Design of Integrated Micro-robotic Fish

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Background

- Design a “micro-fish” that can program their motion after being put into ocean, using **AC osmosis-based method.**

- Why microdevices?

  “Allow manipulation with fast response times.

  Handle small fluid volumes.

  Sense and control flows on small length scales.”

- Programable micro-fish with low applied voltage amplitude to investigate deep ocean/ collect plastic particle, etc. in **saline environment.**

How to set fish into motion?

- How? (my interpretation)

Pump produces fluid flow -> velocities gradient -> fish can swim.

Move small amounts of fluids containing various particles along channels

Pumping
Combination electrochemical reactions
Thermal gradients
Piezoelectricity
Mechanical actuators (create valves or pumps)
Electric fields

hard to downscale

- **Electric fields**

  DC electric field along the channel to induce electro-osmosis
  AC traveling wave on an electrode array to create pumping.

- **Asymmetric** electrode array.
- In a locally asymmetric environment without dissipation, a fluid should be globally set into **motion in the direction of broken symmetry**, even in the absence of macroscopic gradients (pressure or potential).

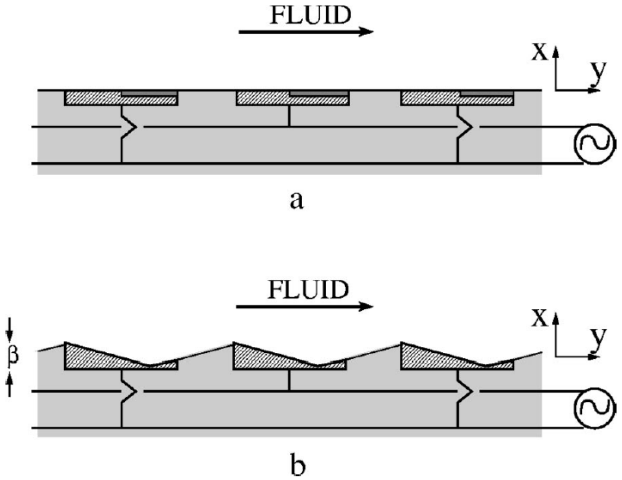


FIG. 1. Schematic examples of periodic asymmetric arrays of electrodes. The asymmetry or polarity is obtained by a modulation of (a) the surface electrochemical properties, or (b) the shape of the surface. When an oscillating potential is applied pumping in the y direction results.

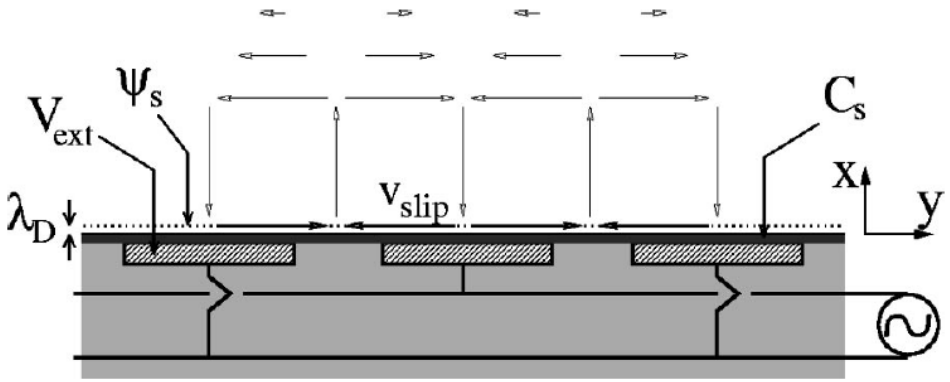


FIG. 2. Symmetric electrode array: schematic description of the instantaneous recirculation flow for fast vorticity diffusion. The flow alternates in time at a frequency ω/π.

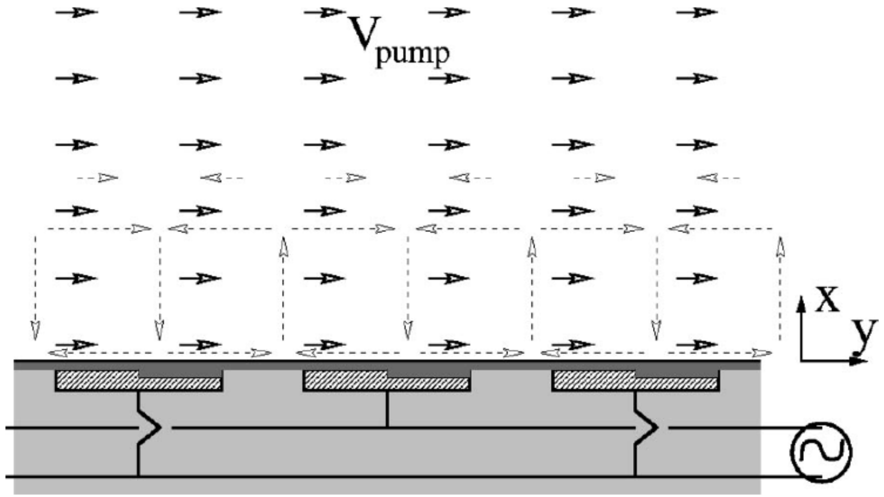
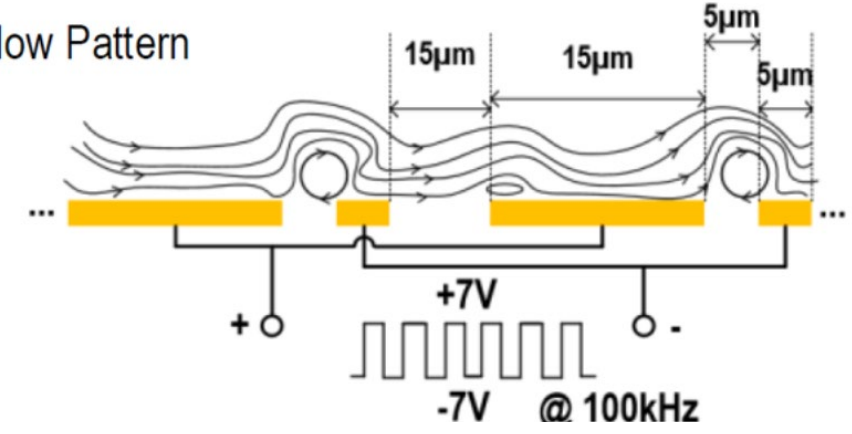
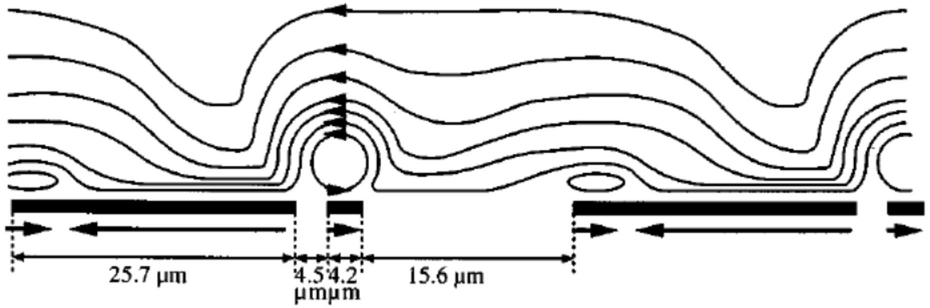


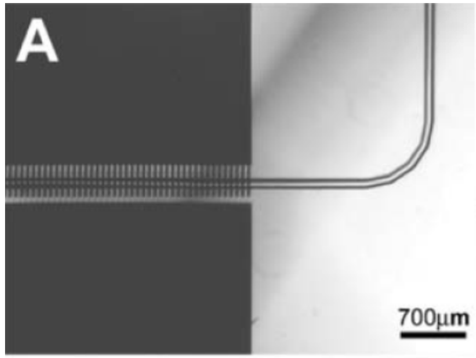
FIG. 3. Asymmetric electrode array: schematic representation of the the time-averaged flow as the sum of spatially periodic flows (dashed arrows) and of a homogeneous ''plug'' flow (solid arrows) due to a systematic bias in the slip velocity.

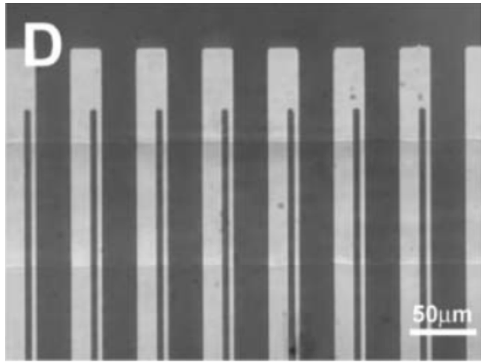
- **CMOS Driven AC osmosis bulk fluid flow**

Liquid Flow Pattern









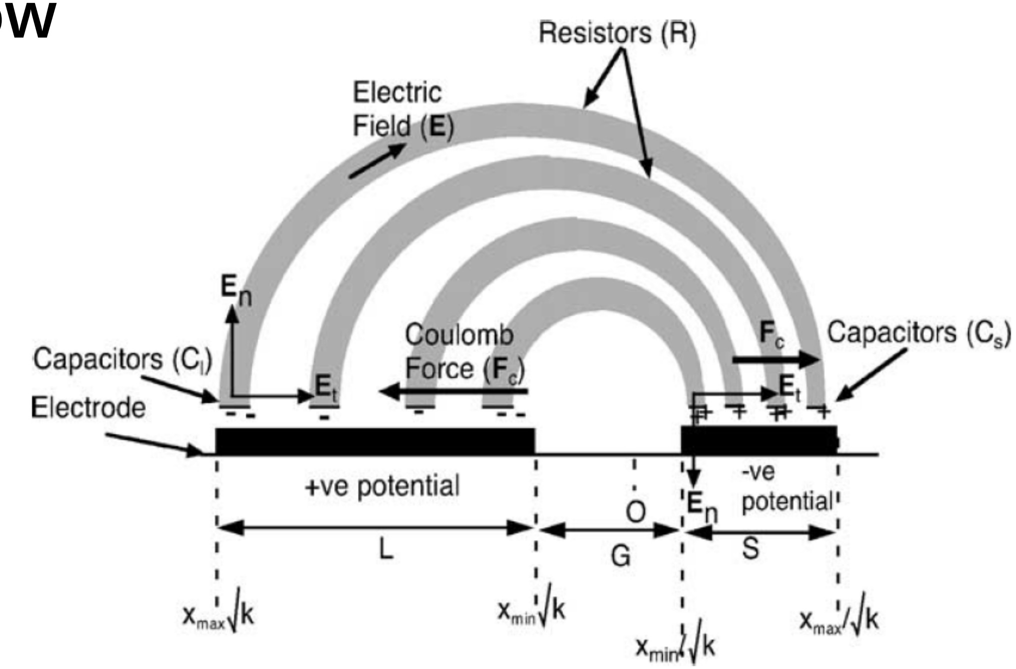


Fig. 1. Electrical equivalent model. An electrical circuit equivalent of the process at an instant when there is a positive potential on the large electrode and a negative potential at a small electrode. The electrical double layer is represented by the capacitors C_l and C_s, on the large and small electrodes, respectively. The bulk fluid is represented by resistors R. The non-uniform semi-circular lines represent the electric field between the electrodes. The direction of the force F_c is always in the same direction because as the potential changes polarity on the electrodes, the charges in the double layer also change, this results in a continuous motion of the fluid.

- Focus
  - ➢ Simple architecture/model.
  - ➢ Achieve the fluid flow with low AC voltage (< 5V, 10 V).
  - ➢ Fluid flow velocity's dependency?
    - Driving signal amplitude (low voltage).
    - AC signal frequency (kHz).
    - Ionic strength of electrolyte (Solution concentration).
    - Dimension of the asymmetric electrode array.
    - Plug flow in constricted channels.
    - Charge injection from electrodes (electrode materials).

    ...
  - ➢ In still water / in saline environment.
  - ➢ 2D / 3D velocity field.

1. Build Asymmetric electrode array theoretical model.

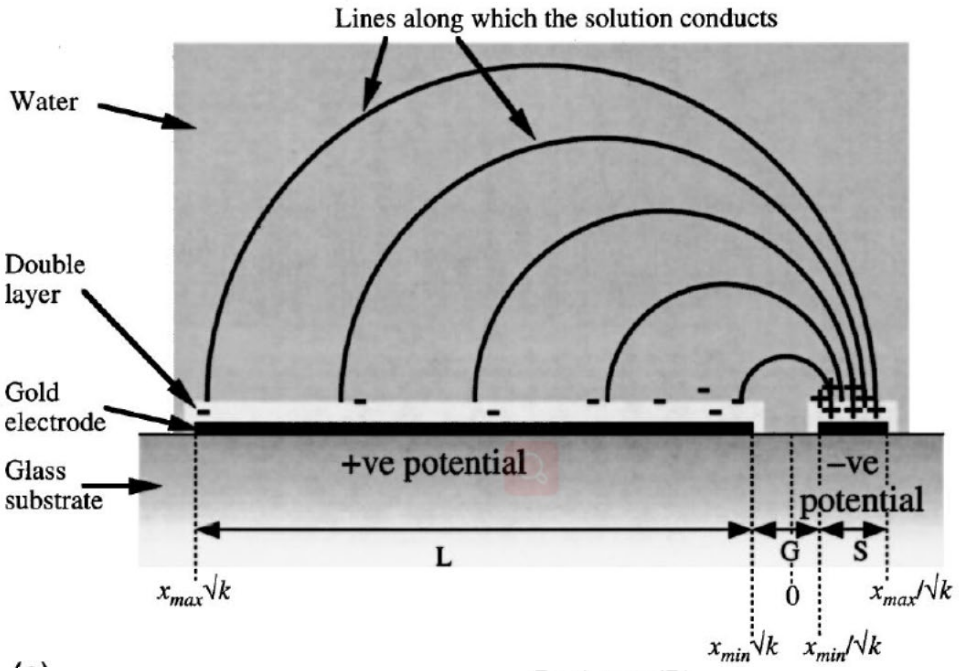
- General electrodes pair model (here in water):

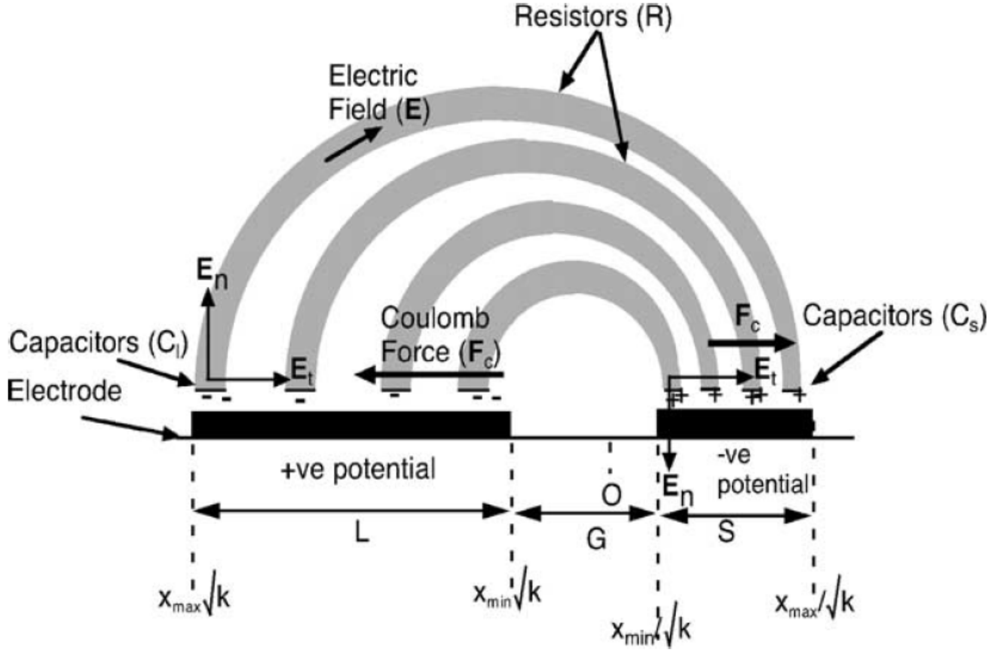
a. Applied frequency is lower enough or applied potential is lower than the ionization potential, electrolysis doesn't happen.

b. Bulk water behave in a resistive manner.

c. A double layer with a separation of charge will form at the electrode surfaces as a capacitor.

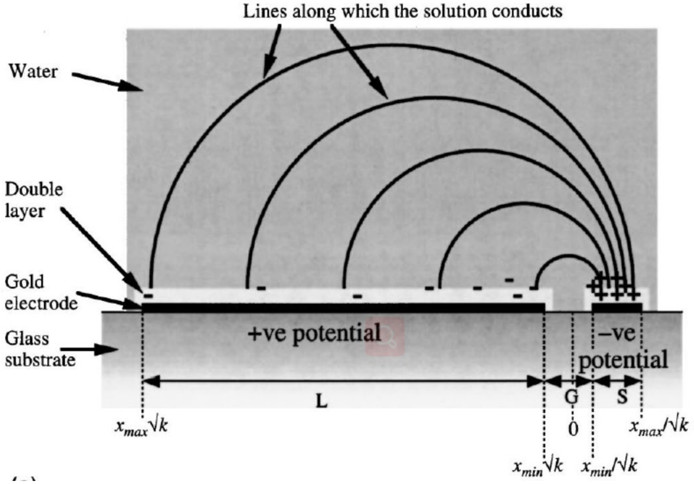
d. If ignore the distortion of the field lines at the edges of the electrode ->

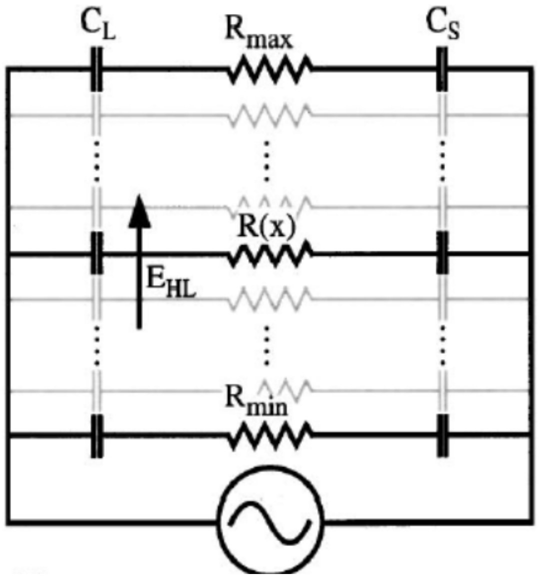




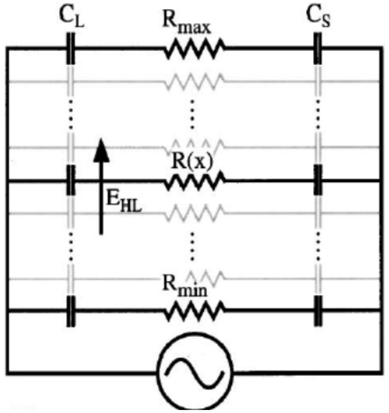
e. The current will flow parallel to the field lines from one electrode to the other.
f. The amount of charge separated in the double layers increases.

- Parameterizations of the fluid flow, double layer capacitance, average velocity…





Modeling approach (my interpretation):



- Resistor & Capacitors.

Calculate the slip velocity by the condition that the viscous drag across the layer .

$$R(x)=\frac{\pi x(\sqrt{k}+1/\sqrt{k})}{\quad} \qquad C_{DS}=\varepsilon\,\delta x/\sqrt{k}\lambda_D \qquad v_{DL}=\frac{\lambda_D\rho_{DL}E_{HL}}{\eta},$$

$$V_{\text{ave}}=\frac{\int_{x_{\min}}^{x_{\max}}\langle v_D(x)\rangle dx}{x_{\max}-x_{\min}}=\frac{\Psi_0^2 v_0}{2(x_{\max}-x_{\min})}\left(\frac{(\omega\sqrt{x_{\min}x_{\max}}/\omega_0)^2\left(\frac{x_{\max}}{x_{\min}}-\frac{x_{\min}}{x_{\max}}\right)}{\left((\omega\sqrt{x_{\min}x_{\max}}/\omega_0)^2+\frac{x_{\min}}{x_{\max}}\right)\left((\omega\sqrt{x_{\min}x_{\max}}\omega_0)^2+\frac{x_{\max}}{x_{\min}}\right)}\right)$$

- Flow in bulk electrolyte

Stokes's equation, Double layer, total surface charge density -> electro-osmotic slip velocity.

$$\mathbf{v}_{slip}=[\lambda_D\sigma_D(t)/\eta]\,E_y(x=0,t)\,\mathbf{y}.$$

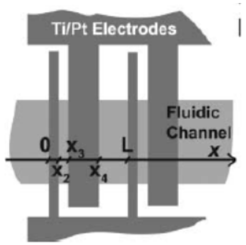
$$\begin{cases} -\boldsymbol{\nabla}p+\eta\Delta\mathbf{v}=\rho\partial_t\mathbf{v} \\ \nabla\cdot\mathbf{v}=0, \end{cases}$$

2. Achieve fluid flow along the channel.

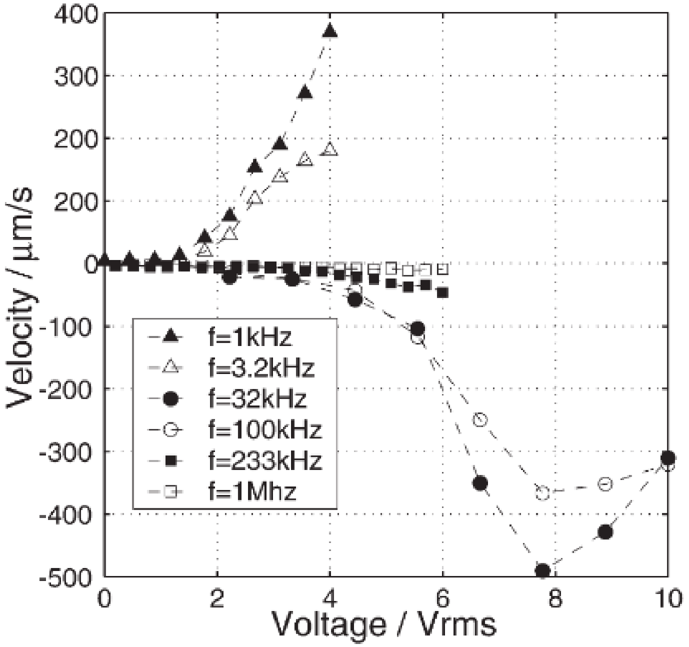
3. Study the performance of the pump system at low voltage with various factors.

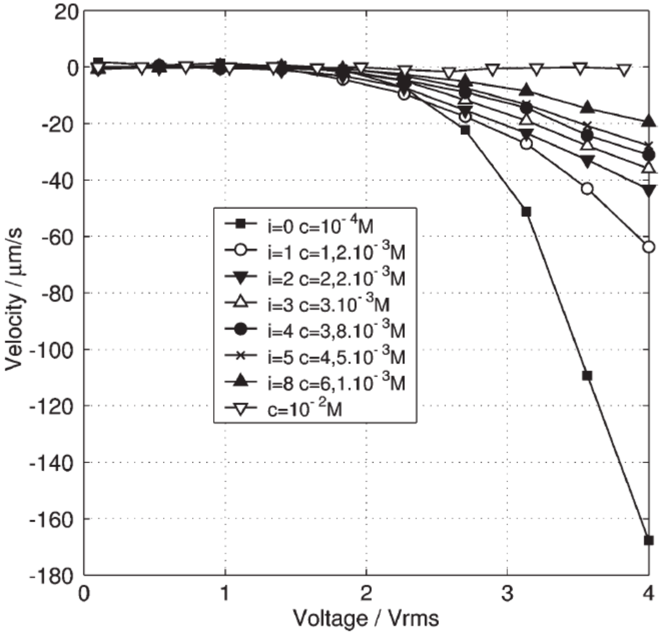
Possible approach （in saline solution）：

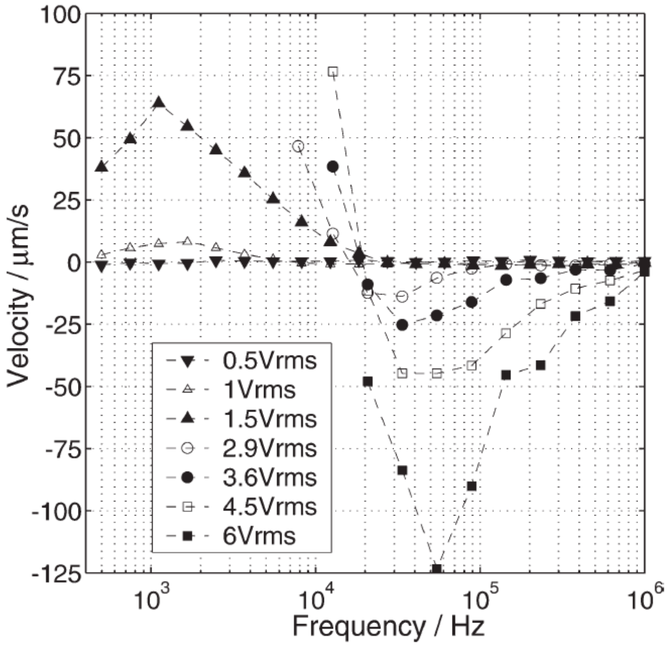
a. Velocity VS. driving signal amplitude, frequency, KCL concentration



- Fluid velocity: taking pictures within intrinsic interval.

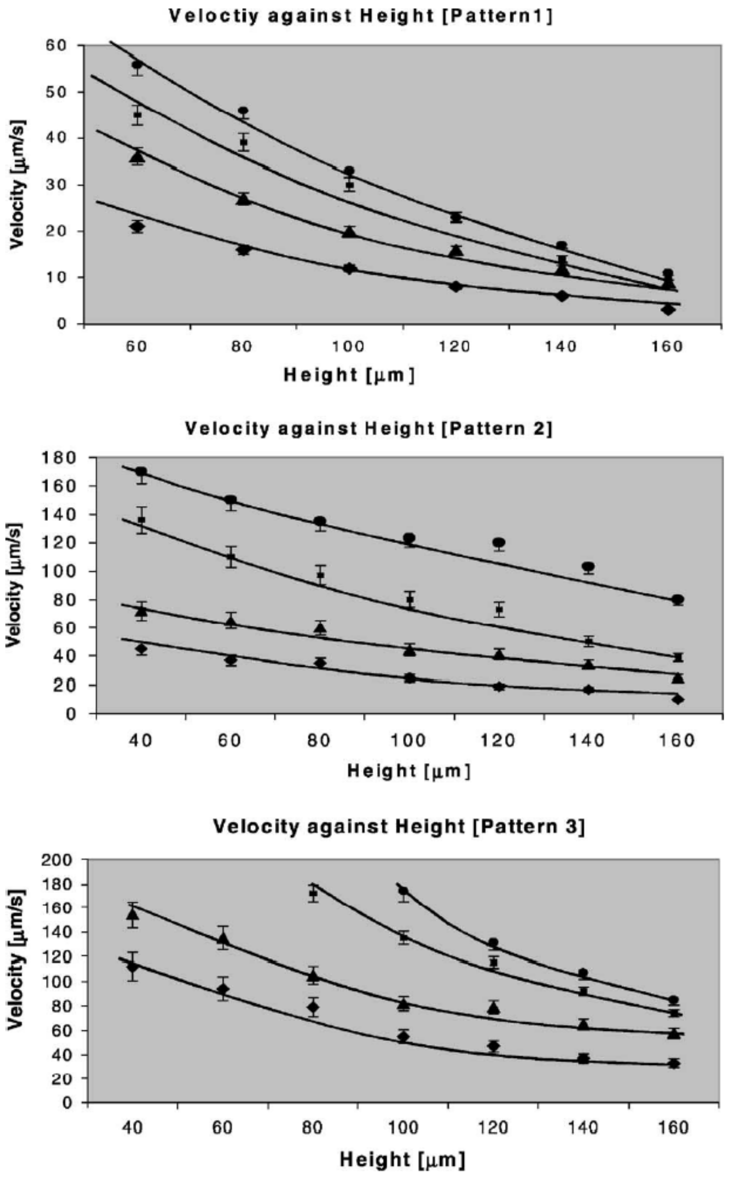






- L = 50 mm, x2 = 4.2 mm, x3 = 8.7 mm and x4 = 34.4 mm.

b. Velocity vs dimension of asymmetric electrodes



(◆) 1.0 V, (▲) 1.4 V, (■) 1.8 V, (●) 2.2 V.

Patterns used in this work

Patterns	S (μm)	L (μm)	G (μm)	G_1 (μm)	I (μm)
Pattern 1	5	25	5	15	50
Pattern 2	3	15	3	9	30
Pattern 3	2	10	2	6	20

Maximum average velocity

Voltage (V_{rms})	Velocity (μm/s)		
	Pattern 1	Pattern 2	Pattern 3
1.0	40	63	150
1.4	50	93	200
1.8	75	182	309
2.2	100	207	477

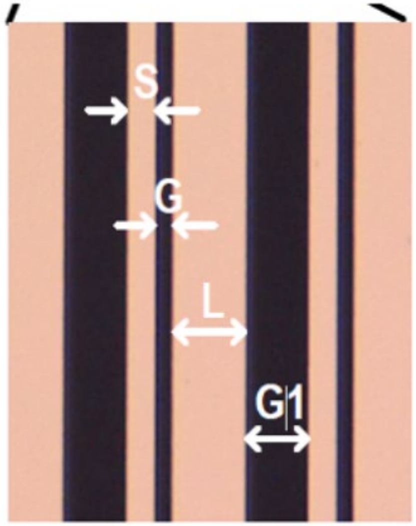
Values for x_{min} and x_{max}

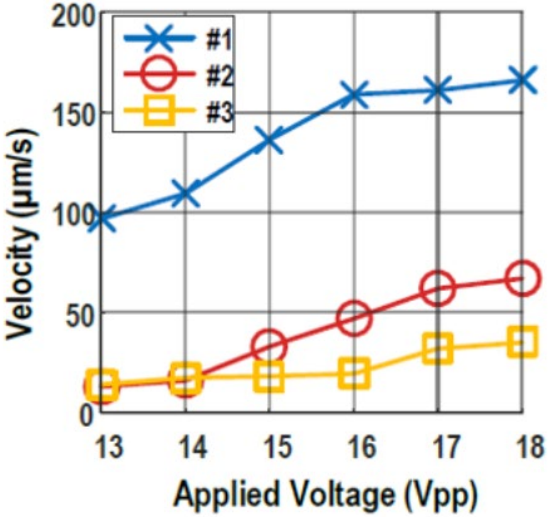
Patterns	x_{min} (μm)	x_{max} (μm)
Pattern 1	1.86	13.04
Pattern 2	1.12	8.94
Pattern 3	0.75	5.22

Comparisons of frequency and v_{ave}

	Pattern 1	Pattern 2	Pattern 3
Theoretical resonant frequency (kHz)	1.1	1.7	2.7
Experimental resonant frequency (kHz)	6	14	17
Theoretical ratio of v_{ave}	1	1.5	2.5
Experimental ratio of v_{ave}	1	2	4

c. Velocity VS. dimension, frequency, concentration, voltage





Electrode Dimensions for AC Osmosis

Patterns	*S (μm)*	*G (μm)*	*L (μm)*	*G1 (μm)*
#1	5	5	15	15
#2	5	5	20	15
#3	5	5	25	15