

Heterogeneous Surface Charge Enhanced Micromixing for Electrokinetic Flows

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Enhancing the species mixing in microfluidic applications is key to reducing analysis time and increasing device portability. The mixing in electroosmotic flow is usually diffusion-dominated. Recent numerical studies have indicated that the introduction of electrically charged surface heterogeneities may augment mixing efficiencies by creating localized regions of flow circulation. In this study, we experimentally visualized the effects of surface charge patterning and developed an optimized electrokinetic micromixer applicable to the low Reynolds number regime. Using the optimized micromixer, mixing efficiencies were improved between 22 and 68% for the applied potentials ranging from 70 to 555 V/cm when compared with the negatively charged homogeneous case. For producing a 95% mixture, this equates to a potential decrease in the required mixing channel length of up to 88% for flows with Péclet numbers between 190 and 1500.

In the quest for continual miniaturization, efficient mixing of reagents in the low Reynolds and Péclet number regimes remains a bottleneck hindering advancements in microfluidic technologies. Critical to a host of applications ranging from DNA hybridization to cytometric analysis and immunoassays, enhanced mixing is a prerequisite critical for full realization of the extraordinary potential of lab-on-a-chip devices. Advantages of this emerging technology are numerous, including reductions in analysis time, decreased consumption of reagents and production of possibly harmful byproducts, and improvements in resolution and portability, not to mention decreased cost of manufacture, operation, and disposal.

Overcoming the challenges associated with microscale mixing has been the focus of numerous endeavors intent on introducing supplementary mechanisms, such as advection, to the lengthy diffusion-based processes typical of uniaxial, laminar flow. For applications where external power supplies, actuators, and auxiliary equipment are conveniently integrable, mixing schemes based on a variety of technologies such as piezoelectrics,^{1–2} pneumatics,³ and acoustic radiation⁴ as well as oscillating voltage

fields⁵ have been successfully developed for microfluidic devices. In many applications, however, where ease of manufacturability and simplicity of design take precedence, passive mixing schemes, which do not rely on external stimulation or intricate components, are preferable.

Two approaches to flow manipulation are prevalent in passive micromixers, the first relying on channel geometry to generate chaotic advection and increased circulation and the second on channel surface properties. Notable initiatives, amenable to intermediate Reynolds number flows (i.e., >1) of the geometric category, have included helical or zigzag microchannels, in which mixing occurs as a result of eddies present at the channel bends.^{6–8} Alternatively, oblique ridges formed on the bottom of the channel and designed to introduce a transverse component of flow have also proven effective for pressure-driven flows with Reynolds numbers between 0 and 100 and channel lengths on the order of centimeters.⁹ This technique has also demonstrated a negligible increase in bulk flow resistance, a constraint limiting the effectiveness of mixers based on parallel lamination for electrokinetic applications.¹⁰

The trend toward electroosmotically driven flows, as motivated by ease of implementation and increased flow control, has expanded the potential of surface chemistry as a means of mixing enhancement. Paralleling the use of patterned solvophobic–solvophilic or electrokinetic surface properties as numerically demonstrated in pressure-driven flows,^{11–13} surface charge heterogeneities have been suggested as a mechanism for enhanced mixing in electroosmotic flows.^{14–19} Specifically, by selectively patterning positively charged molecules on a negatively charged

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- (1) Yang, Z.; Goto, H.; Matsumoto, M.; Maeda, R. *Electrophoresis* **2000**, *21*, 116–119.
- (2) Woias, P.; Hauser, K.; Yacoub-George, E. *Micro Total Analysis Systems 2000*; Kluwer Academic Publishers: Dordrecht, 2000; p 277.
- (3) Hosokawa, K.; Fujii, T.; Endo, I. *Micro Total Analysis Systems 2000*; Kluwer Academic Publishers: Dordrecht, 2000; p 481.
- (4) Yasuda, K. *Sens. Actuators, B* **2000**, *64*, 128–135.

- (5) Oddy, M. H.; Santiago, J. G.; Mikkelsen, J. C. *Anal. Chem.* **2001**, *73*, 5822–5832.
- (6) Liu, R. H.; Sharp, K. V.; Olsen, M. G.; Stremmer, M.; Santiago, J. G.; Adrian, R. J.; Aref, H.; Beebe, D. J. *J. Microelectromech. Syst.* **2000**, *9*, 2, 190–198.
- (7) Mengeaud, V.; Jossierand, J.; Girault, H. H. *Anal. Chem.* **2002**, *74*, 4279–4286.
- (8) Stooch, A. D.; Dertinger, S. K. W.; Ajdari, A.; Mezi, I.; Stone, H. A.; Whitesides, G. M. *Science* **2002**, *295*, 647–651.
- (9) Haverkamp, V.; Ehrfeld, W.; Gebauer, K.; Hessel, V.; Lowe, H.; Richter, T.; Wille, C. *Fresenius J. Anal. Chem.* **1999**, *364*, 617–624.
- (10) Beebe, D. J.; Adrian, R. J.; Olsen, M. G.; Stremmer, M. A.; Aref, H.; Jo, B. *Mech. Ind.* **2001**, *2*, 343–348.
- (11) Kuksenok, O.; Yeomans, J. M.; Balazs, A. C. *Langmuir* **2001**, *17*, 7186–7190.
- (12) Zhao, B.; Moore, J. S.; Beebe, D. J. *Anal. Chem.* **2002**, *74*, 4259–4268.
- (13) Erickson, D.; Li, D. *Langmuir* **2002**, *18*, 8949–8959.
- (14) Erickson, D.; Li, D. *Langmuir* **2002**, *18*, 1883–1892.
- (15) Hong, S.; Thiffault, J.; Fréchette, L. G.; Modi, V. *Proc. IMECE'03*, Washington DC, 2003.
- (16) Stroock, A. D.; Weck, M.; Chiu, D. T.; Huck, W. T. S.; Kenis, P. J. A.; Ismagilov, R. F.; Whitesides, G. M. *Phys. Rev. Lett.* **2000**, *84*, 3314–3317.

channel wall, flow disruption and increased circulation, resulting from differences in electrostatic potential between the homogeneous and heterogeneous surfaces, have been numerically demonstrated for a variety of configurations including checkerboard, diagonal, and herringbone arrays with positive results.^{14,15} To our knowledge, experimental observation of flow in the presence of surface heterogeneity has been limited to directional control and simple configurations (longitudinal and transverse).^{16–18} Advantages of the surface charge patterning technique for mixing enhancement include its promising theoretical performance in the low Reynolds number regime (i.e., $Re < 1$) together with its particular compatibility with electrokinetic applications.

This paper will describe experimental development of a passive electrokinetic micromixer for lab-on-a-chip applications based on the use of surface charge heterogeneity. The surface charge patterns are designed to create localized flow disturbances, thereby inducing an advective component to the traditionally diffusion-dominated mixing. Specifically, the objectives of this study were to visualize the effects of surface charge heterogeneity on microscale species transport, to optimize the design of heterogeneous patterning using validated numerical models, and to characterize the performance of the developed micromixer experimentally in terms of mixing efficiencies and required channel lengths.

EXPERIMENTAL SECTION

Chemicals and Materials. Positive masters were constructed by exposing SU-8 25 negative photoresist (MicroChem, Newton, MA) and developing in 4-hydroxy-4-methyl-2-pentanone (Fluka Chemie, Messerschmittstr). Microchannels were fabricated from poly(dimethylsiloxane) (PDMS) using a Sylgard 184 silicone elastomer kit (Dow Corning, Midland, MI) with an elastomer-to-curing agent ratio of 20:1 to obtain improved sealing of the PDMS with glass.

All solutions were prepared using deionized filtered water (Fischer Scientific). Surface charge heterogeneities were selectively patterned using a positively charged polymer solution of 5% (by mass) Polybrene dissolved in water. Glass surfaces were prepared by flushing with 0.1 M sodium hydroxide prior to Polybrene coating and rinsed with deionized water subsequent.

Sodium bicarbonate, 1 M, and sodium carbonate, 1 M, were combined in equal ratio to form a sodium carbonate/bicarbonate buffer with an ionic strength, $I = 0.05$ and pH 9.0. The buffer was diluted with water to 25 mM. For fluorescent imaging, fluorescein was dissolved with 25 mM buffer to a concentration of 100 μM . Solutions were filtered with 0.2- μm pore size syringe filters prior to use.

Microchannel Fabrication. Microchannels were fabricated using a rapid prototyping/soft lithography technique.²⁰ Specifically, photomasks were designed in AutoCAD, exported as PDF files, and printed on a 3500 dpi image setter (UTPress, Toronto, ON, Canada). Glass slides were soaked overnight in acetone, dried on a hot plate at 200 °C, exposed to oxygen plasma (Harrick

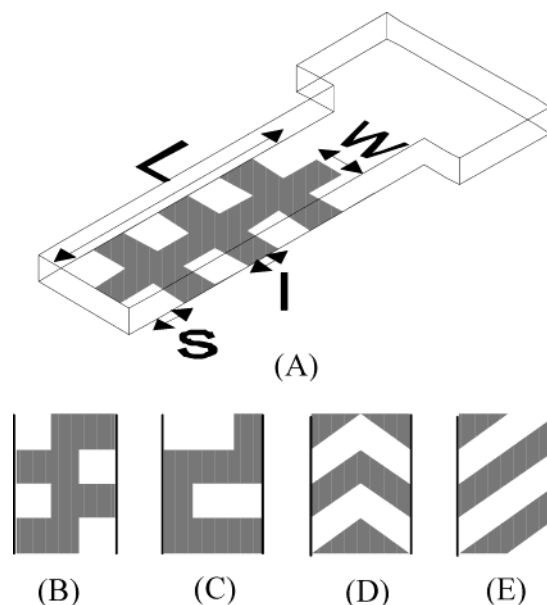


Figure 1. Surface charge patterning configurations with a mixing region length L consistent for all configurations, a patch length l , a patch width w , and patch spacing s for (A) in-line pattern, (B) staggered pattern, (C) serpentine pattern, (D) herringbone pattern, and (E) diagonal pattern.

Plasma Cleaner model PDC-32G) for 5 min, and again heated to 200 °C subsequently, to prepare the surface for coating. A 1.5-mL sample of SU-8 25 photoresist was then distributed onto each slide and degassed in a high vacuum. The photoresist was spin-coated at 1800 rpm for 10 s and at 4000 rpm for 40 s with a ramping phase of 5 s between stages in order to obtain a smooth film with a thickness of 8 μm (Special Coating System Spin Coat model G3P-8). Films were baked at 65 °C for 3 min and at 95 °C for 7 min to harden. The photomasks were positioned on the photoresist films and exposed to UV light for 1 min. A two-stage postexposure bake at 65 °C for 1 min and 95 °C for 2 min was then conducted. Masters were developed in 4-hydroxy-4-methyl-2-pentanone for ~ 2 min or until the photoresist rinsed cleanly off. After developing, masters were placed under a heat lamp for several hours. To form the microchannels, PDMS was poured over the masters and cured at 65 °C for ~ 2 h at a pressure of -34 kPa (gauge). Silanization of the masters was not necessary as the PDMS casts did not adhere to the hardened photoresist.

Surface Charge Patterning. The rapid prototyping/soft lithography technique as described in the previous section allowed for control of and flexibility in surface charge patterning configurations, examples of which are detailed in Figure 1. To selectively pattern the surface charge heterogeneity, the following procedure was followed (Figure 2). The PDMS master, featuring a channel configuration corresponding to the pattern of heterogeneities to be examined, was reversibly sealed to a glass slide. Using suction forces with an approximate flow rate of 2.5 mL/min, the PDMS master was flushed sequentially with 0.1 M sodium hydroxide for 2 min, deionized water for 4 min, and 5% Polybrene solution for 2 min, resulting in selective regions of positive surface charge while leaving the majority of the glass slide with its native negative charge. This polyelectrolyte coating procedure is based on that developed by Liu et al.²¹ for capillary electrophoresis microchips. All fluid was then removed from the channel, and the system was

(17) Barker, S. L. R.; Ross, D.; Tarlov, M. J.; Gaitan, M.; Locascio, L. *Anal. Chem.* **2000**, *72*, 5925–5929.

(18) Hau, W. L. W.; Trau, D. W.; Sucher, N. J.; Wong, M.; Zohar, Y. *J. Micromech. Microeng.* **2003**, *13*, 272–278.

(19) Qiao, R.; Aluru, N. R. *Sens. Actuators, A* **2003**, *104*, 268–274.

(20) Duffy, D. C.; McDonald, J. C.; Schueller, O. J. A.; Whitesides, G. M. *Anal. Chem.* **1998**, *70*, 4974–4984.

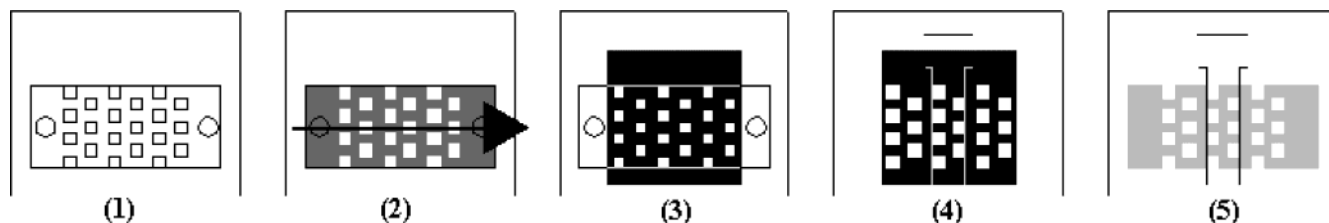


Figure 2. Schematic of selective patch patterning procedure: (1) PDMS microchannel master featuring a channel configuration corresponding to a staggered pattern of heterogeneities and reversibly sealed to a glass slide. (2) PDMS master flushed with charge-reversing solutions to selectively pattern charge heterogeneities. (3) Landmarking of surface heterogeneities achieved by aligning the corresponding photomask under $5\times$ magnification with the PDMS master and firmly attaching it to the opposite side of the slide. (4) Removal of PDMS master and permanent sealing of oxidized T-channel to the glass slide such that the surface heterogeneities are appropriately positioned within the mixing channel. (5) Removal of attached photomask and completion of micromixer fabrication.

left undisturbed for 40 min before flushing again with water for 20 min. To promote bonding of the polymer to the surface, the slide was aged in air for 24 h prior to use. Before removing the PDMS master, the location of the heterogeneities was landmarked. A T-shaped microchannel, $200\ \mu\text{m}$ in width and $\sim 8\ \mu\text{m}$ in depth, was then permanently sealed to the glass slide such that the patterned surface heterogeneities were appropriately positioned within the mixing channel. The presence of the Polybrene coating did not visibly affect the reversible seal.

Electroosmotic Mobility Measurements. Using the well-established current monitoring technique,²² the ζ potentials of the native-oxidized PDMS and the Polybrene-coated surface were determined using a sodium carbonate/bicarbonate buffer of pH 9.0. Briefly, a dilute buffer was introduced into a uniaxial PDMS channel with the surface treatment of interest. The current was monitored and allowed to stabilize under a constant applied voltage potential. A concentrated buffer was then introduced through one reservoir, and the time required for the current to reach a new plateau corresponding to the higher concentration of buffer was recorded. The electroosmotic mobility of the native-oxidized PDMS was determined to be $-5.9 \times 10^{-4}\ \text{cm}^2/\text{V}\cdot\text{s}$ compared with $2.3 \times 10^{-4}\ \text{cm}^2/\text{V}\cdot\text{s}$ for the Polybrene-coated surface, results that compared well with previous findings.²¹

Image Acquisition and Processing. The effect of the surface charge patterns on mixing efficiency was then examined in T-shaped microfluidic chips. To perform the mixing experiments, 25 mM sodium carbonate/bicarbonate buffer and $100\ \mu\text{M}$ fluorescein were introduced through either inlet channel. The system was illuminated by a mercury arc lamp equipped with a fluorescein filter set. The steady-state transport of the dye was observed using a Leica DM LM fluorescence microscope with a $5\times$ objective and captured using a Retiga 12-bit cooled CCD camera. Digital images were obtained by QCapture 1394 and OpenLab 3.1.5 imaging software at an exposure time of 1 s. The acquired images were of resolution 1280×1024 pixels with each pixel representing a $2.5\text{-}\mu\text{m}$ square in the object plane. Images were exported in TIF format to MATLAB for digital processing. Dark-field subtraction and bright-field normalization was performed to eliminate anomalies introduced by the image acquisition system. Following image processing, concentration profiles prior to and after the heterogeneous region were developed directly from values of pixel

intensities. Profiles were smoothed using a convolution filter and linearly scaled to range between 0 and 1. Results for the surface charge patterned channels were compared to those for a uniform and negatively charged PDMS/glass system herein referred to as the homogeneous case. Specifically, mixing efficiencies, ϵ , were calculated and compared using the following definition similar to that of previous mixing studies:¹⁴

$$\epsilon = \left(1 - \frac{\int_0^W |C - C_\infty| dx}{\int_0^W |C_0 - C_\infty| dx} \right) \times 100\% \quad (1)$$

where $C_\infty = 0.5$ corresponds with perfect mixing on a normalized scale, C_0 is the concentration distribution over the channel width, W , at the channel inlet, and C is the concentration distribution at some distance downstream.

RESULTS AND DISCUSSIONS

The goal of this study was to develop an improved passive electrokinetic micromixer suitable for the low Reynolds flow regime by introducing surface charge heterogeneities and to experimentally characterize its performance in terms of the overall mixing efficiency. To facilitate optimization of surface charge patterning, the BLOCS (Bio-Lab-On-a-Chip Simulation) finite element code^{14,23,24} was adapted to simulate the experimental conditions and surface charge heterogeneity. Specifically, channel dimensions of $200\ \mu\text{m}$ in width and $8\ \mu\text{m}$ in depth were modeled along with the physiochemical properties of fluorescein, namely, a diffusion coefficient $D = 4.37 \times 10^{-10}\ \text{m}^2/\text{s}$ and an electrophoretic mobility $\mu_{\text{ep}} = 3.3 \times 10^{-8}\ \text{m}^2/\text{V}\cdot\text{s}$. Numerical models were validated experimentally and used to support further mixing analyses.

Optimization of Surface Patterning. The numerical models were used to optimize the pattern of surface charge heterogeneity and to characterize the effects of channel depth, ζ potentials, and diffusivity on mixing enhancement. Simulations indicated that a nonsymmetrical configuration of oppositely charged surface heterogeneities is optimal for mixing enhancement. Figure 3 presents the numerical results for the variety of configurations as detailed in Figure 1. For each configuration, the patch length and spacing parameters were selected to maintain a constant ratio of heterogeneous-to-homogeneous surface areas over a channel length of

(21) Liu, Y.; Fanguy, J. C.; Bledsoe, J. M.; Henry, C. S. *Anal. Chem.* **2000**, *72*, 5939–5944

(22) Sze, A.; Erickson, D.; Ren, L.; Li, D. *J. Colloid Interface Sci.* **2003**, *261*, 402–410.

(23) Erickson, D.; Sinton, D.; Li, D. *Lab Chip* **2003**, *3*, 141–149.

(24) Erickson, D.; Li, D.; Krull, U. J. *Anal. Biochem.* **2003**, *317*, 186–200.

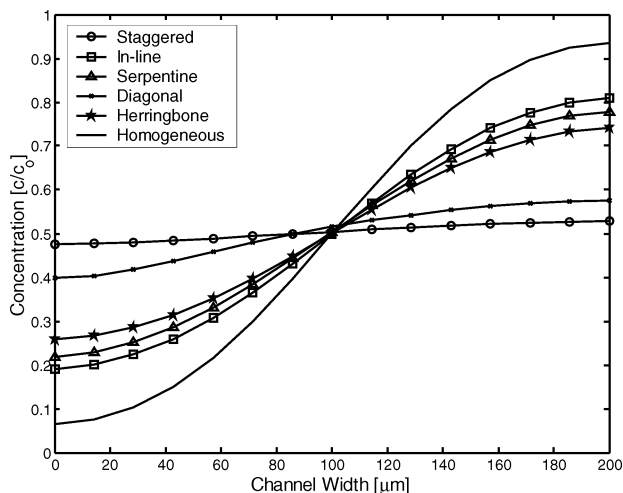


Figure 3. Numerically simulated concentration profiles across the channel width for the staggered pattern after the mixing region for an applied potential of 280 V/cm for varying configurations of surface charge heterogeneity as defined in Figure 1.

1.8 mm. Evidently, the nonsymmetrical patterns, namely, the staggered and the diagonal, generated better mixing distributions in comparison to the symmetrical herringbone and in-line arrangements. With a theoretical mixing efficiency of 96%, the staggered configuration provided the greatest degree of mixing, outperforming the diagonal, the herringbone, and the serpentine configurations by 8, 31, and 36%, respectively. In comparison with the homogeneous case, the staggered configuration provided a 61% increase in mixing efficiency.

The staggered configuration was thus examined in more detail to determine the optimal patch length and spacing parameters. For a 1.8-mm mixing region length, the optimal patch length was determined to be 300 μm with a 2-fold increase or decrease from this optimal value resulting in a 10% reduction in mixing efficiency. In comparison, additional design factors proved insignificant, with a 2- and 5-fold increase in channel depth resulting in a 1 and 9% decrease in mixing efficiency, respectively, while a difference of 2.6% resulted from variations in spacing parameters.

Values of electroosmotic mobility in both the homogeneous surface and patch regions were critical for defining flow characteristics. Challenges of manufacturing may limit precise control of the electroosmotic mobility, as does the possible interaction of the negatively charged fluorescein molecules with the positively charged patches. Current monitoring experiments performed over a period of 5 h to quantify the latter interaction over time indicated that the electroosmotic mobility of the buffer and the fluorescein/buffer solutions as used in this study varied by less than 10%. Previous studies have reported more substantial variations with observable changes in mobility of approximately 33%.²⁵ However, these experiments were conducted with a much greater concentration of fluorescein, 1.2 mM, as compared to the 100 μM dilutions used in this study. As has been reported in previous studies,¹⁴ for significant flow circulation, the patch electroosmotic mobility must be of opposite sign. Numerical simulations revealed, however, that increasing the magnitude of the patch mobility above that generated by the Polybrene layer does not significantly

increase mixing efficiency, with a 2-fold increase resulting in a less than 2% change in mixing efficiency. This implies that the presence of oppositely charged surface heterogeneities rather than their magnitude is the defining factor for mixing enhancement. Thus, the interaction of fluorescein molecules with the positively charged patches should not significantly affect mixing efficiency. Furthermore, charge-altering treatments such as the Polybrene coating used in this study should prove adequate. An alternate technique, which employs soft lithography to selectively pattern positively charged poly(allylamine hydrochloride) molecules, has also been successfully demonstrated.¹⁸ Using this technique, electroosmotic mobilities roughly twice that obtainable with Polybrene have been reported with the additional benefit of increased coating stability. Future development of the micromixer presented in this study may benefit from the incorporation of this technique of micropatterning.

Experimental Visualization. Based on the above analysis, the optimized micromixer consisting of six offset staggered patches (Figure 1B), spanning 1.8 mm downstream and offset 10 μm from the channel centerline with a width of 90 μm and a length of 300 μm , was analyzed experimentally. Mixing experiments were conducted at applied voltage potentials ranging between 70 and 555 V/cm as corresponded to Reynolds numbers of 0.08 and 0.7 and Péclet numbers of 190 and 1500. As can be seen in Figure 4, experimental results compared well with numerical simulations with images of the steady-state flow for the homogeneous and heterogeneous cases exhibiting near-identical flow characteristics and circulation at 280 V/cm.

Qualitatively, experimental visualization of a staggered configuration of heterogeneities exhibited the formation of highly unsymmetrical concentration gradients indicative of flow constriction and localized circulation in the patterned region. Bulk flow was forced to follow a significantly narrower and more intricate route thereby increasing the rate of diffusion by means of local concentration gradients. Convective mechanisms were also introduced by local flow circulation, which transported a portion of the mixed downstream flow upstream. Additionally, sharp, length-wise gradients absent in the homogeneous case resulted in an additional diffusive direction and enhanced mixing as exhibited in Figure 5, which plots the centerline concentration against the downstream channel length for an applied voltage potential of 280 V/cm. Clearly evident are these oscillating local concentrations induced by the surface charge patterning. Oscillations become substantially lower in magnitude at greater downstream distances as increased species homogeneity is achieved.

Concentration profiles comparing the homogeneous and heterogeneous mixing channels at 70 (Figure 6A) and 280 V/cm (Figure 6B) indicate a substantial increase in species mixing with consistent correspondence between experimental and numerical results. Mixing was visibly enhanced for all voltages in comparison with a homogeneous T-channel, with a more marked improvement at increasingly higher voltages.

Characterization of Micromixer Performance. Experimental and numerical profiles were consistent with values of mixing efficiencies within 2.5% at low voltage potentials (70 V/cm) and within 5% at higher potentials (555 V/cm). Using the developed micromixer, mixing efficiencies were improved from 75.3 to 97.2% at 70 V/cm and from 22.7 to 90.2% at 555 V/cm in comparison

(25) Ross, D.; Locascio, L. E. *Anal. Chem.* **2003**, *75*, 1218–1220.

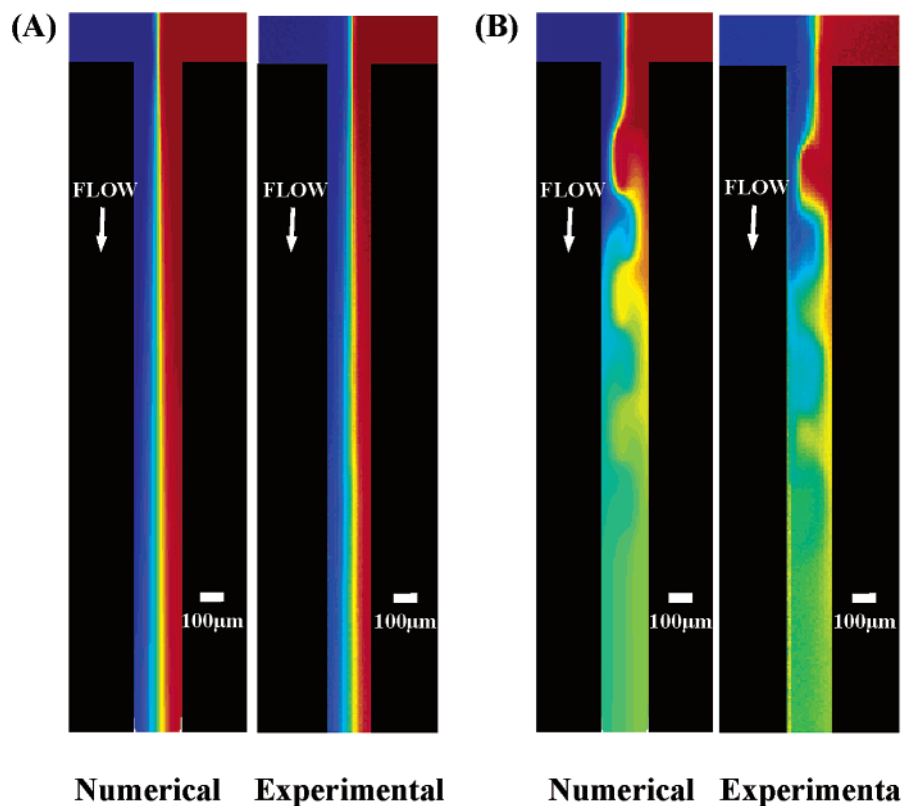


Figure 4. Images of steady-state species transport for an applied potential of 280 V/cm for (A) the homogeneous microchannel and (B) the heterogeneous microchannel with six offset staggered patches as derived through numerical and experimental analysis.

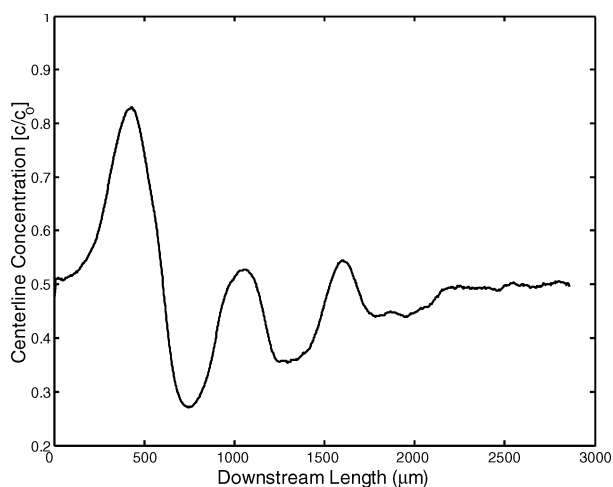


Figure 5. Experimental measurement of the centerline normalized concentration along the channel length with an applied potential of 280 V/cm for the optimized offset staggered micromixer design.

with the homogeneous system. Figure 7 presents a graph of the mixing efficiencies for varying voltage potentials for the developed micromixer compared with the homogeneous channel. Mixing is consistently enhanced with a more substantial improvement observable at higher voltage potentials where diffusive mechanisms are increasingly inefficient. As the mixing efficiency appears to become asymptotic at increasingly higher voltages in both experimental and numerical results, a maximum applied voltage potential of 555 V/cm was deemed sufficient to fully characterize micromixer performance.

In terms of required channel lengths, numerical analysis indicated that, at 280 V/cm, a homogeneous microchannel would require a channel mixing length of 22 mm for 95% mixture. By implementing the developed micromixer, an 88% reduction in required channel length to 2.6 mm was experimentally demonstrated. Practical applications of reductions in required channel lengths include improvements in portability and shorter retention times, both of which are valuable advancements applicable to many microfluidic devices.

This enhanced micromixer technology can be applied to a wide range of lab-on-a-chip applications involving a variety of fluids ranging from fluorescent dyes with diffusion constants on the order of 10^{-10} m²/s to large molecules of DNA and proteins with diffusion constants on the order of 10^{-12} m²/s. Hence, the sensitivity to diffusion constants is of interest for the characterization of micromixer performance. This study was based on a fluorescein dye with diffusion constant $D = 4.37 \times 10^{-10}$ m²/s. With a staggered patch configuration, mixing efficiency was increased from 36 to 96% in comparison with the homogeneous case for an applied potential of 280 V/cm. Numerical simulations indicated that, for a diffusion constant 2 orders of magnitude lower, mixing efficiencies are improved from 3.6% in the homogeneous case to 70% with staggered surface charge heterogeneities. Regardless of diffusion constant, the improvement in mixing efficiency over the purely diffusive case is substantial. As results are highly sensitive to diffusion coefficients, however, required channel lengths for complete mixing will be largely application dependent.

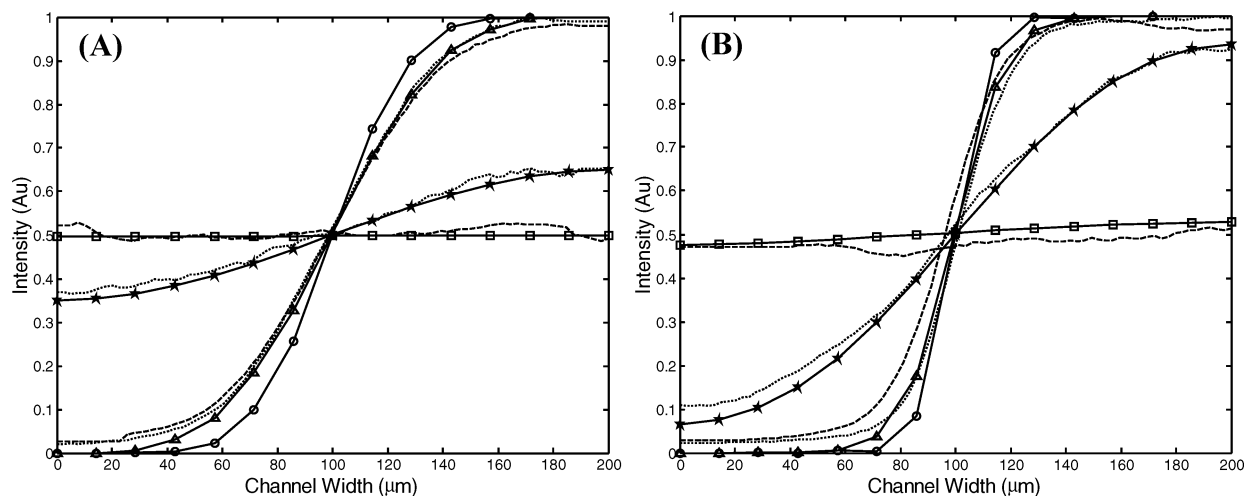


Figure 6. Experimental concentration profiles (homogeneous channel, dotted lines; micromixer, dashed lines) and numerical (solid lines) across the channel width for both the homogeneous case prior to the mixing region (circular markers) and after the mixing region (star markers) and for the developed micromixer prior to the mixing region (triangular markers) and subsequent (square markers) for (A) 70 and (B) 280 V/cm.

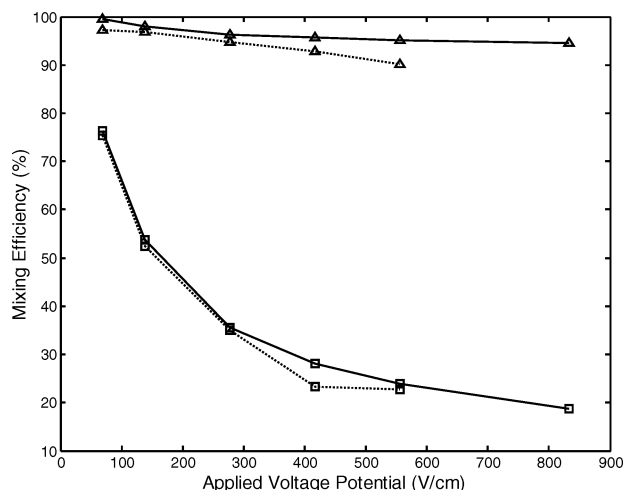


Figure 7. Mixing efficiencies for varying applied potentials for the homogeneous (square markers) channel and for the developed micromixer (triangular markers) as determined by experimental (dotted lines) and numerical (solid lines) analysis.

CONCLUSIONS

This study aimed to overcome the inefficiencies of diffusion-dominated mixing processes typical of the low Reynolds number regime as experienced in a number of lab-on-a-chip applications. By selectively patterning an arrangement of surface charge

heterogeneities, a passive electrokinetic micromixer was experimentally developed and demonstrated to increase flow narrowing and circulation, thereby increasing the diffusive flux and introducing an advective component of mixing. Mixing efficiencies were improved by 22–68% for voltages ranging from 70 to 555 V/cm. For a 95% mixture, this equates to a potential decrease in the required mixing channel length of up to 88% for flows with Péclet numbers between 190 and 1500 and Reynolds numbers between 0.08 and 0.7. Practical implications of these findings include reductions in retention time and increased portability. Decreased costs of manufacture and operation may also be realized as external power supplies or auxiliary equipment is not required in this passive approach to enhanced mixing.

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