Microfluidics

M. Mielnik

FYS4230

7th nov. 2006

Outline:

- General intro
- Mechanics of fluids
- Surface tension and related phenomena
- Electrokinetics
- Mixing

These topics are important for design of well-functioning fluidic microsystems.

General introduction

Microfluidics – what is it?

- Study and manipulation of fluid flows in microsystems

- Combination of fluid mechanics, thermodynamics, surface- and colloid chemistry, electrohydrodynamics (electrokinetics), magnetohydrodynamics, and more.....

- Also: fluid logics (like electronics)
  - Fluid logic circuits

- Typical reservoir/channel dimensions: ~5 – 500µm

- Overall system dimensions from few millimeters to several centimeters

Microfluidics

- Heat exchangers (also with boiling)
- Sensors, thrusters, microengines
- Two-phase flow systems
- Microreactors
- Microfluidics (refers to general flow manipulation and measurement techniques)
- Lab-on-a-chip (chemical)
- Optical systems
- BioMEMS

Microfluidics

- **Typically laminar flows (no turbulence)**
- **High surface – to – volume ratio (~ 10^5 m^{-1})**
  - ⇒ **Surface forces dominate**
  - ⇒ **“Special” effects encountered on the microscale:**
    - **Flow generation by electrical fields, magnetic fields, and capillary forces**
    - **Bi-directional flow in a single channel**
    - **Complex flow patterns in simple geometries**
    - **Counter-current two phase flow without mixing**
    - **Precise generation and manipulation of droplets and liquid plugs**
- **Benefits of downscaling:**
  - **Ability to manipulate and detect small volumes**
  - **Low consumption of reagents**
  - **Quick system response**
  - **Manipulation and processing of biological material**
  - **High rates of heat transfer**
  - **Batch production => low prices**

Mechanics of fluids

Viscosity   Senturia 13.2.1

- Deformation of fluids in the presence of shear forces
- The property of a fluid that resists the action of a shear force
- η[Pa s]

- Newtonian fluid:

$$\tau = \eta \frac{U}{h}$$

$$\tau = \eta \frac{\partial U_x}{\partial y}$$

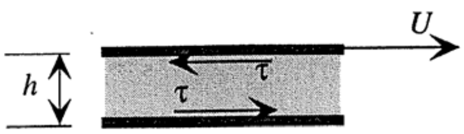
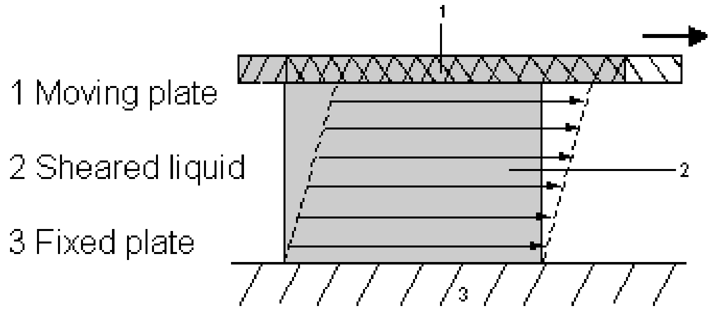


Figure 13.1. Fluid between two plates. The upper plate moves to the right with velocity U, setting up shear forces τ.



Navier-Stokes equations

- Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

- Newton's 2nd law for a fluid

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v}\right) = -\nabla p + \eta \nabla^2 \vec{v}$$

Reynolds number

$$\mathrm{Re} = \frac{\rho U L}{\eta}$$

- Laminar or turbulent flow?
- Ratio of inertial forces to viscous forces
- Reynolds number:
  ratio of kinetic energy of a volume of fluid in the flow to the energy dissipated by the volume in the shear caused by interaction with its solid boundaries.

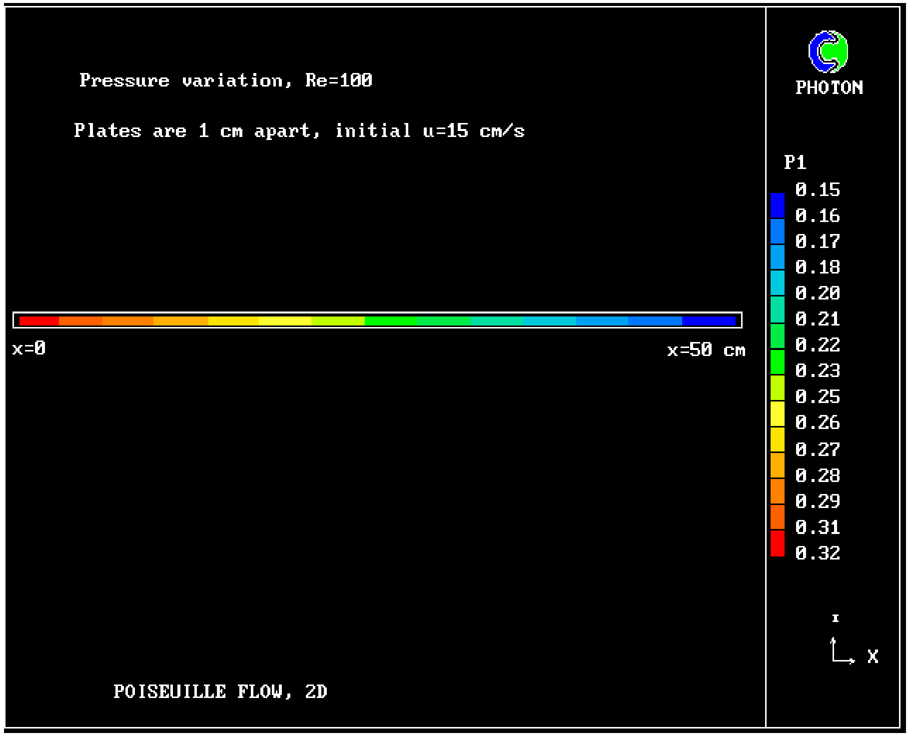
- Microchannel:
- 1 cm long
- 1 mm wide
- 100 μm deep

- $L=50\ \mu m$
- $\rho=1000\ kg/m^2$
- $\eta=0.001\ kg/ms$

Laminar for flow speeds less than 10m/s

Example: Poiseuille flow

- Pressure driven flow in channel
- Pressure drop along channel
- Steady flow
- Incompressible flow
- Flow in x-direction, only
- No-slip boundary condition



Poiseuille flow

$$\eta \frac{\partial^2 U_x}{\partial^2 y} + \frac{\Delta p}{L} = 0$$

Integrate twice:

$$U_x(y) = -\frac{1}{2\eta}\frac{\Delta p}{L} y^2 + c1y + c2$$

No slip boundary condition gives:

$$U_x(y) = \frac{1}{2\eta}\frac{\Delta p}{L}\left[(a/2)^2 - y^2\right]$$

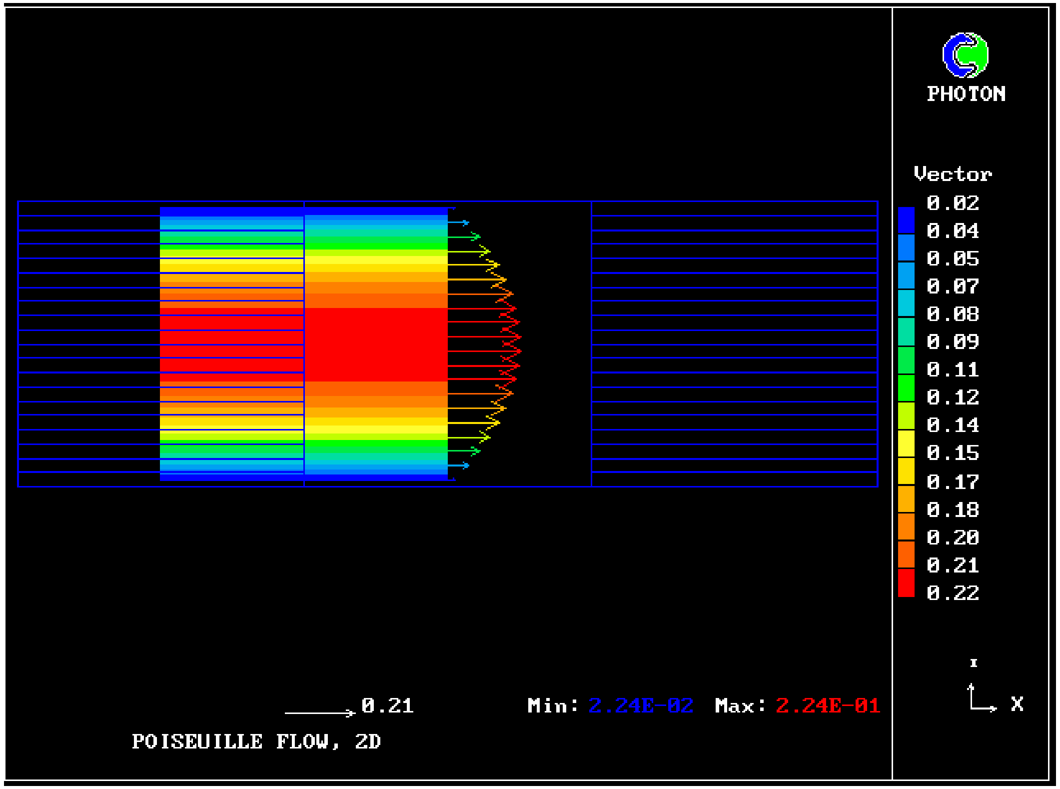
Flow rate:

$$Q = \int_0^{l_z} dz \int_{-a/2}^{a/2} U_x(y) dy$$

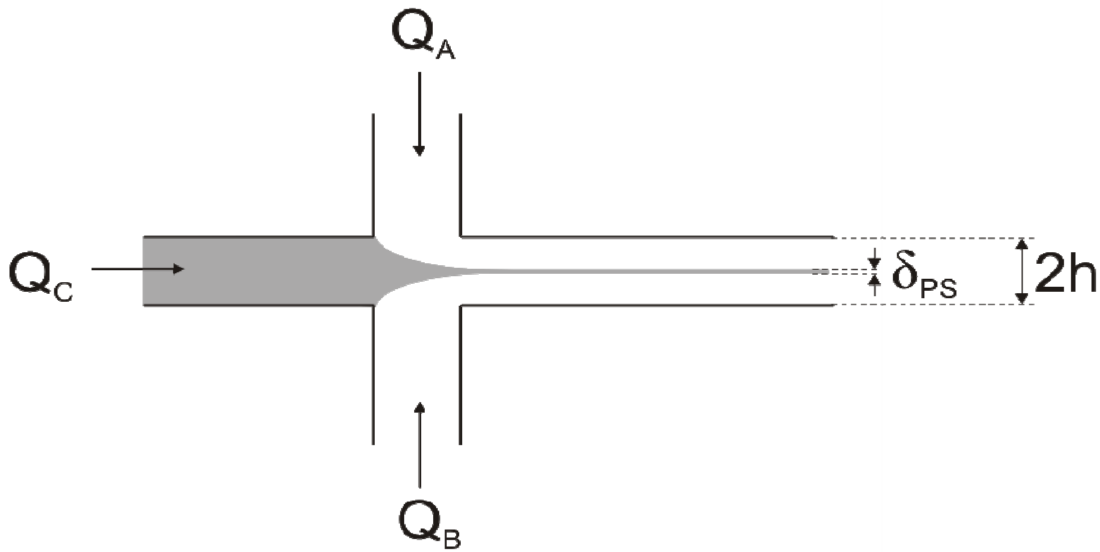
$$Q = \frac{l_z a^3}{12\eta}\frac{\Delta p}{L}$$

Circular pipe:

$$Q = \frac{\pi\ a^4}{8\eta}\frac{\Delta p}{L}$$



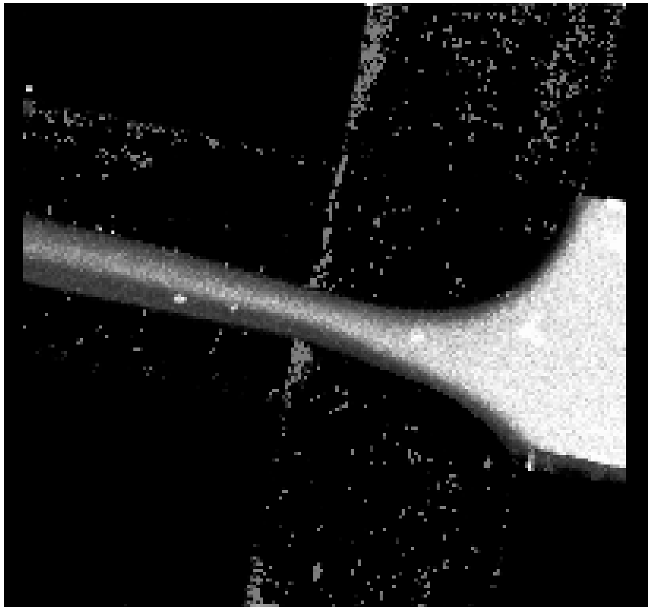
Example: flow manipulation by hydrodynamic focusing

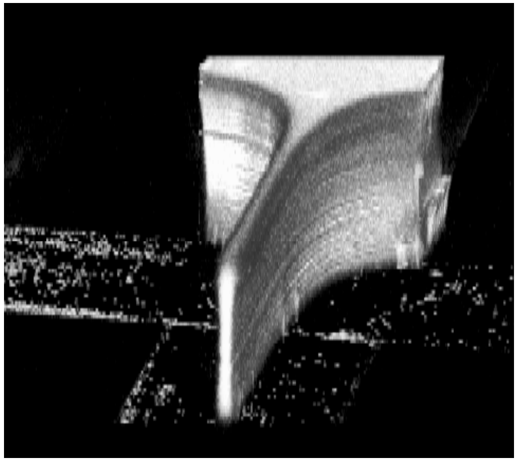


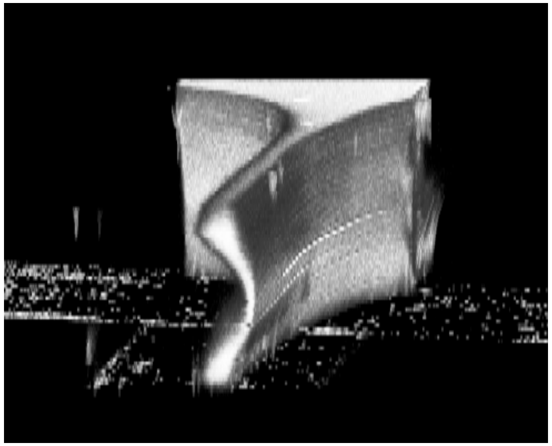
- Q_A & Q_B: buffer streams
- Q_C: stream seeded with fluorescent particles
- Sheet thickness: $\delta_{PS}/2h \propto Q_C/(Q_A+Q_B)$
- Sheet position: $f(Q_A/Q_B)$
- Requirement: stable flow conditions at focusing intersection

Example: flow manipulation by hydrodynamic focusing

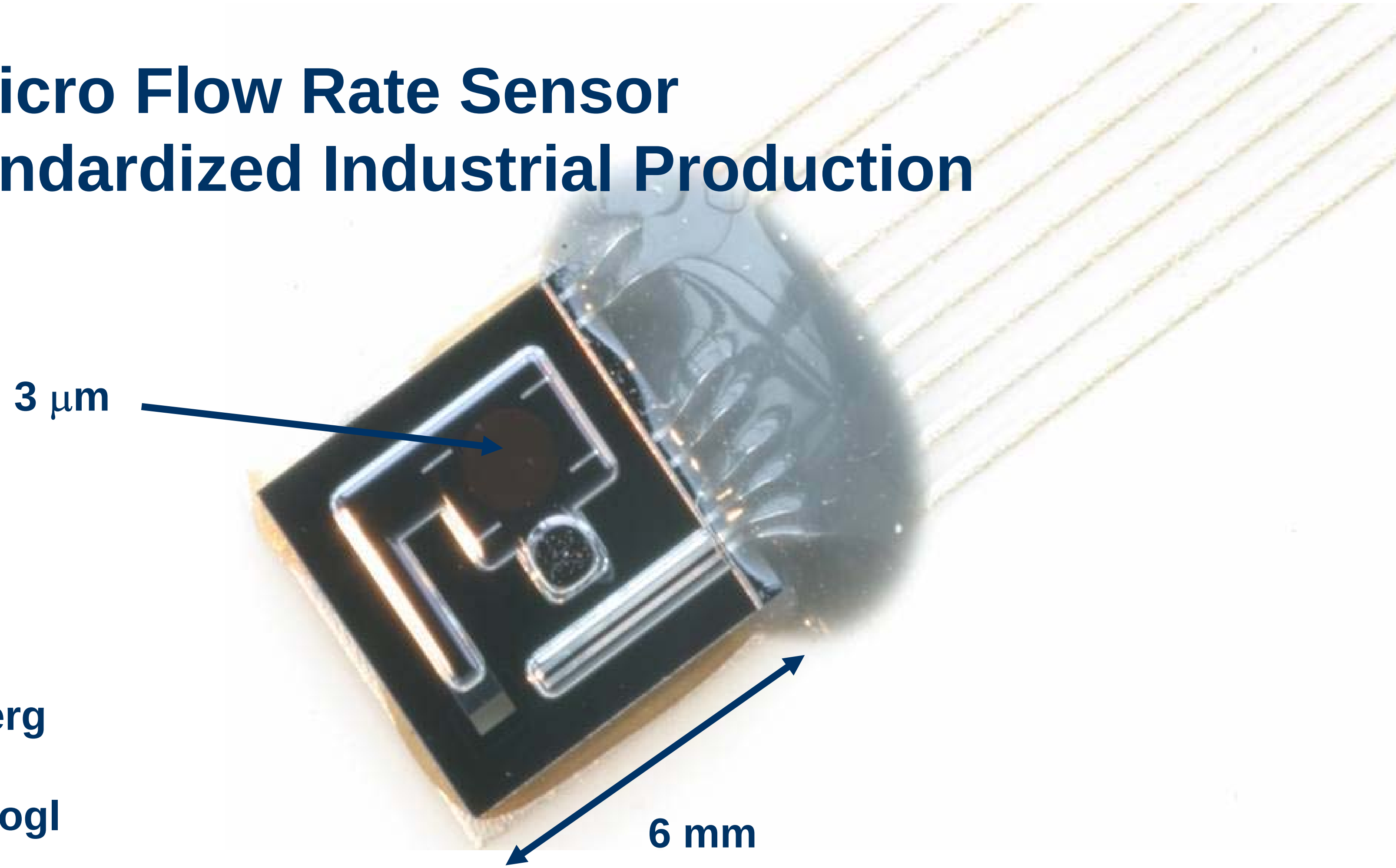
- Flow adressing
- Rapid mixing
  - Decreased diffusion length
- Manipulation of particles
  - Stretching of DNA strands
- Selective coating of particles
- Polymer membrane generation
- Multiple buffer layers possible







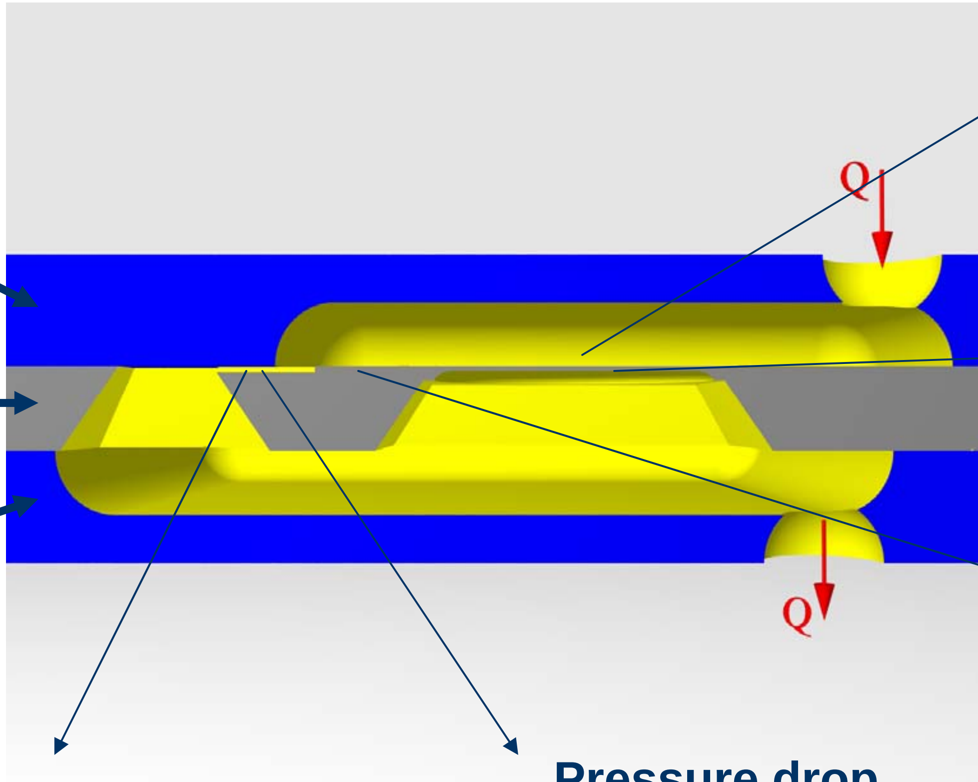
New Micro Flow Rate Sensor for Standardized Industrial Production



Liv Furuberg
Dag Wang
Andreas Vogl

Microsystems and Nanotechnology
SINTEF Information and Communication Technology

The new design suggests a low-noise, mechanically robust flow sensor



Pyrex

Silicon

Pyrex

Sensitive and strong membrane

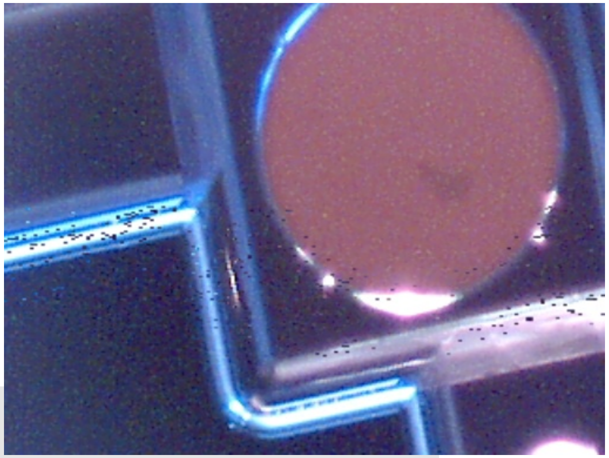
Protected piezoresistors for stress measurements

Temperature sensing diode

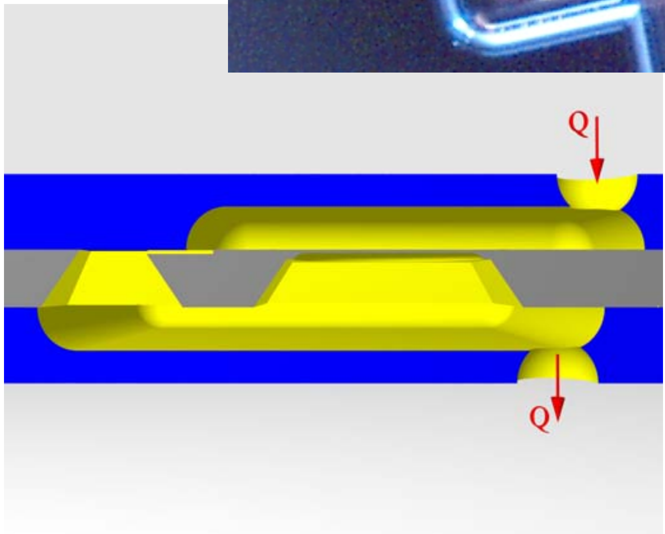
Channel depth 11 μm

Pressure drop proportional to the flow rate

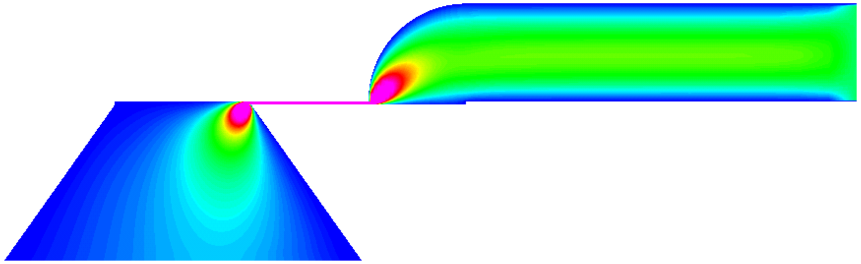
Volum-strømningsmåler



- Applikasjoner: Dosering, tilføring av reagenter, måle flow gjennom analysesystem
- Væskestrøm gjennom brikken
- Glass-silisium-glass brikke
- Laminær strøm, lave Re tall
- Differensiell trykksensor (membran + piezomotstander)
- Trang kanal med trykkfall, Pouseille strøm
- Trykkfall ~ 100 -200 Pa
- Integrert temperaturmåler



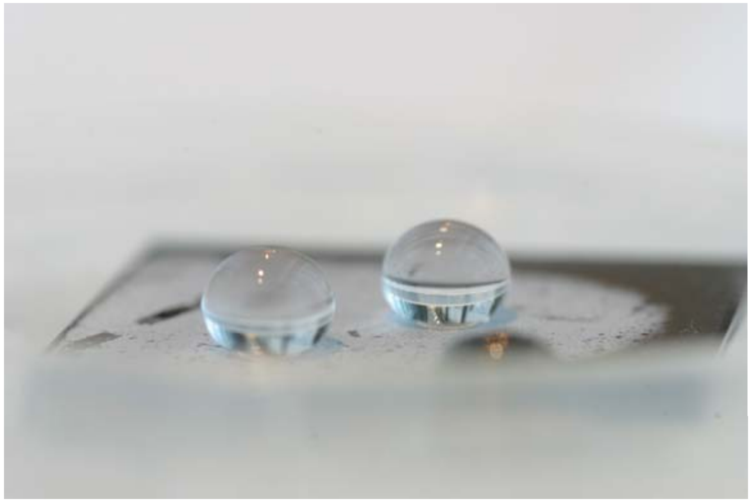
- Kanal: 800x1500x10 μm
- Flow rate 2 μl/min

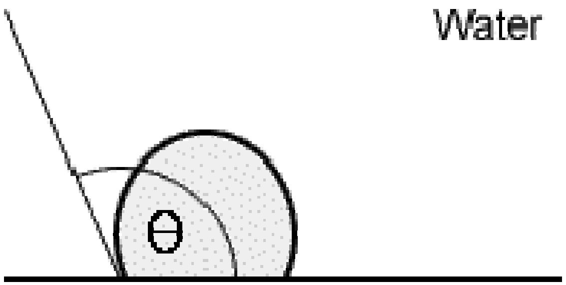


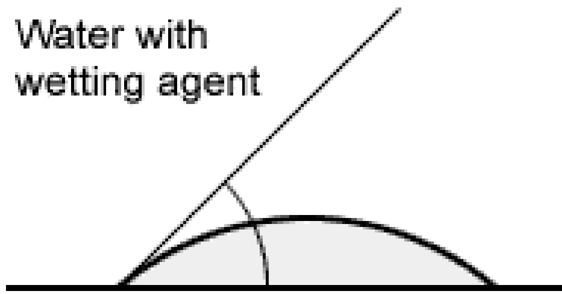
$$\Delta p = \frac{12 \cdot \eta \cdot l \cdot Q}{w \cdot h^3}$$

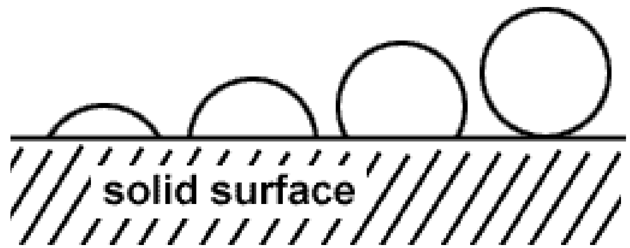
Surface tension and related phenomena

Wetting / Non-wetting

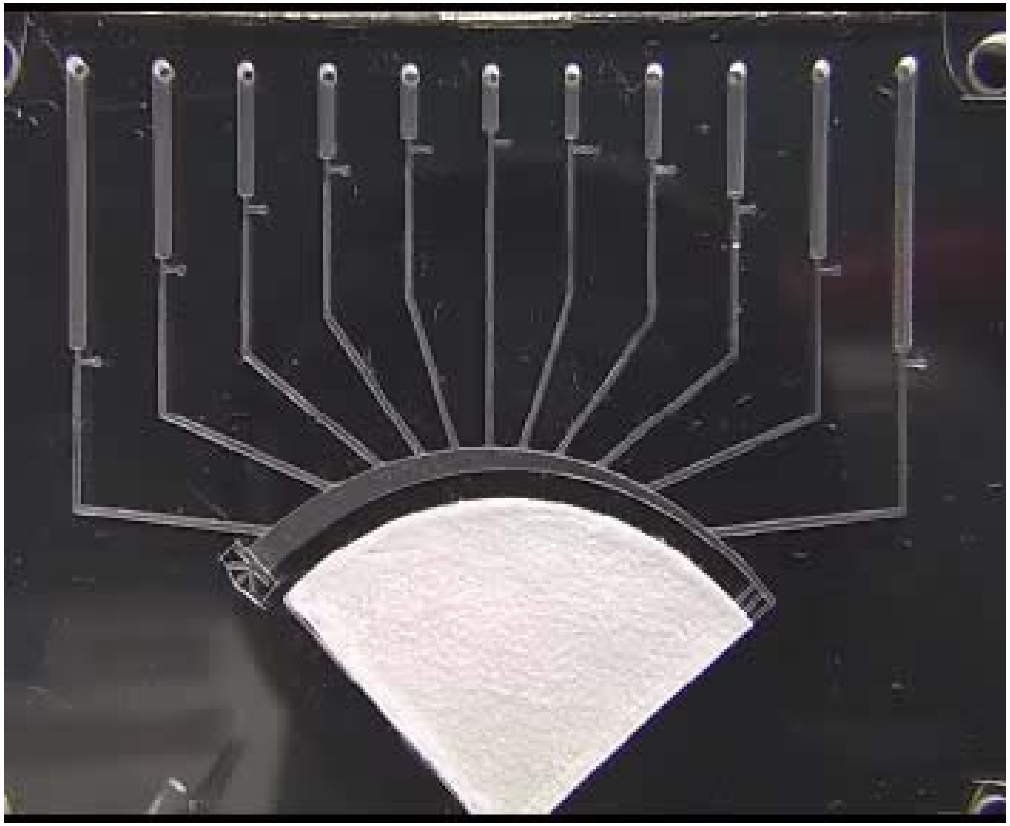




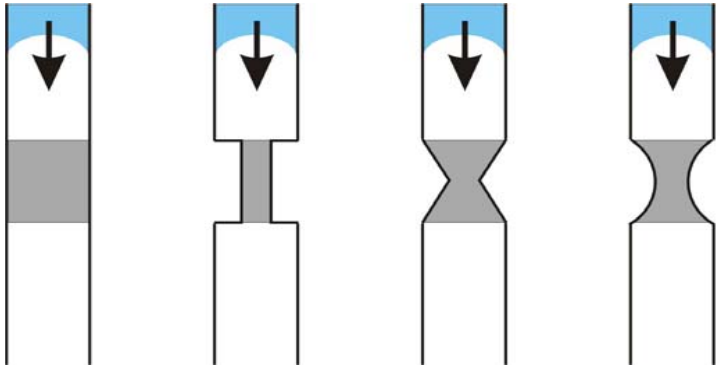




Capillary filling

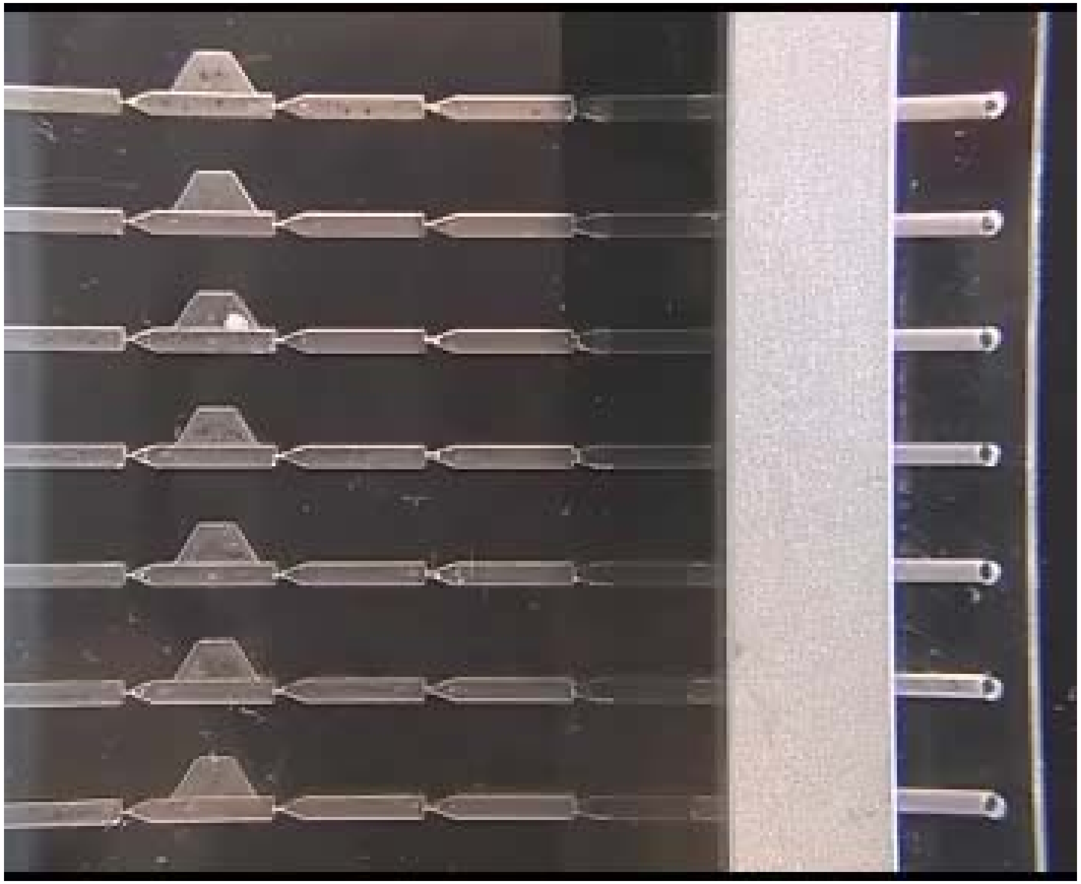


Capillary valving (surface manipulation to change wetting properties



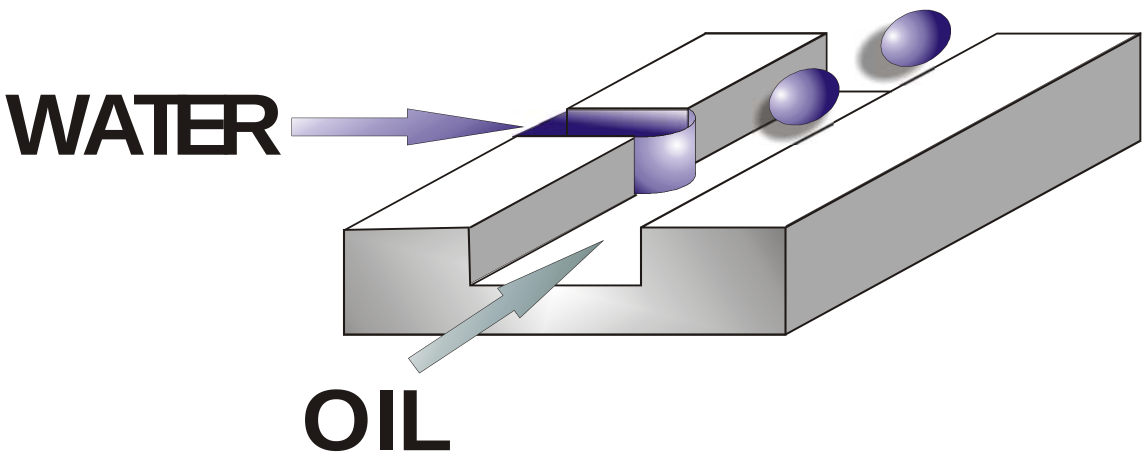
- Hydrophobic valves
- Small restriction – high pressure required to "break" the valve
- Can efficient flow control using a single pressure source for many parallel channels be achieved?

Capillary valving (surface manipulation to change wetting properties



Two-phase (liquid-liquid) flows

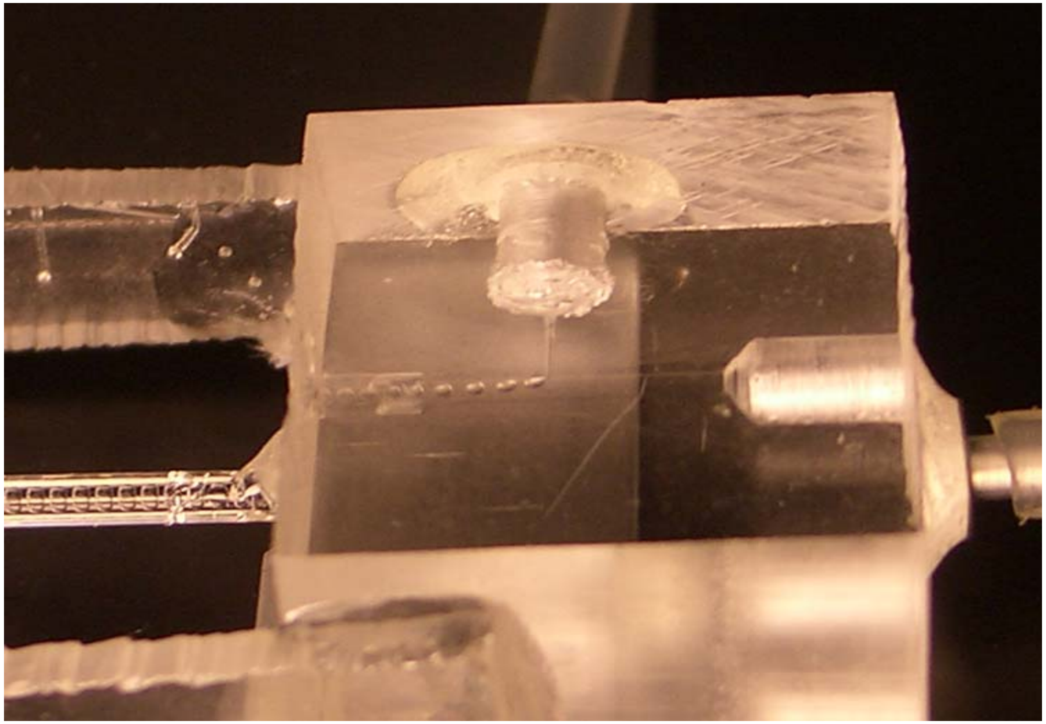
- Simple T-junction geometry
- Two immiscible liquids
- Shear forces exerted by the oil deform, and eventually break off a water droplet

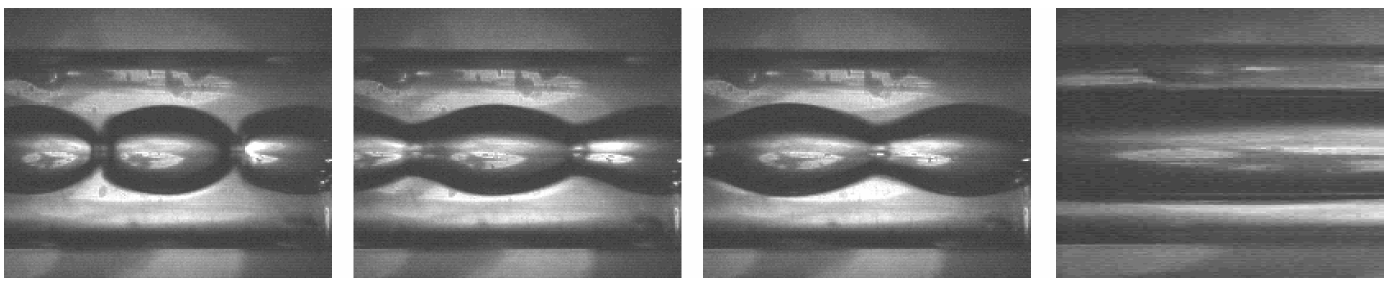


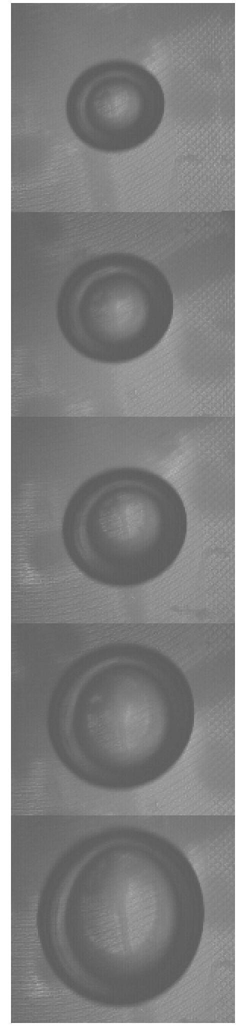
Two-phase (liquid-liquid) flows

droplet formation.avi

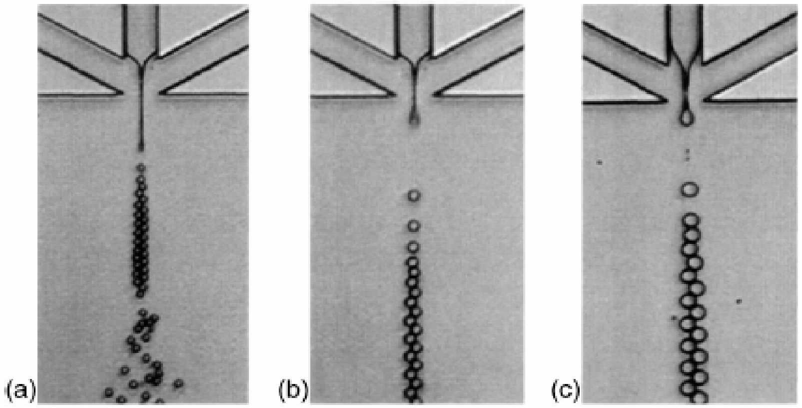
Two-phase (liquid-liquid) flows



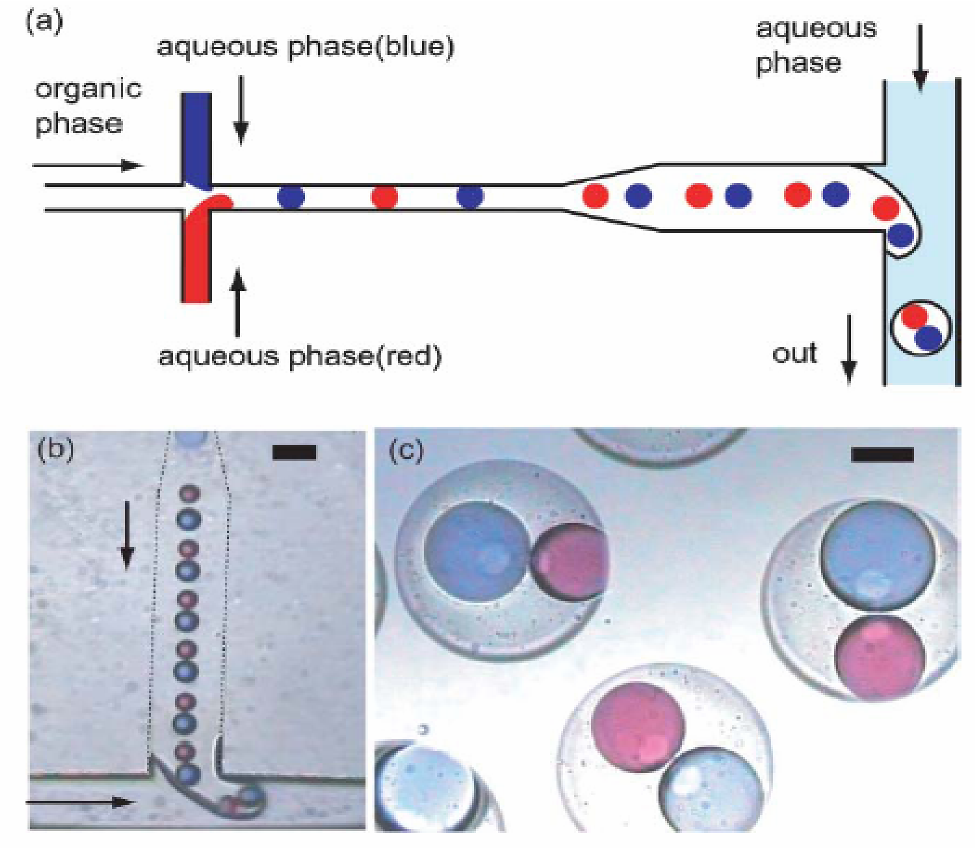




Two-phase (liquid-liquid) flows



Xu et al. (2004)
Droplet size: 9µm



Nisisako et al. (2005)

Droplet generation - applications

- Monodisperse emulsions
- Bidisperse emulsions
- Production of polymer particles
- Chemical reactors
- Transportation of biological species
- Encapsulation of drugs, reagents, etc.

Electrokinetics

Electroosmotic Flow

- Flow driven by electric field
- Voltage applied between electrodes immersed in electrolyte
- Force on fluid near the boundaries, excess of charged particles
- Debye layer, typically 10nm - 100nm
- Disadvantages:
  - Sensitivity to impurities
  - Ohmic generation of heat
  - Need for high voltage
- Advantage:

  Plug flow

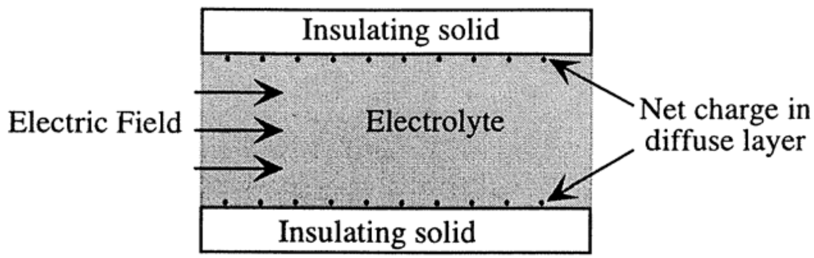


Figure 13.11. Illustrating electroosmotic flow

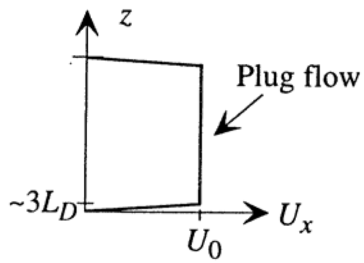
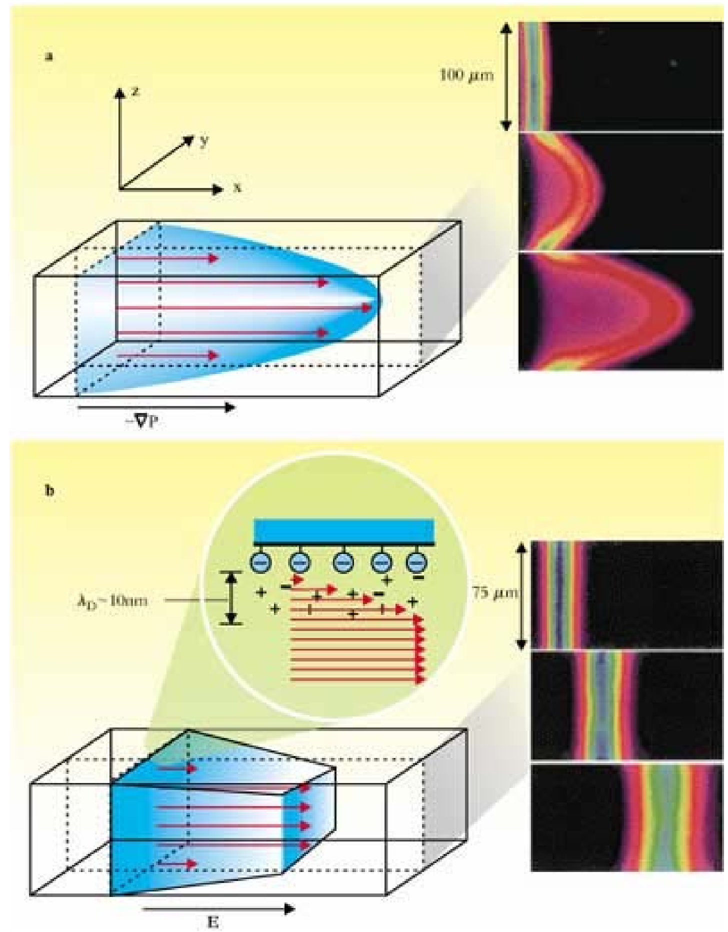


Figure 13.12. Electroosmotic flow profile.

Electroosmotic flow

- Poiseuille flow vs. electroosmotic flow
- Advantage in 3D visualization/detection

- Three pictures after creation of fluorecent molecule:
  - 0s
  - 66ms
  - 165ms
- Separation based on charge-to-size ratio of molecules.
- Separated bands of species



Electrophoresis

- Species carried along with electroosmotic flow
- Drift relative to the moving velocity:

$$v_{ep} = \mu_{ep}\varepsilon_x$$

  - Electrophoretic mobility

  - Apply voltages to channels
  - Create controlled plug of species
  - Separate molecules by charge and volume by electrophoresis

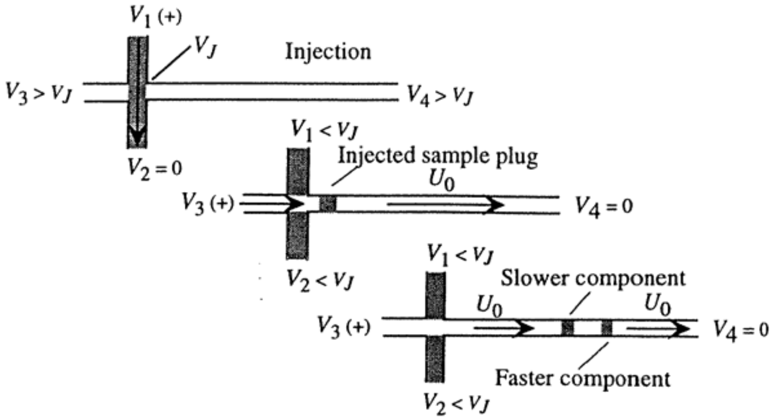
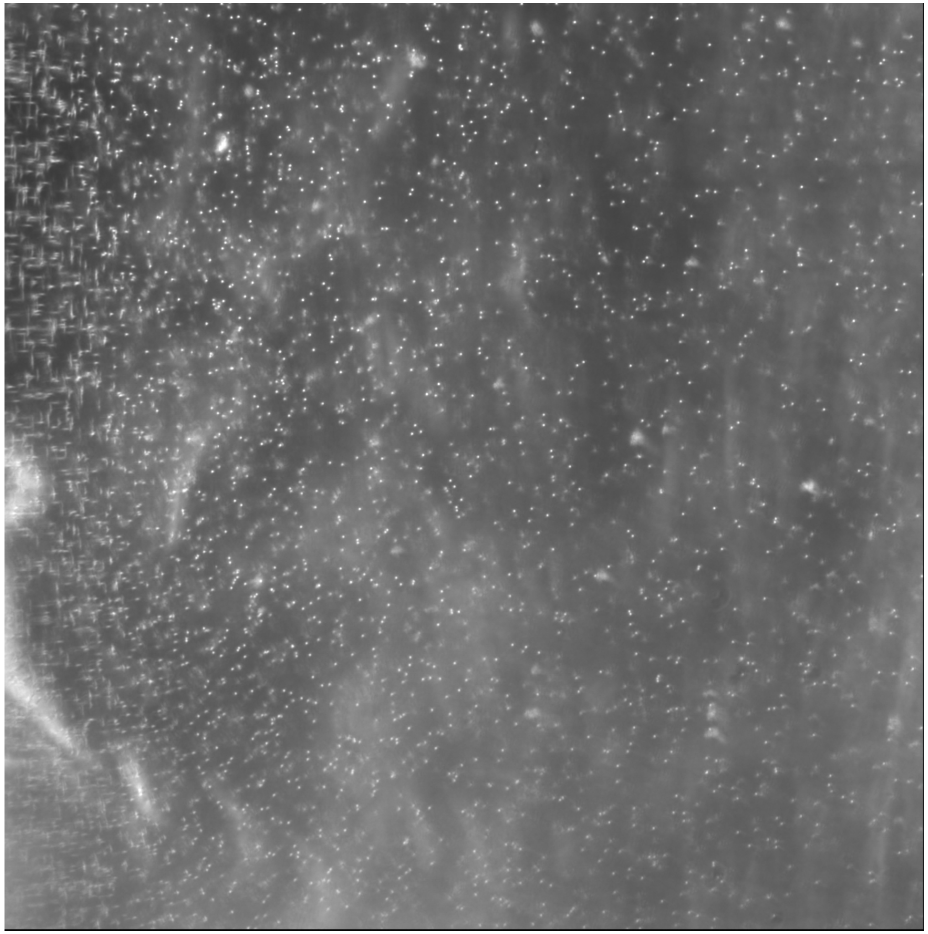
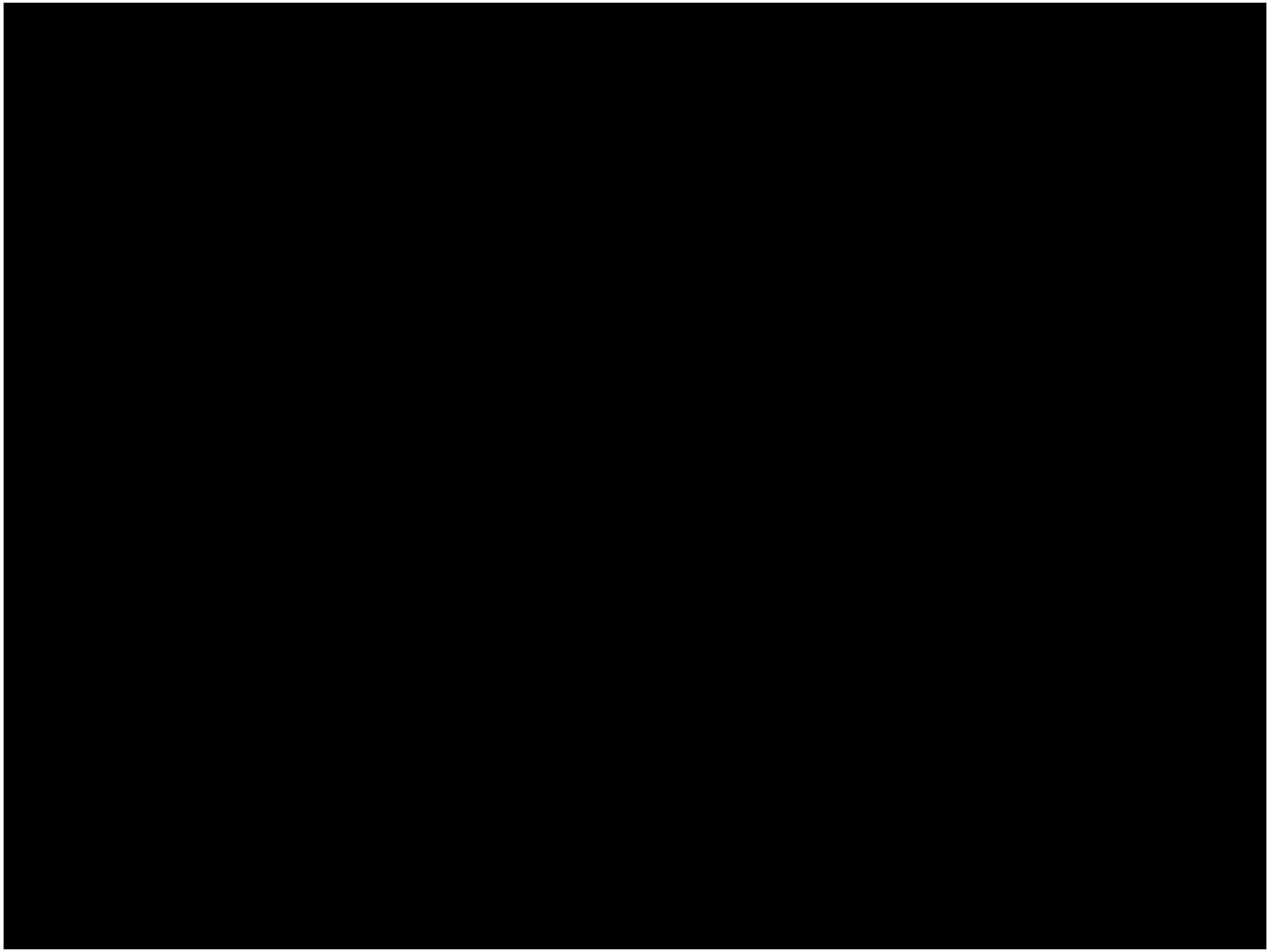


Figure 13.14. Illustrating electrophoretic separation with electroosmotic flow. The voltages used during the injection and separation sequence are described in the text.

Oscillating electroosmotic flow



Electrokinetic instabilities



Mixing

Mixing

- Laminar flow
- Mixing by diffusion only

- Diffusion equation

$$\frac{\partial C(r,t)}{\partial t} = D\nabla^2 C(r,t)$$

  - Average displacement of diffusing particle:

$$l = \sqrt{2Dt}$$

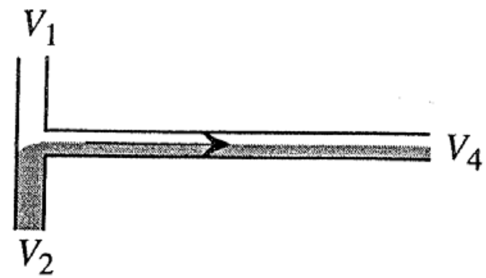


Figure 13.16. Illustrating laminar flow when two streams are combined. Mixing occurs only by diffusion.

Mixing

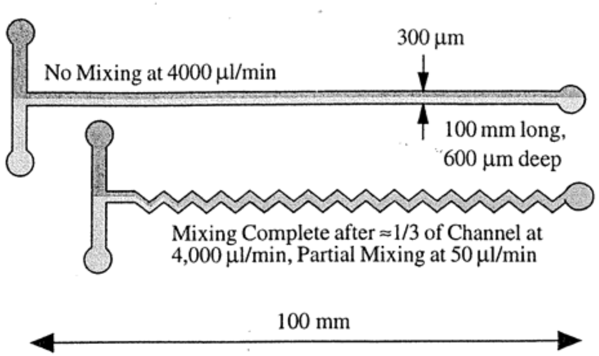


Illustration of miniature fluidic channels used to compare mixing in macroscopic and microscale fluidics. After Branebjerg, et al. (1994).