission peak at about 580 nm. Through a 10× objective, a high-resolution CCD camera (SensiCam-QE, Cooke Corp) was used to acquire the fluorescence images. The CCD camera was connected to a workstation (host computer) via a digital delay generator (Berkeley Nucleonics, Model 565) for the timing control of the image acquisition, data storage and imaging processing. For the present study, the exposure time of the CCD camera was set as 7.0 ms. 500 instantaneous fluorescence images were captured at a frame rate of 10 Hz for each test case.

It should be noted that the depth averaging along the optical axis is an artifact of epi-fluorescence imaging to study microflows. All the fluorescent molecules across the imaging depth of the 10× objective would contribute to the measured fluorescence intensity. Based on the formula suggested by Inoue and Spring (1997), the depth of focus for the 10× (NA = 0.4) objective used in the present study is estimated to be about 5.0 μm. For all the experimental results reported here, the focus plane of the 10× objective was set in the middle plane of the 130 μm depth microchannel.

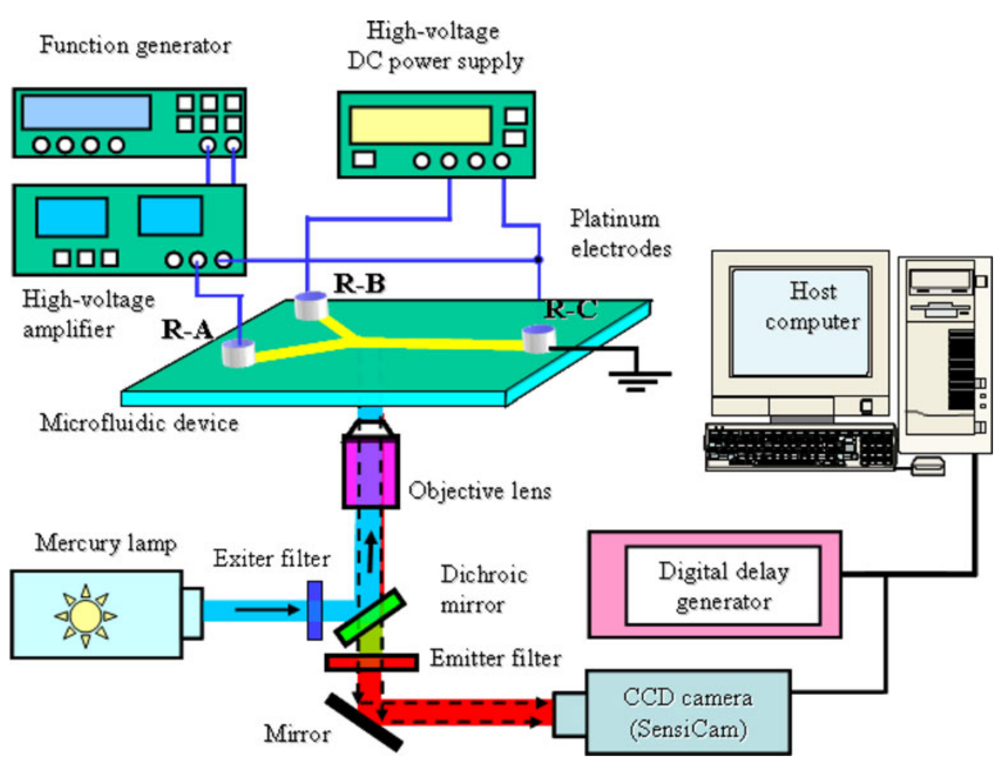


**Fig. 3** Schematic of experimental setup

## 3 Quantification of fluid mixing effectiveness

In order to correct the effects of the non-uniformity of the illumination intensity, background noise and the dark current of the CCD camera, we use the method suggested by Posner and Santiago (2006) to obtain the concentration at each pixel:

$$C_i(x,y) = \frac{I_i(x,y)_{\text{raw}} - \overline{I(x,y)_{\text{dark}}}}{\overline{I(x,y)_{\text{flat}}} - \overline{I(x,y)_{\text{dark}}}} \tag{2}$$

where

$$\overline{I(x,y)} = \frac{\sum_{i=1}^{n} I_i(x,y)}{n} \tag{3}$$

The instantaneous image index is $i$ and the subscripts raw, flat and dark denote the raw, flat-field and dark-field images, respectively. The flat-field images are recorded with the channels filled with a uniform concentration of dye to correct illumination non-uniformity and detector response. The dark-field images are recorded with the channels filled with buffer. The dark-field images correct for external light scattered off channel walls and not chromatically filtered fluorescence of wall adsorbed dye, and sensor dark-noise. Two hundred dark and flat-field images are recorded before each experiment.

Following the work of Johnson et al. (2002), a statistical approach was used in the present study to quantify the fluid mixing process in the Y-shaped microchannels. The mixing efficiency in the region of interest is defined as:

$$\eta = 1 - \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_i - C_{\text{ip}}\right)^2}}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(C_{i0} - C_{\text{ip}}\right)^2}} \tag{4}$$

where $n$ is the total number of pixels in the interest region, $C_i$ the concentration at the $i$th pixel, $C_{i0}$ the concentration at the $i$th pixel with no mixing or diffusion and $C_{\text{ip}}$ the concentration at the $i$th pixel for a homogeneous mixture (i.e., perfect mixing). The concentration values for $C_{i0}$ were determined by doubling the concentration profile, $C_{\text{ip}}$, at half the channel width, and then setting the concentration of the opposite half of the channel to zero. The mixing efficiency $\eta$ would vary from 0 to 1.0 with $\eta = 0$ indicating no mixing and $\eta = 1.0$ for perfect mixing. In the present study, for each acquired instantaneous image, the instantaneous mixing efficiency in the region of interest (as shown in the Fig. 4) was calculated by using the Eq. 4 at first. Then, the averaged mixing efficiency was obtained based on 500 instantaneous measurements for each test case.

In order to quantify the effectiveness of adding alternating electric perturbations to the applied static electric fields to manipulate convective EKI waves for further enhancement of fluid mixing inside the microchannel, MAF is introduced in the present study, which is defined as:

$$\text{MAF} = \frac{\eta_{\text{static+perturbation}}}{\eta_{\text{static}}} \tag{5}$$

where $\eta_{\text{static + perturbation}}$ is the mixing efficiency when both static and alternating electric fields are applied to the microchannel, while $\eta_{\text{static}}$ is the mixing efficiency when the same static electric field is applied to microchannel only. When the MAF is >1.0, it indicates that adding the alternating electric perturbation to the static electric field would enhance the fluid mixing process inside the microchannel. On the contrary, if MAF is <1.0, it means that the alternating electric perturbation would suppress the mixing process inside the microchannel.

It should be noted that, although the measurement results given in the present paper were mainly based on the measurements in the middle planes of the 130-μm depth microchannels, a series of measurements were also conducted at five different locations along the depth of microchannels (from −60 to +60 μm off the middle plane) for some selected cases. It was found that the flow field was quite two-dimensional along the depth of the microchannels with the variation of the time-averaged mixing efficiency within 2.0% for different measurement planes.

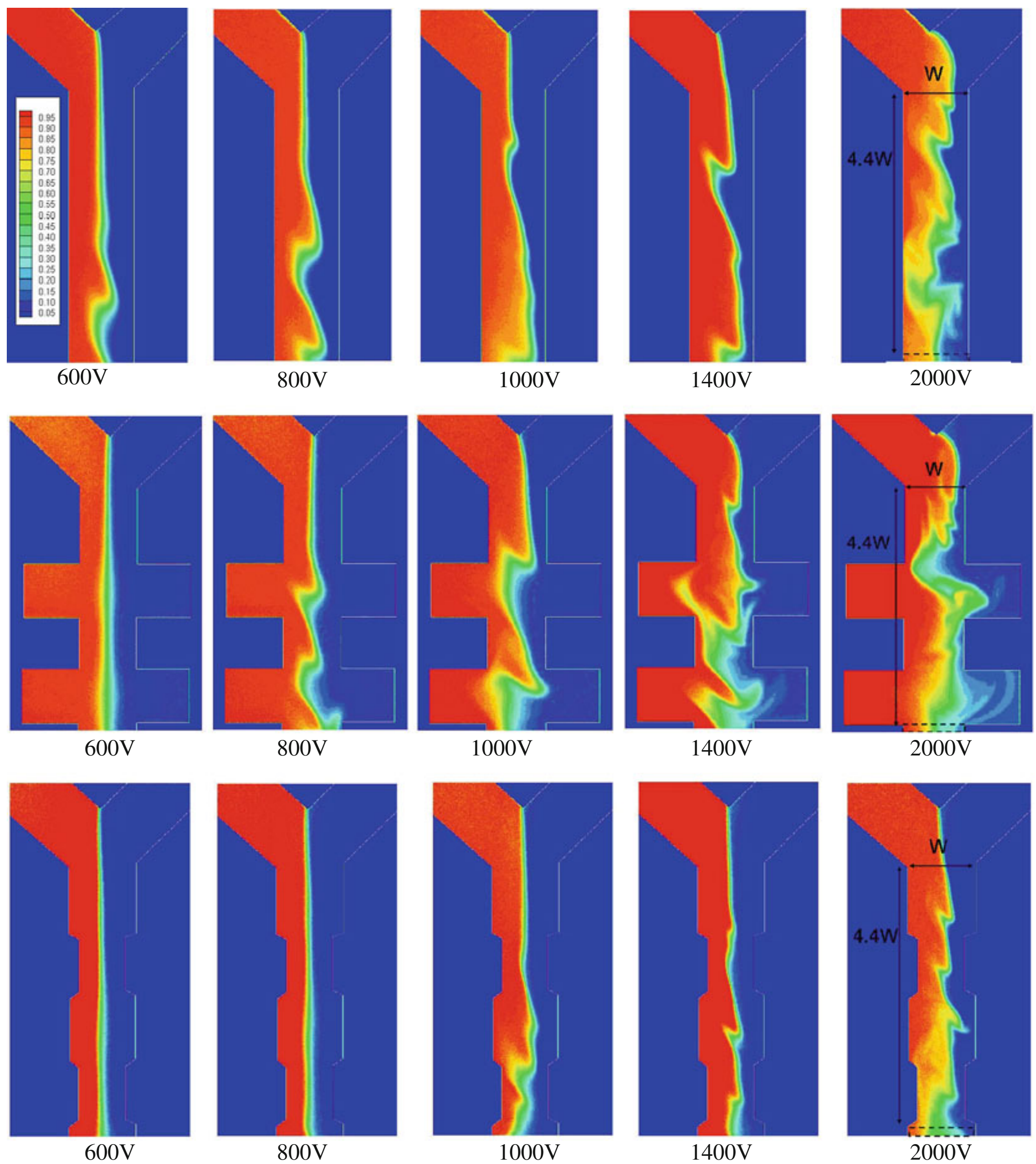


**Fig. 4** The instantaneous concentration fields of the Y-shaped microchannels under different strengths of the applied static electric fields

## 4 Experimental results and discussions

### 4.1 The effects of the applied static electric field strength on the evolution of EKI waves

A systematic investigation was conducted to study the effects of the strength of the applied static electric fields on the evolution of the convective EKI waves and the fluid mixing process inside the Y-shaped microchannels. During the experiments, the same static electric field was applied to the inlet reservoirs R-A and R-B, with the applied voltage varied from 100 to 2,000 V.

Figure 4 shows the typical instantaneous concentration fields inside the Y-shaped microchannels under different strengths of the applied static electric fields. When the applied static voltage is relatively weak (i.e., $\leq$600 V), observable convective EKI waves were found to be generated only inside the straight channel. Downstream propagating EKI waves were observed in the channel with micro-cavities when the strength of the applied static electric field was increased to over 700 V. Apparent convective EKI waves were not found

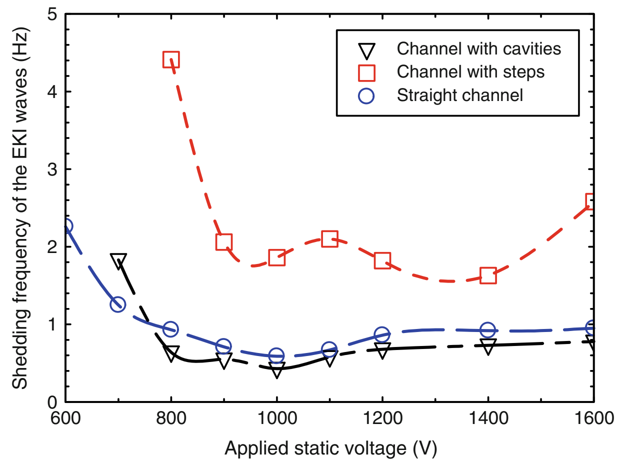


**Fig. 5** Shedding frequency of convective EKI waves versus applied static electric field

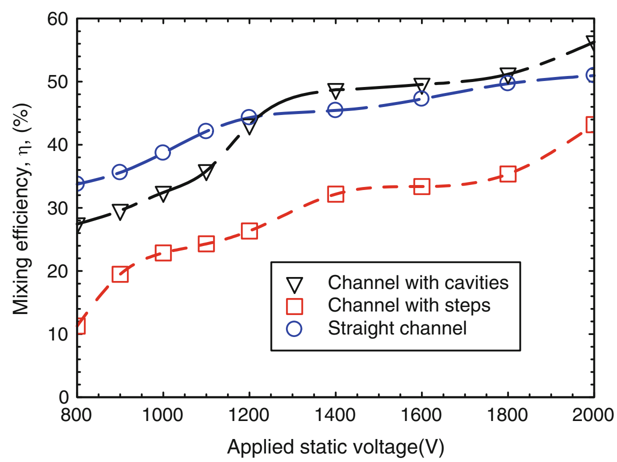


**Fig. 6** Mixing efficiency versus applied static electric field

inside the channel with micro-steps until the strength of the applied static electric field was increased to 800 V. While the amplitude of the interface fluctuations, i.e., the size of the convective EKI waves, was found to increase rapidly as the applied static voltage increased for all the three studied microchannels, the EKI waves in the Y-shaped microchannel with micro-steps were found to have the smallest oscillating amplitude among the three studied microchannels.

The generation of the convective EKI waves was found to be periodic. Following the work of Posner and Santiago (2006), the shedding frequency of the convective EKI waves were identified from the scalar temporal power spectra derived from the time sequence of the 500 instantaneous concentration field measurements for each case, and the results are given in Fig. 5. While shedding frequencies of the EKI waves were found to follow similar trend and have comparable values for the straight channel and the channel with micro-cavities, the shedding frequencies of the EKI waves in the channel with micro-steps were found to be much higher than those of the other two microchannels.

By increasing the strength of the applied static voltage, additional smaller EKI waves are also found to be generated in the braid regions of the large convective EKI waves. The smaller EKI waves seem to propagate upstream instead of downstream, which are believed to be corresponding to the absolute instability mode of EKI as suggested by Chen et al. (2005). As the applied static voltage became >1,600 V, the fluid mixing process in the studied microchannels was found to become much intensive and more chaotic. The scalar temporal power spectra based on the time sequence of the 500 acquired fluorescence images were found to become continuous energy spectra, and no obvious peak can be identified.

As shown in Fig. 5, the region of interest for mixing efficiency calculation was selected to locate at 4.4 W (i.e., ~1.4 mm) downstream of the conjunction of the Y-shaped microchannels, which has an area of 240 × 25 pixels. The effects of the strength of applied static electric field on the mixing process of the microchannels can be quantified clearly by calculating the mixing efficiency in the region of interest, which are given in Fig. 6. It can be seen clearly that the mixing efficiency was found to increase monotonically with the increasing strength of the applied static electric field for all the three studied microchannels. The channel with micro-steps was found to have the poorest mixing enhancement performance among the three studied microchannels. As shown in Fig. 4, since it needs higher strength of the applied static electric field to trigger the convective EKI waves in the channel with micro-cavities compared with those in the straight channel, the channel with micro-cavities was found to have slightly lower mixing efficiency values when the strength of the applied static electric field was relatively low (i.e., ≤1,100 V). However, when the applied static electric field became relatively high (i.e., ≥1,200 V), the channel with micro-cavities was found to have the best mixing performance among the three studied microchannels.

## 4.2 The effects of the alternating electric perturbations on the fluid mixing process

A comprehensive study was also conducted to explore the effectiveness of adding alternating electric perturbations to the applied static electric fields to manipulate the convective EKI waves to further enhance fluid mixing in the Y-shaped microchannels. During the experiments, while a static voltage of 1,000 V was applied to the reservoir R-B, the sum of a static electric field and an alternating electric perturbation was applied to the inlet reservoir R-A, which can be expressed as:

$$V = 1,000\,V + V_{AC}\sin(2\pi ft) \tag{6}$$

where $V_{AC}$ is the magnitude of the alternating electric perturbation imposed on the applied static electric potential and $f$ is the frequency of the alternating electric perturbation. By changing the magnitude and frequency of the alternating electric perturbations, the effects of the applied alternating electric perturbations on the evolution of the convective EKI waves and fluid mixing enhancement in the microchannels were investigated. As previously defined, a MAF is used in the present study to quantify the further mixing enhancement caused by the alternating electric perturbation adding to the applied static electric field.

### *4.2.1 The effects of the frequency of the alternating electric perturbations*

To study the effects of the frequency of the alternating electric perturbations on the fluid mixing inside the Y-shaped microchannels, we chose the magnitude of the alternating electric perturbation to be 250 V, while the frequency of the alternating electric perturbations was changed from 0.1 to 100 Hz. The region of interest for the mixing efficiency calculation was kept as the same as that mentioned above.

Figure 7 shows the MAF as a function of the frequency of the imposed alternating electric perturbation. Since the MAF were found to be always >1.0 for all the three studied microchannels, it indicates that the

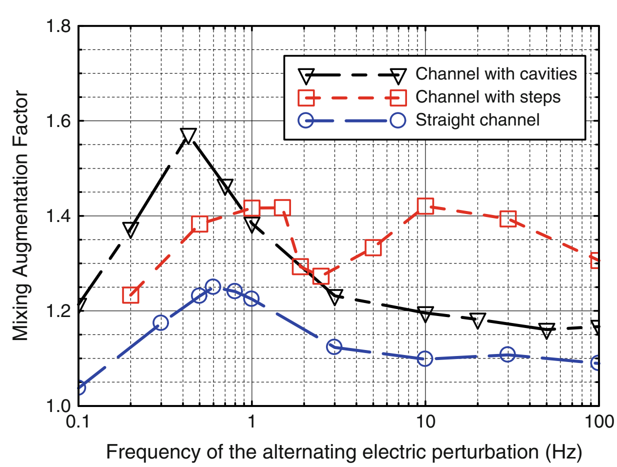


**Fig. 7** Mixing augmentation factor versus the frequency of the alternating electric perturbations

fluid mixing process in the Y-shaped microchannels can always be enhanced by adding the alternating electric perturbations to the applied static electric field.

According to the measurement data given in Fig. 4, the “natural shedding frequency” of the convective EKI waves for the straight channel, the channel with micro-cavities and the channel with micro-steps under the applied static electric of 1,000 V only was found to be 0.6, 0.43 and 1.9 Hz, respectively. The measurement data given in Fig. 7 revealed clearly that, for the straight channel and the channel with micro-cavities, the MAF was found to reach its peak value when the frequency of the imposed alternating electric perturbation was close to the “natural shedding frequency” of the EKI waves (i.e., the frequency of the EKI waves under the applied static electric field of 1,000 V only). This fact may be explained by the concept of hydrodynamic resonance, which has been widely employed in many active flow control studies (Bryden and Brenner 1996; Lee et al. 2000). For both the straight channel and the channel with micro-cavities, the MAF does not vary too much when the frequency of the imposed alternating perturbation is >10 Hz. However, for the channel with micro-steps, the MAF was found to have relatively high values at neighborhood of 1.0 and 10 Hz, and no obvious optimum frequency can be identified. It also should be noted that the channel with micro-cavities was found to have the highest MAF peak among the three studied channels.

### *4.2.2 The effects of the amplitude of the alternating electric perturbation*

As described above, the fluid mixing process was found to be most enhanced when the frequency of the applied alternating electric perturbation is close to the “natural shedding frequency” of the convective EKI waves for the straight channel and the channel with micro-cavities. Therefore, the frequency of the alternating electric perturbations was set to be 0.6 and 0.43 Hz for the straight channel and the channel with micro-cavities in order to investigate the effects of the amplitude of the alternating electric perturbation on the fluid mixing inside the microchannels. Although no optimum frequency was found for the channel with micro-steps, we still chose to have the frequency of the applied alternating electric perturbation being its “natural frequency” of 1.9 Hz. During the experiment, the amplitude of the applied alternating electric perturbation was changed from 50 to 500 V.

Figure 8 shows the ensemble-averaged concentration fields (based on 500 instantaneous measurements for each case) with different amplitudes of the applied alternating electric perturbations for the three studied microchannels. It can be seen clearly that the fluid mixing inside the microchannels is quite sensitive to the amplitude of the applied alternating electric perturbations. The stronger the alternating electric perturbation is, the better fluid mixing between the two streams inside the microchannels can be obtained. Almost perfect mixing was found to achieve for the channel with micro-cavities when the amplitude of the imposed alternating electric perturbation increased to 500 V. Figure 9 shows the profiles of the measured MAF versus the amplitude of the applied alternating electric perturbations. For the straight channel and the channel with micro-steps, their MAFs were found to increase slightly when the magnitude of the perturbation is relatively low (<300 V). However, for the channel with micro-cavities, the MAF was found to increase rapidly at a much higher increasing rate when compared with those of the other two channels as the amplitude of the applied alternating electric perturbations increased.

## 5 Conclusions

An experimental study was conducted to assess the effectiveness of manipulating convective EKI waves to actively enhance/control fluid mixing inside three Y-shaped microchannels, which include a conventional straight channel, a channel with micro-steps and a channel with micro-cavities. Epi-fluoresence imaging technique was used to conduct qualitative flow visualization and quantitative scalar concentration field measurements inside the microchannels. The effects of the applied static and alternating electric fields on the evolution of the convective EKI waves and the resultant fluid mixing process were quantified in terms of scalar concentration distributions, shedding frequency of the EKI waves, fluid mixing efficiency and MAF. The measurement results revealed clearly that fluid mixing efficiency would increase monotonically with the increasing strength of the applied static field for all the three studied microchannels. It was also found that fluid mixing process can be further enhanced by adding alternating electric perturbations to the applied static electric fields, regardless the frequency and magnitude of the alternating electric perturbations. For the straight channel and the channel with micro-cavities, the fluid mixing process was found to be most enhanced when the frequency of the imposed alternating electric perturbations is close to the “natural

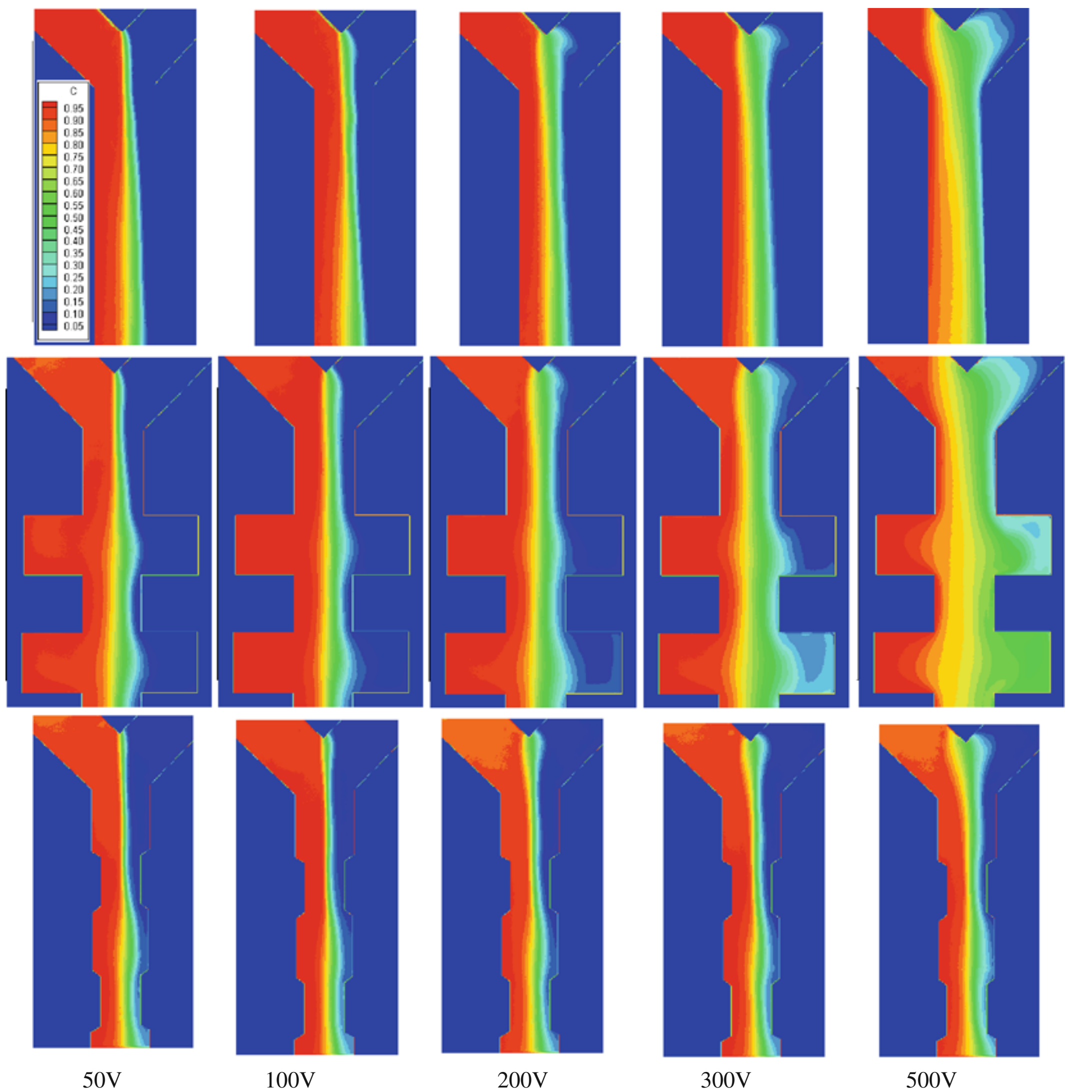


**Fig. 8** The ensemble-averaged concentration fields with different amplitudes of the alternating electric perturbations

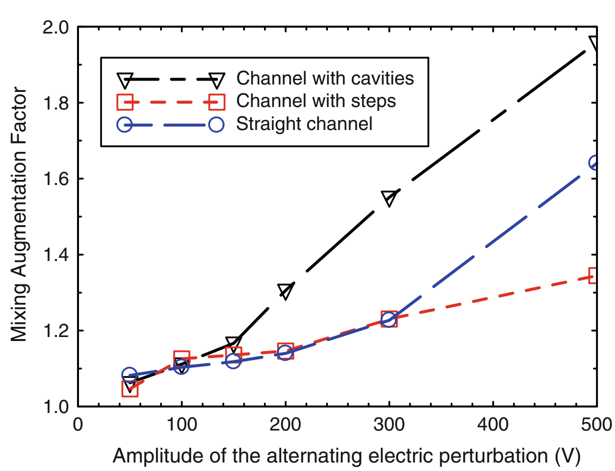


**Fig. 9** Mixing augmentation factor versus the amplitude of the alternating electric perturbation

shedding frequency" of the convective EKI waves (i.e., the shedding frequency of the EKI waves with the applied static electric fields only). In addition, the mixing enhancement was also found to be sensitive to the amplitudes of the applied alternating electric perturbations. While the channel with micro-steps was found to have the poorest mixing enhancement performance, the channel with micro-cavities was found to have the best overall mixing enhancement performance among the three studied microchannels. The findings derived from the present study can be used to further our understanding about EKI and to explore/optimize design paradigms for the development of robust EKI micro-mixers for various microfluidics and "Lab-on-a-Chip" applications.

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