Induced charge electro-osmotic concentration gradient generator

Mranal Jain,^{1,a)} Anthony Yeung,¹ and K. Nandakumar²

¹*Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta T6G 2V4, Canada*

²*Cain Department of Chemical Engineering, Louisiana State University, Baton Rouge, Louisiana 70803, USA*

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Biomolecule gradients play an important role in the understanding of various biological processes. Typically, biological cells are exposed to linear and nonlinear concentration gradients and their response is studied for understanding cell growth, cell migration, and cell differentiation mechanisms. Recent studies have demonstrated the use of microfluidic devices for precise and stable concentration gradient generation. However, most of the reported devices are geometrically complex and lack dynamic controllability. In this work, a novel microfluidic gradient generator is presented which utilizes the induced charge electro-osmosis (ICEO) by introducing conducting obstacle in the microchannel. With the ICEO flow component, significant transverse convection can be generated within the microchannel, which can, in turn, be used to create nonlinear as well as asymmetric gradients. The characteristics of the developed concentration gradient are dependent on the interplay between fixed charge electro-osmotic and ICEO flows. It is shown that the proposed device can switch between linear and nonlinear gradients by just altering the applied electric field. Finally, the formation of user-defined concentration profiles (linear, convex, and concave) is demonstrated by varying the conducting obstacle size.

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I. INTRODUCTION

Biomolecule gradients are utilized for various cell biology studies involving growth, differentiation, and migration. The biological cells are subjected to linear and nonlinear biomolecule gradients and their response is helpful in understanding many biological phenomena including wound healing, cancer metastasis, inflammation, and embryogenesis. Several approaches are developed for gradient based studies such as the Boyden chamber,¹ Dunn chamber,² micropipettes,³ and hydrogels.⁴ Although these conventional techniques have been used for a long time, they have limitations in terms of gradient stability, reproducibility, predictability, and controllability.

Recent advances in microfabrication technology have complemented this research field as many microfluidic devices have been reported in the recent past for gradient generation.^{5–7} Various microfluidic techniques are categorized into four different classes by Keenan and Folch:⁸ Substrate bound, time evolving, parallel flow, and flow resistive methods. As the name suggests, substrate-bound method involves the binding of biomolecules on the cell culture substrates via adsorption. This technique is found to be uncomplicated in terms of equipment and methods and gradients can be easily created. However, only limited gradient types can be generated by this method owing to the technique dependence on various factors that influence adsorption kinetics, such as temperature, number of functional sites, local concentration, and steric hindrance. The time evolving gradient generators are appropriate for studies where temporal gradients are required; such gen-

^{a)} Author to whom correspondence should be addressed. Electronic mail: mjain@ualberta.ca.

erators are not suited for studies where long exposure to a particular type of gradient is needed. In parallel flow type gradient generators, two or more solutions flow adjacently through a T-channel and gradient formation is due to transverse diffusion. Various modifications of basic T-channel gradient generator are reported which proved to be adequate for generating various kinds of stable gradient patterns. Again, these types of generator require continuous supplies of biomolecules and exert flow-induced forces on the biological cells. Lastly, flow resistive techniques provide near convection free gradient generation based on diffusion; however these methods are found to be insufficient for complex gradient generation. A discussion of various conventional techniques and microfluidic techniques, as well as their comparison and corresponding references, can be found in an extensive review by Keenan and Folch.⁸

As the proposed design in this study is a modification of the simplest parallel flow gradient generator, T-sensor, we will review here the most notable parallel flow type gradient generators. Jeon and co-workers⁹ proposed a hierarchical network of T-channels where solutions are split, mixed, and recombined to arrive at a particular gradient type. It was used to study the effect of biomolecule gradients on neutrophil migration,⁵ breast cancer cell chemotaxis,¹⁰ etc. Although a variety of gradients can be generated with the proposed design, it is geometrically complex and with limited dynamic controllability. In a similar study utilizing the T-channel, Walker *et al.*¹¹ observed the effect of virus gradients on biological cells. Another modification of the T-channel gradient generator is named as “Universal Gradient Generator,” where Irimia *et al.*⁶ demonstrated the generation of complex gradient types. The user-defined concentration profiles are developed by suitably positioning the dividers/walls to restrict the transverse diffusion. Again dynamic controllability is limited in this design as switching from one type of gradient to another requires repositioning of the dividers. The study by Wang *et al.*¹² provides a systematic representation of T-channel based gradient generators, where the generator was decoupled into various microfluidic elements with simple geometry and each element was analytically modeled. Yet another study utilized stepwise addition of solute through microtunnel to achieve linear and nonlinear axial gradients in the microchannel.⁷ All parallel flow type gradient generators provide stable gradients at the expense of continuous reagent consumption and are restricted in terms of dynamic controllability.⁸

In this study, we propose to exploit induce charge electrokinetics to generate various gradient types. The proposed design is geometrically simple and can switch between various gradients type by simply altering the applied electric field and more importantly, without altering the device geometry. The small time scales associated with electrokinetic and induced-charged electrokinetic flows¹³ make it a promising candidate for achieving dynamic controllability while retaining the simple T-channel geometry. The organization of this article is as follows: Section II describes the basics of induced charge electrokinetics. Section III will describe the proposed design and mathematical models. In Sec. IV, the workability of the proposed design is demonstrated via generation of various gradient types followed by the conclusions.

II. BASICS OF INDUCED CHARGE ELECTRO-OSMOSIS

The most common nonmechanical means of driving fluid flow in microdevices is electro-osmosis. When a charged solid surface comes in contact with an electrolyte, an electric double layer (EDL) of ions is formed due to the interplay between electrical and diffusive forces. The flow of liquids containing dissolved ions under the influence of electrical body forces is known as electro-osmosis; it is a subject treated in depth in the colloid science literature.^{14,15} Electro-osmosis is considered as a promising technique for biomicrofluidic devices as it is often preferred over pressure-driven flows due to the ease of control and integration with microdevices.¹⁶ In the context of this paper, traditional electro-osmosis is referred as “fixed charge electro-osmosis”¹³ (FCEO), as the charges are fixed on the solid nonconducting wall/surface and are independent of the applied electric field. When fluid transport is due to FCEO, the velocity profile is effectively plug flow in the thin EDL limit.

Another phenomenon, known as induced charge electro-osmosis (ICEO), is similar to FCEO except that the charges are induced on polarizable and electrically conducting surface by an

FIG. 1. Schematic showing FCEO slip velocity on (fixed negatively charged) nonconducting wall and ICEO slip velocity on polarizable metal surface (charges are induced due to external electric field). The charges on the solid surface attract counterions from the electrolyte solution and form EDL.

externally applied electric field. The FCEO slip on nonconducting fixed charge surface and ICEO slip over polarizable surface is schematically shown in Fig. 1. Initially, the electric field lines intersect the conducting surface at right angles and induce surface charges on the conducting surface. When electrolyte solution is present, due to the nature of induced charges, a bipolar EDL is formed near the conducting surface. At steady state, the electric field lines are expelled from the EDL due to the screening charges contained within it; thus, the bulk profile is that of an insulator. The distribution of induced charges over the conducting surface at steady state is nonuniform and the net induced charge is equal to zero. The magnitude of induced charges is proportional to the applied field strength, which makes ICEO flow field nonlinear and due to its quadratic dependence on electric field, steady ICEO flows persist in dc and ac fields. Initially, this effect was studied by Gamayunov *et al.*¹⁷ and Murtsovkin¹⁸ when they conducted theoretical and experimental investigations of nonlinear flow field near the polarized particles in the presence of an electric field. Recently, such a phenomenon was studied with reference to microfluidic applications by various researchers. Gonzalez *et al.*¹⁹ studied this effect by applying ac field directly on the microelectrodes and the flow is termed as ac electro-osmosis. In an extensive review, Bazant, Squires, and co-workers^{13,20–22} studied ICEO around a polarizable metal cylinder in ac and dc electric fields. The effect of hydrodynamic and electrostatic forces on polarizable cylindrical particles adjacent to a wall is examined by Zhao and Bau.²³ Wu and Li^{24,25} proposed a numerical correction method to estimate the steady state induced zeta potential on the conducting surface and demonstrated the use of conducting triangles embedded within the microchannel for mixing and flow regulation. A similar study by Jain *et al.*²⁶ proposed the use of semicircular conducting obstacles for enhancing mixing while solving the full Poisson–Nernst–Planck (PNP) model. Both the correction method and PNP model are compared by Jain *et al.*²⁶ and the modeling results are found to be in agreement.

FIG. 2. Top-view of the proposed design.

TABLE I. Simulation parameters (default values).

Parameter	Value	Description
W	100 μm	Width of the microchannel
κW	100	Ratio of channel width to Debye length (PNP model)
a	25 μm	Radius of conducting half cylinder
L	1 mm	Length of microchannel
D	$1 \times 10^{-9} \text{ m}^2/\text{s}$	Diffusivity of electrolyte ions (PNP model)
D_s	$1 \times 10^{-11} \text{ m}^2/\text{s}$	Diffusivity of species to be mixed
S_f	-25 mV	Fixed zeta potential on nonconducting wall

III. PROPOSED DESIGN AND MATHEMATICAL MODEL

The proposed design (top view shown in the Fig. 2) consists of conducting half cylinders, of radius a , embedded within the nonconducting channel wall. The conducting surface is assumed to be initially uncharged and highly polarizable so that Faradaic reactions (i.e., electrochemical reactions at the metal-electrolyte interface where electrons are transferred between the two phases by reduction or oxidation of ions in the electrolyte) at the interface are negligible. Although the flow in the channel is inherently three dimensional, with the assumption of homogeneous nonconducting top and bottom channel walls, essential flow features can be captured using a two-dimensional model^{24,25} at considerably less computational effort, permitting a more detailed parametric study.

The steady ICEO flow problem can be solved using two approaches: (1) The PNP model and (2) correction potential method-slip velocity model. The PNP model resolves the EDL and solves for electrolyte ion concentration distributions. The PNP model can be used for both thin and thick EDLs and accounts for surface conduction; however it is very much computationally intensive as compared to the correction method. This approach was used by Zhao and Bau²³ and Jain *et al.*²⁶ for modeling steady ICEO flow. On the other hand, correction method, proposed by Wu and Li,^{24,25} is a numerical approach for estimating the induced zeta potential on a conducting surface and further utilizes it to estimate the slip velocity at a conducting surface (adopting the Smoluchowski limit for thin EDL). Recently, we utilized this approach to arrive at the optimal obstacle shape for ICEO mixers.²⁷ When compared to PNP model, correction method provides equivalent results for smaller field strengths/induced zeta potential values. For higher field strengths/induced zeta potential values, the disagreement between the two modeling approaches increases with increasing field strength. Recently, Wu and Li²⁵ reported a reasonable agreement between experimental data and numerical modeling results based on correction potential modeling approach. In this study, we have used both models, initially PNP model to demonstrate the concept and correction method toward the end; for generation of user-defined concentration gradients. Both methods are discussed (with appropriate equations and boundary conditions) later in this section.

To describe the mathematical model, we introduce the following reference quantities and dimensionless variables:

$$L_{\text{ref}} = W, \quad \psi_{\text{ref}} = \frac{K_b T}{ze}, \quad c_{\text{ref}} = c_0, \quad E_{\text{ref}} = \frac{\psi_{\text{ref}}}{L_{\text{ref}}}, \quad u_{\text{ref}} = \frac{\epsilon_0 \epsilon_r \psi_{\text{ref}}}{\mu} E_{\text{ref}},$$

and

$$\bar{x} = \frac{x}{L_{\text{ref}}}, \quad \bar{y} = \frac{y}{L_{\text{ref}}}, \quad \bar{\psi} = \frac{\psi}{\psi_{\text{ref}}}, \quad \bar{c}_i = \frac{c_i}{c_{\text{ref}}}, \quad \bar{u} = \frac{u}{u_{\text{ref}}}, \quad \bar{E} = \frac{E}{E_{\text{ref}}}, \quad \bar{p} = \frac{p}{\rho u_{\text{ref}}^2}, \quad \bar{q}_s = \frac{q_s L_{\text{ref}}}{\epsilon_0 \epsilon_r \psi_{\text{ref}}}.$$

The notations/symbols, along with all default parameter values used in the simulation, used above are described in Table I. The nonconducting channel walls are negatively charged and the conducting metal surface will acquire surface charges as an electric field is applied. A 1:1 electrolyte is used in the simulation with constant diffusivity D for both types of ions. Also, the solution is

assumed to be an incompressible, Newtonian fluid with fixed dielectric constant ϵ_r , viscosity μ , and density ρ .

A. PNP model

In the fluid domain, the Poisson equation relates the electric potential ψ to the charge densities. In its nondimensional form, the Poisson equation is

$$\bar{\nabla} \cdot (-\bar{\nabla}\bar{\psi}) = \frac{1}{2}\kappa^2 W^2 (\bar{c}_1 - \bar{c}_2). \quad (1)$$

The above equation relates the electric potential to the volumetric charge densities. In the above equation, $\bar{\nabla}$ is the dimensionless gradient operator, W is the channel width, $\bar{c}_1$ and $\bar{c}_2$ are the scaled concentrations of positive and negative electrolyte ion, respectively, and κ is the inverse of Debye length given by

$$\kappa = \left(\frac{2z^2 e^2 N_A c_0}{\epsilon_0 \epsilon_r K_b T} \right)^{1/2}. \quad (2)$$

In Eq. (2), z is the valence of the electrolyte ions, e is the elementary charge, N_A is the Avogadro number, c_0 is the bulk electrolyte concentration, and K_b , T , and ϵ_0 represent Boltzmann constant, absolute temperature, and permittivity of free space, respectively.

As the electrolyte ions cannot penetrate inside the metal cylinders, the electric potential distribution is given by the Laplace equation inside the metal domain,

$$\bar{\nabla} \cdot (-\bar{\nabla}\bar{\psi}) = 0. \quad (3)$$

At the channel inlet, a constant potential V_0 relative to the outlet potential is applied, giving rise to a steady electric field E in the x direction. Also, a constant surface charge density q_s is imposed on the channel walls and potential continuity is applied at the metal-fluid interface. The electric displacement (D_E) may or may not be continuous at the metal-electrolyte interface depending on the presence of surface charge. Considering an initially uncharged cylinder, the interfacial boundary condition can be written as $n(D_{E1} - D_{E2}) = 0$, as used by Zhao and Bau.²³

The flow field in the fluid domain is governed by the continuity and Navier–Stokes equations. These equations, in their dimensionless forms, are

$$\text{Re}(\bar{\mathbf{u}} \cdot \bar{\nabla}\bar{\mathbf{u}}) = -\bar{\nabla}\bar{p} + \bar{\nabla} \cdot (\bar{\nabla}\bar{\mathbf{u}}) - \frac{1}{2}\kappa^2 W^2 (\bar{c}_1 - \bar{c}_2) \bar{\nabla}\bar{\psi}, \quad (4a)$$

$$\bar{\nabla} \cdot \bar{\mathbf{u}} = 0. \quad (4b)$$

In Eq. (4a), the rightmost term is due to the electrical body force within EDL and Re is the Reynolds number (ratio of inertial forces to viscous forces) and can be written as

$$\text{Re} = \frac{L_{\text{ref}} u_{\text{ref}} \rho}{\mu} = \frac{\epsilon_0 \epsilon_r W K_b T \rho}{ze\mu^2}. \quad (5)$$

A steady state ion conservation equation can be written for electrolyte ions in domain 1, with the Peclet number Pe (ratio of convective transport to diffusive transport) appearing with the convective term as

$$\text{Pe}(\bar{\mathbf{u}} \cdot \bar{\nabla}\bar{c}_i) = \bar{\nabla} \cdot (\bar{\nabla}\bar{c}_i) + \bar{\nabla} \cdot (\bar{c}_i \bar{\nabla}\bar{\psi}). \quad (6)$$

The Peclet number is defined as

$$\text{Pe} = \frac{u_{\text{ref}} L_{\text{ref}}}{D} = \frac{\varepsilon_0 \varepsilon_r (K_b T)^2}{\mu D (ze)^2}. \quad (7)$$

For fluid flow, zero pressure conditions are imposed at the inlet and outlet, while the no slip condition is imposed at fluid-solid boundaries. Similarly, zero flux condition is imposed at the channel walls including metal surface for electrolyte ions and other species.

B. Correction potential method

Assuming thin EDL, the electric potential distribution at steady state can be described using the Laplace equation. In nondimensional form, the Laplace equation is

$$\bar{\nabla}^2 \bar{\psi} = 0. \quad (8)$$

A steady electric field E is applied in the x direction (as mentioned earlier for PNP model) and at the channel as well as the obstacle surface, normal component of electric field is specified as zero, i.e., $n \cdot \nabla \psi = 0$.

The flow field in the computational domain is governed by the continuity and Navier–Stokes equations. These equations, in their dimensionless forms, are

$$\text{Re}(\bar{u} \cdot \bar{\nabla} \bar{u}) = -\bar{\nabla} \bar{p} + \bar{\nabla}^2 \bar{u}, \quad (9a)$$

$$\bar{\nabla} \cdot \bar{u} = 0. \quad (9b)$$

It should be noted that the electrical force term in the Navier–Stokes equation is accounted by the slip velocity boundary condition, as given by the Hemholtz–Smoluchowski's equation,

$$\bar{u} = \bar{\varsigma} \bar{E} \quad \text{where} \quad \left\{ \begin{array}{l} \bar{\varsigma} = \bar{\varsigma}_f \text{ at nonconducting surface} \\ \bar{\varsigma} = \bar{\varsigma}_i \text{ at conducting surface} \end{array} \right\}. \quad (10)$$

In the above equation, ς_f is the fixed zeta potential on the nonconducting surface, whereas ς_i is the induced zeta potential on the conducting surface; the magnitude of ς_i is dependent on the applied electric field as well as on the obstacle shape. The induced zeta potential is estimated using the Correction method^{24,25} as follows:

$$\bar{\varsigma}_i = -\bar{\psi} + \bar{\psi}_c. \quad (11)$$

Here ψ_c is the constant correction potential given by

$$\psi_c = \frac{\int_s \psi dA}{A}. \quad (12)$$

In the above equation, A represents the surface area of the conducting obstacle. At the inlet and outlet zero pressure conditions are imposed, while Smoluchowski's slip condition [Eq. (10)] is imposed at fluid-solid boundaries. For calculation of slip velocity, fixed zeta potential ς_f is imposed on the nonconducting channel walls, whereas induced zeta potential ς_i is calculated using Eqs. (11) and (12). It should be noted that ICEO slip velocity has quadratic dependence on electric field as induced zeta potential scales linearly with electric field. Therefore, at high electric fields ICEO flow dominates within the microchannel.

The steady state ICEO flow problem can be solved using any one of the models outlined above. Further, the steady transport of the species is governed by the convection-diffusion equation and can be written in dimensionless form as

FIG. 3. Comparison between full PNP model (dashed lines) and correction method (solid lines) for $\zeta_f = -50$ mV at various fields i.e., (a) $E=200$ V/m, (b) $E=1000$ V/m, (c) $E=2000$ V/m, and (d) $E=4000$ V/m. The error between the results increases as electric field/induced zeta potential is increased. For $E=4000$ V/m, the magnitude of ζ_i is approximately eight times of thermal voltage (25 mV) and error is 5.5%.

$$(\bar{u} \cdot \bar{\nabla} \bar{c}_s) = \bar{\nabla} \cdot (\bar{\nabla} \bar{c}_s) \frac{D_s}{u_{\text{ref}} L_{\text{ref}}}. \quad (13)$$

In the above equation, $\bar{c}_s$ and D_s represent species concentration and diffusion coefficient, respectively. For species transport, a constant concentration condition is imposed at the channel inlets (i.e., scaled concentrations of 1 and 0 at inlets 1 and inlet 2, respectively). The aforementioned condition is implemented at the inlet boundary using a smoothed Heaviside function (with continuous second derivative). Further, it is assumed that species concentration is sufficiently low such that it does not affect the flow profile. At the conducting surfaces and nonconducting channel walls, zero flux condition is imposed for the species, while convective-flux only boundary condition is applied at the channel outlet. The above model is solved using the direct (UMFPACK) solver available within the commercial finite element method package, COMSOL 3.4. Due to ICEO flows, the location of the interface between two streams varies spatially; hence adaptive meshing is employed for accurate solution near the interface. For full PNP model, fine meshes are used near wall and polarizable obstacles (so as to resolve the EDL accurately) and the results presented in Sec. IV are mesh independent.

IV. RESULTS AND DISCUSSION

Initially, the full PNP model is compared to correction potential approach for the proposed design and the results for exit species concentration profile are shown in Fig. 3. The obtained results suggest a good agreement between two approaches even for induced zeta potential higher than thermal voltage. However, the error between the two approaches increases with increasing electric field/induced zeta potential. To ensure accuracy, full PNP model is used for analysis, except for the optimization part, which requires iterative solution and correction approach is best suited in terms of computational effort.

For the proposed design, the concentration gradient formation in the microchannel is governed by the following mechanisms; (a) transverse diffusion, (b) axial convection due to FCEO flow, and

FIG. 4. Induced zeta potential plotted along the conducting surface. The magnitude of induced zeta potential scales linearly with applied electric field.

(c) transverse convection which originate due to ICEO flow. With very weak external applied field, the FCEO and ICEO flows are weak due to linear and quadratic dependence on electric field, respectively. Therefore for small field strength, diffusion is the dominant mechanism and yields a constant concentration profile at the exit. At intermediate field strength, FCEO flow will govern the gradient formation resulting in an error function type profile (which can be approximated as linear profile¹²) and at high fields, ICEO flow will induce transverse convection locally (near conducting obstacle) to generate asymmetric and nonlinear gradients.

In Fig. 4, induced zeta potential is plotted along the length of conducting surface (L_{cs}) for various applied field strength. As evident from Fig. 4, the induced zeta potential increases linearly with applied field with close to eight times of thermal voltage for $E=4000$ V/m, whereas $\zeta_f = -25$ mV. A very fine mesh (minimum element size $\sim 1 \times 10^{-3}$) is employed at the solid-fluid boundary [Fig. 5(a)] for accurate estimation of gradients in the EDL. The next plot [Fig. 5(b)] shows the surface plot for α , where $\alpha = \bar{c}_1 - \bar{c}_2$ is the difference between positively and negatively charged electrolyte ion concentrations. The variable α represents the excess charge and takes on positive and negative values at the left and right half of the semicylinder, respectively (due to induced charges). Also, a cross-sectional plot for α is shown in Fig. 5(c). Both Figs. 5(b) and 5(c) suggest that the α value goes to zero outside the EDL, confirming electroneutrality (or uniform bulk conductivity) outside the EDL.

Next we analyze the fluid streamlines near the conducting surface (Fig. 6) and its effect on the species concentration (Figs. 7 and 8) with respect to the electric field strength. At small field strength ($E=200$ V/m), the flow is weak and due to transverse diffusion, a constant concentration profile is obtained at the exit, as shown in Fig. 7(a) and profile (a) in Fig. 8. With an increase in electric field strength, the FCEO and ICEO flows start to overcome diffusion, resulting in an error function concentration profile at the exit, as observed in Fig. 7(b) and profile (b) in Fig. 8.

Upon further increase in electric field, ICEO flow dominates near the conducting surface, which results in an increased vortex size, as seen in Fig. 6. The strong circulations near conducting obstacle directly affect the species concentration, as observed in Figs. 7(c) and 7(d). It should be noted that ICEO does not mix the species rather alters their path by creating an additional resistance through flow circulations. The transverse convection generated due to nonlinear slip at

FIG. 5. The applied unstructured mesh is plotted (near the interface) in (a). The extremely fine mesh at interface is used to capture the gradients in EDL. The excess charge α is plotted as surface plot in (b) and cross-sectional plot in (c). The excess charge is contained in the thin EDL and the bulk is electroneutral corresponding to $\alpha=0$, as seen in (b) and (c).

conducting surface can be utilized to generate asymmetric and nonlinear gradients, as observed in profile (c) in Fig. 8. The nonlinear and asymmetric nature of generated gradient [Fig. 8(c)] is due to ICEO flow circulations and this nonlinearity increases as the test cross section is moved closer to obstacle, as shown in Fig. 9. Further, the magnitude of the transverse velocity component can be altered by the applied field strength as well as by the shape of the conducting surface. Therefore, by employing a range of such conducting obstacles (with different shapes and sizes), transverse convection of varying magnitude can be introduced at different spatial locations in the channel and can be exploited to attain user-defined concentration profiles. All the concentration surface and cross-sectional plots (Fig. 7–10) are for species concentration solved using convection-diffusion equation [Eq. (13)].

An optimization problem is formulated for generating user-defined profiles (Fig. 10), where the objective function is defined as the squared difference between the cross-sectional species

FIG. 6. Fluid streamlines near the conducting obstacle corresponding to electric field of (a) 200 V/m, (b) 1000 V/m, (c) 4000 V/m, and (d) 6000 V/m. The ICEO flow (and size of the vortex) increases with electric field. Further increase in electric field will generate another vortex to the left of conducting obstacle.

concentration profile and the targeted user-defined function, i.e., $e = (\bar{c}_s - c^*)^2$. The objective function is minimized using genetic algorithms with the electric field (E) and the conducting cylinder radii (a_i , $i=1-5$) as parameters. The lower and upper bounds for a_i are chosen as $[0.05w-0.45w]$, while the electric field could take any on value between 10 and 150 V/cm. As mentioned earlier, the gradient properties are governed by the interplay of diffusion, FCEO, and ICEO. Therefore, it is important to note that there could be multiple solutions for obtaining a user-defined profile, e.g., a similar profile can be obtained via an alternate combination of D_s , E , s_f , or with different shapes/sizes of conducting obstacle. The nonlinearity in the gradient occurs with dominant ICEO flows, which depend on the size/shape of conducting obstacle and the externally applied field. For instance, for a given electric field, variation in obstacle radii will generate transverse flows of varying magnitude at different spatial locations (Fig. 10), thereby adding nonlinearity to the

FIG. 7. Species concentration surface plot for various regimes, i.e., (a) diffusive regime ($E=200$ V/m), (b) FCEO flow regime ($E=1000$ V/m), and [(c) and (d)] ICEO flow regime ($E=4000$ V/m and $E=6000$ V/m).

FIG. 8. Cross-sectional species concentration profile at exit for (a) $E=200$, (b) $E=1000$, and (c) $E=4000$ (in V/m). The obtained profiles correspond to diffusive, FCEO, and ICEO dominant operating regimes, respectively.

gradient, which is the unique feature of the proposed design. The proposed design is also advantageous in terms of dynamic controllability, the ability to change the gradient during midexperiments. As demonstrated earlier in Fig. 8, just by altering the applied field strength and keeping all other parameters same, the proposed design can easily switch from linear gradient to a nonlinear gradient. Also, the time scales associated with FCEO/ICEO flows are quite small (approximately in order of 10^{-4} s),¹³ which suggests rapid formation of nonlinear gradients and therefore, offers an enhanced controllability for the proposed design.

FIG. 9. Cross-sectional species concentration profile for $E=4000$ at various test cross sections, i.e., (a) at $\bar{L}=10$ (exit), (b) at $\bar{L}=9.5$, and (c) at $\bar{L}=9.2$. The nonlinearity and asymmetric nature of gradient increase for test section closer to the obstacle.

FIG. 10. Concentration surface plots and comparison between targeted profile (solid line) and numerically obtained profile (dashed line).

V. CONCLUSIONS

A new microfluidic device is proposed for concentration gradient generation based on the ICEO flows. In comparison with the other reported designs, the proposed method is geometrically simpler and has the unique characteristic of inducing transverse flows locally, which can be controlled by the magnitude of the applied field and by the shape of the conducting protrusion. For analysis, both full PNP model and correction method based on slip velocity approach are used to model the steady ICEO flow. It is shown that the proposed device is capable of generating variety of gradients and could switch between linear and nonlinear gradients by simply altering the applied electric field, demonstrating the superior dynamic controllability of the proposed design.

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