Design of a Sample Preparation Device Using Induced-Charge Electroosmosis

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Abstract

Mixing samples with reagents for chemical/biological detection is one of the most time consuming operations on microfluidic platforms due to the low rate of diffusive transport. However, the recently identified phenomena of induced-charge electroosmosis (ICEO) can drive fluid motion at the microscale by forming electric double layers at metal surfaces. An applied potential can force ions in these layers to move, using AC or DC fields, which generates slip boundary conditions. By taking advantage of ICEO, mixing devices were designed, fabricated, and tested in less than 6 months. Rapid turn-around was achieved through collaboration between experiments and simulation to identify key system behavior.

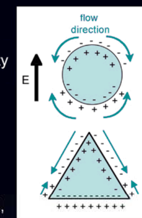
"The perception that mixing is easy and simple, and that all necessary knowledge is available in textbooks, continues to plague chemical engineering practice", SM Kresta, 2004

Background

Microfluidic mixing falls into two broad classes
- Passive mixing - force liquids through tortuous paths (baffles, turns, etc)
  - Primary weakness: it continually dilutes the sample as long as the process continues
- Active mixing - recirculating flows
- MHD, ultrasonic (these tend to be larger, bulky systems)
- Oscillatory electroosmosis (Santiago, Stanford)
  - Creates instability in flow using 4000 volt, 5 Hz (very high voltage)
  - Mix dyes in a few seconds, but requires specific properties of the reagents
- ICEO/AC electroosmosis
  - Can mix dyes in a few seconds
  - Can produce time dependent, 3D flows
  - Chaotic behavior can be obtained even in laminar flows if they are time dependent and at least weakly 3D. In general, chaotic flows provide the best mixing

Computational Approach

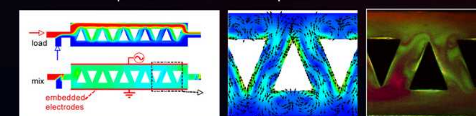
- Laplace's equation is solved for the electric field
- The field polarizes a metal object and attracts counter ions to form a double layer (metal completely screened, $\partial\phi/\partial n = 0$)
- The field acts on the mobile charge and induces a fluid velocity
- When the AC field switches direction the polarization and counter ion charge switches sign, such that the flow direction is unchanged
- Navier-Stokes is solved for the flow field
- A slip velocity boundary condition is used on all metalized surfaces; $u = -\varepsilon\zeta E_t/\mu$, scales as square of the applied voltage
- Zeta potential, $\zeta = \phi - \phi_0$, where ϕ_0 is the potential of the metal, obtained from $\int \zeta dA = 0$ (zero charge condition)
- An asymmetric object induces an asymmetric, and mostly uni-directional, flow field



Modeling Framework

- The designs considered are very non-intuitive
- Modeling was indispensable to their identification and rapid assessment
- Inlet and outlet channels were included to simulate the loading and off loading of the devices

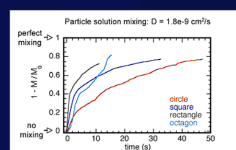
- Mixing step: the ICEO flow results in lateral transport between the two liquids



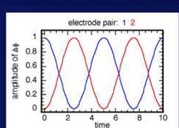
Anaylsis

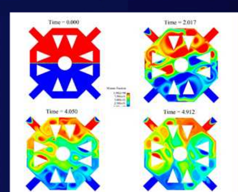
- A metric was defined to help quantify device performance

$$M = \frac{\int |c - \bar{c}| dV}{V}$$



- Steady flows approach perfect mixing only asymptotically, a characteristic well known from mixing theory
- Unsteady flows approach perfect mixing more rapidly by creating chaotic particle paths
- The octagon uses two sets of electrodes to create a time dependent flow
  - **Applied potential 180° out of phase**
  - **Continually rotates electric field**
  - **Rotates flow field with it**



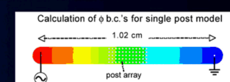


- The results for a given device can be scaled for other conditions

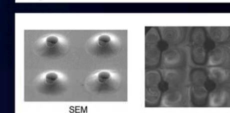
$$\tau_{mix} = \mu L^2 / \varepsilon \Delta\phi^2$$

Model Validation

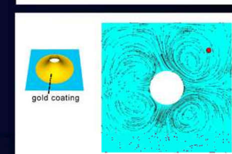
- An existing chip (porosity3) was used in the experiments



- A gold coating was applied to side surfaces of the posts for the ICEO experiments.
- Flow visualization using fluorescent beads revealed the flow pattern

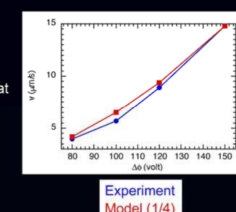


- Since the flow pattern was periodic, only the ICEO flow around a single post was modeled.
- The calculated flow pattern is in good agreement with the experimental result



Validation Results

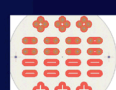
- The experiments showed that the velocity increases quadratically with the applied potential, in agreement with the model
- The absolute results from the model had to be reduced by a factor of 100 to get the agreement shown.
- Others have shown experimental results that were a factor of 3 less than theory (Levitan 2005, measured u = 100 µm/s) using different fabrication techniques and models
- If the trend shown continues $\Delta\phi$ need only be increased by a factor of 10 to get the factor of 100 back in velocity
- This trend may not continue, so we are planning different fabrication approaches and higher fidelity modeling



Device Fabrication

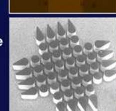
- Fabricating these devices helped to develop the process
- The new fabrication process places a gold coating everywhere at first, and then removes it from selected regions using ion milling
- This process was made possible by collaborating with Cornell University
- They also are being used in ongoing experiments to determine the flow speeds generated in comparison to the porosity3 experiments
- A device with electrically addressable posts to be used in fixed-potential-ICEO experiments is in fabrication
- The rectangle and octagon devices are in fabrication

The mask used for to make the practice devices

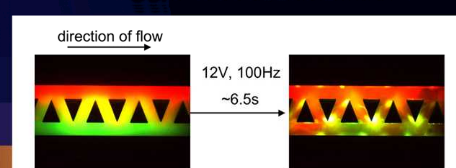


A close up of one of the devices

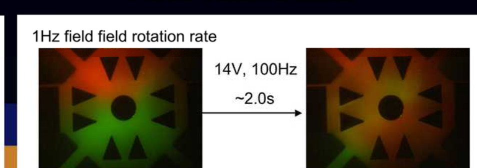
An SEM of the high aspect ratio posts with a metal coating



Continuous Flow Mixer



Fixed Volume Mixer



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