Introduction to BioMEMS & Medical Microdevices

Microfluidic Principles Part 2

Electrokinetic Phenomena

- **Electro-osmosis**
  - Fluid movement relative to a stationary charged or conducting surface through application of an electric field.

- **Electrophoresis**
  - In the presence of an electric field the particle can be induced to move relative to a *stationary* (e.g. gel) or moving liquid.

- **Streaming potential**
  - Occurs when an aqueous ion containing solution is forced to flow through a capillary or microchannel under an applied hydrostatic pressure in the absence of an applied electric field. An *electroviscous effect* occurs, or resistant to flow.

- **Dielectrophoresis**
  - Movement of dielectric particles in a spatially nonuniform electric field.

- **Electrowetting**

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Electric Double Layer (EDL)

Also called the Stern layer


Wikipedia

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EDL about a Spherical Particle…
Origin of Surface Charge…

1. Most materials obtain a surface charge when they are brought into contact with an aqueous solution.
2. Both glass and polymer microfluidic devices tend to have **negatively charged** surfaces.
3. Ionization of acidic vs basic surface groups.
4. Different affinities for ions of different signs to two phases:
   - The distribution of anions and cations between two immiscible phases such as oil and water,
   - Preferential adsorption of certain ions from an electrolyte solution onto a solid surface, or
   - Preferential dissolution of ions from a crystal lattice.
5. Charged crystal surfaces.
Electro-Osmotic Flow (EOF)
Calculation Assumptions…

- Uniform zeta potential.
- Electric double layer is thin compared to the channel dimensions.
- Electrically insulated channel walls.
- Low Reynolds numbers.
- Parallel flow at inlets and outlets.
- Uniform fluid properties.
- Constant viscosity and electrical permittivity.

The **Poisson equation** describes the electrical field potential in a dielectric medium.

The **Boltzmann equation** describes the distribution of ions near a charged surface.

The **Poisson-Boltzmann equation** is used to describe the ion and potential distributions in the diffuse layer.

The **Debye-Huckel parameter** is used to define the characteristic thickness of the diffuse layer.

The **Helmholtz-Smoluchowski** equation is used for both **electro-osmotic flow velocity** and **electrophoretic velocity** determination.
Charge distribution around an electrophoretic particle:

Example: Gel Electrophoresis

Horizontal Gel Electrophoresis  Vertical Slab Gel Electrophoresis
A particle’s electrophoretic velocity may be calculated by the Helmholtz-Smoluchowski equation:

$$v_{ep} = -\frac{E_z \varepsilon_r \varepsilon_0 \zeta}{\mu},$$

Where

- $v_{ep}$ is the particle's electrophoretic velocity (m/s),
- $E_z$ is the applied electrical field (V/m),
- $\varepsilon_r$ (epsilon-relative) is the dielectric constant of the medium,
- $\varepsilon_0$ (epsilon-nought) is the permittivity of a vacuum ($8.85 \times 10^{-12}$ F/m),
- $\zeta$ (zeta) is the zeta potential at the shear plane (V), and
- $\mu$ (mu) is the dynamic viscosity (kg/(m·s)).
Electrophoretic motility is defined as the electrophoretic velocity per unit of applied electrical field strength, characterizing how fast a particle moves in an electrical field:

\[ v_E = \frac{v_{ep}}{E_z} = \frac{\varepsilon_r \varepsilon_0 \zeta_p}{\mu} \]
Illustration of the *flow-induced electrokinetic field* in a microchannel:

**Steady State:** $I_{net} = 0$, i.e., $I_s = I_c$

Fluid is forced through channel.

Dielectrophoresis

- Physical phenomenon whereby dielectric particles (uncharged particles), in response to a \textit{spatially nonuniform electric field}, experience a net force directed toward locations with \textit{increasing} or \textit{decreasing} field intensity according to the \textit{physical properties of the particles and medium}. 
Dielectrophoresis is defined as the lateral motion imparted on uncharged particles as a result of polarization (relative to the surrounding medium) induced by non-uniform electric fields.

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Young’s equation (after Thomas Young who first proposed it in 1805) describes the simple balance of force between the liquid-solid, liquid-vapor, and solid-vapor interfacial surface energies of a droplet on a solid surface:

\[ \gamma_{LG} \cos \theta + \gamma_{SL} = \gamma_{SG}, \]

where

- \( \gamma_{LG} \) (gamma liquid-gas) is the liquid-gas interfacial tension,
- \( \gamma_{SL} \) (gamma solid-liquid) is the solid-liquid interfacial tension,
- \( \gamma_{SG} \) (gamma solid-gas) is the solid-gas interfacial tension, and
- \( \theta \) (theta) is the contact angle.
Electrowetting

Non-wetting under no potential

Wetting under electric potential

Reversible

1. Create droplets from reservoir

2. Cut

3. Merge

4. Transport

The effect of a potential $V$ on the contact angle is then determined by the following:

$$\cos \theta(V) - \cos \theta_0 = \frac{\varepsilon_r \varepsilon_0}{2\gamma_{LG} t} V^2,$$

where

- $\theta$ (theta) is the contact angle,
- $\theta_0$ (theta-nought) is the equilibrium contact angle at $V = 0$,
- $V$ is the electric potential across the interface (V),
- $\varepsilon_r$ (epsilon) the dielectric constant of the dielectric layer,
- $\varepsilon_0$ (epsilon) is the permittivity of a vacuum ($8.85 \times 10^{-12}$ F/m),
  (where F = farad per m) and
- $t$ is its thickness (m).
Microvalves

- Passive Valves
  - Check Valves
    - Directional, like a diode.
    - “Smart” polymers, external stimuli.
  - Stop Valves
    - Surface modifications of hydrophobicity/hydrophilicity for immobilization of fluid and materials.
Passive Valve...

- Hydrogel *check valve*:
  (a) Valve leaflets,
  (b) Anchors,
  (c) Expanding and closing the valve, and
  (d) Contacting and opening the valve.

Active Valve Types

- Pneumatic
- Thermopneumatic
- Thermomechanical
- Piezoelectric
- Electrostatic
- Electromagnetic
- Electrochemical
- Capillary force
**Electrostatic Valves**... 

- **Electrostatic valves** are based on the attractive force between two oppositely charged plates:

  \[ F = \frac{1}{2} \varepsilon_r \varepsilon_0 A \left( \frac{V}{d} \right)^2 \left( \frac{\varepsilon_i d}{\varepsilon_r d_i + \varepsilon_i d} \right)^2, \]

  where
  
  - \( A \) is the overlapping plate area,
  - \( d \) is the distance between plates,
  - \( d_i \) is an insulator layer thickness,
  - \( V \) is the applied voltage,
  - \( \varepsilon_r \) (epsilon-relative) is the relative dielectric coefficient of the medium,
  - \( \varepsilon_i \) (epsilon-insulator) is the relative dielectric coefficient of the insulator, and
  - \( \varepsilon_0 \) (epsilon-nought) is the permittivity of a vacuum.

Electromagnetic Valves…

- **Electromagnetic valves** offer the advantage of large deflection and disadvantage of size, low efficiency, and heat generation.

\[
F = M_m \int \frac{dB}{dz} dV,
\]

where

- \( F \) is the vertical force of a magnetic field,
- \( M_m \) is the magnetization (A/m),
- \( V \) the volume of the magnet,
- \( B \) is the magnetic field (Tesla), and
- \( z \) is the direction in which the force is acting.

Capillary-Force Valves...

- **Capillary-force valves** are based on active and passive control of surface tension and capillary forces.
  - *Electrocapillary*
    - Electrowetting phenomena
    - Application of a DC potential moves the fluid towards the negative cathode.
**Thermocapillary valves** – the *Marangoni effect*:

- Slower moving molecules, higher attractive force, higher viscosity and higher surface tension.
- Faster moving molecules, smaller attractive force, lower viscosity and lower surface tension.

Liquid is pulled from area of low to high surface tension.

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Passive mixers have no moving parts, but instead rely on diffusion and geometry of the device.

Active mixing increases the interfacial area between fluids and can be accomplished by piezoelectric devices, electrokinetic mixers, chaotic convection.
Passive Micromixer...

- **T-mixer** and **Y-mixer**:

  ![Diagram of T-mixer and Y-mixer](image)

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● Serpentine mixers:

Micropumps

- Non-mechanical pumping:
  - Electrokinetic methods,
  - Surface tension and capillary effects.

The energy balance in the liquid column and driving pressure are calculated as follows:

\[ 2\pi r_0 h (\gamma_{SG} - \gamma_{SL}) = \Delta p \pi r_0^2 h \quad \text{and} \quad \Delta p = \frac{2\gamma_{LG} \cos \theta}{r_0}, \]

where

\( \gamma_{SG}, \gamma_{SL}, \) and \( \gamma_{LG} \) (gamma) are interfacial tensions (N/m),

\( r_0 \) is the capillary radius (m),

\( h \) is the height of the column (m), and

\( \Delta p \) is the pressure difference across the gas-liquid interface.
Specified in more familiar terms of *surface tension* and *specific weight* the height is determined as follows:

\[ h = \frac{2\sigma \cos \theta}{\gamma r_0}, \]

where

\( \sigma \) (sigma) is the surface tension (N/m) (same as \( \gamma_{LG} \)), and

\( \gamma \) (gamma) is specific weight of the fluid (N/m\(^3\)).
Mechanical Pumps

- **Classification:**
  - Displacement or dynamic,
  - Check-valve pumps.

- **Types:**
  - Peristaltic pumps,
  - Rotary pumps,
  - Ultrasonic pumps,
  - Magnetic pumping.
Ultrasonic pumps work by causing acoustic streaming, which is induced by a mechanical traveling wave (FPW or SAW).

Pump Parameters…

- **Maximum flow rate:**
  - Volume of liquid per unit of time delivered by the pump at zero back pressure ($Q_{\text{max}}$).

- **Maximum back pressure:**
  - Maximum pressure the pump can work against,
  - At this pressure the flow rate becomes zero.

- **Pump head:**
  - Bernoulli equation,
  - Extended Bernoulli equation.

- **Efficiency**

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Bernoulli’s Equation...

- Total pressure (static, hydrostatic, and dynamic) remains constant along a streamline (for a steady, inviscid, and incompressible flow):

\[
 p_{\text{Total}} = p + \frac{\rho V^2}{2} + \gamma z = \text{constant along a streamline}
\]

- Head:

\[
 \frac{p}{\gamma} + \frac{V^2}{2g} + z = \text{constant along a streamline}
\]

where

\( \gamma \) (gamma) is the specific weight of the liquid,
\( p / \gamma \) is the pressure head,
\( V^2 / 2g \) is the velocity head, and
\( z \) is the elevation head.

Daniel Bernoulli lived from 1700 to 1782 and was a Dutch-born mathematician and lived in Switzerland much of his life.

Extended Bernoulli Equation...

- Energy equation for a 1D incompressible, steady flow between two sections, such as an inlet and outlet:

\[
\frac{p_{\text{out}}}{\rho} + \frac{V_{\text{out}}^2}{2} + gz_{\text{out}} = \frac{p_{\text{in}}}{\rho} + \frac{V_{\text{in}}^2}{2} + gz_{\text{in}} + w_{\text{actuator}} - \text{loss}_{\text{friction}}
\]

- Dividing by \( g \) puts the relationship in terms of energy per unit weight or head:

\[
\frac{p_{\text{out}}}{\gamma} + \frac{V_{\text{out}}^2}{2g} + z_{\text{out}} = \frac{p_{\text{in}}}{\gamma} + \frac{V_{\text{in}}^2}{2g} + z_{\text{in}} + h_s - h_L
\]
where $h_s$ is defined as:

$$h_s = \frac{w_{\text{actuator}}}{g} = \frac{\dot{W}_{\text{actuator}}}{mg}$$

(or work per unit mass of the actuator)\(=\) \(\frac{\dot{W}_{\text{actuator}}}{\gamma Q}\),

where

\(\dot{W}_{\text{actuator}}\) is the power delivered to the actuator,
\(\dot{m}\) is the mass flow rate \(= \rho AV = \rho Q\),
\(V\) is the component of fluid velocity normal to the area \(A\), and
\(Q\) is the volume flow rate.

For a pump in control volume, the pump head equals $h_s$ and the head loss is $h_L$.
Efficiency…

The *efficiency* is the ratio of amount or work that produces a useful effect:

\[ \eta = \frac{w_{actuator} - \text{loss}}{w_{actuator}} \text{ and } w_{actuator} = \frac{\dot{W}_{actuator}}{\dot{m}}. \]

Summary

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- **Dielectrophoresis**
  - Movement of dielectric particles in a spatially nonuniform electric field.
• Electrowetting
• Microvalves – passive and active
• Micromixers
• Micropumps