Classic laminar flows created in two-dimensional paper networks

conventional microchannels (1.0)  porous systems (2.0)

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The laminar flow interface in MF 1.0

- **flow focusing (Austin)**
  - [Image of flow focusing](PRL, 1998)

- **H-filter (Yager)**
  - [Image of H-filter](Science, 1999)

- **T-sensor (Yager)**
  - [Image of T-sensor](Nature Biotech, 2001)

- **interfacial fabrication (Whitesides)**
  - [Image of interfacial fabrication](Science, 1999)

- **mixing (almost everyone)**
  - [Image of mixing](Comsol)
A typical microfluidics lab (1.0)

One goal of paper fluidics: eliminate the requirement for supporting instrumentation (pumps, controllers, detectors)
Microfluidics in your kitchen

you need: membrane, scissors, paper clip, paper towel, staple

A traditionally hard experiment made easy and cheap
Outline for today

Can we recreate classic laminar flow processes in capillary-driven porous devices?

• *Demonstrations of analogies* – capillary-driven flow control, hydrodynamic focusing, continuous mixing, H-filter separations, T-sensor detection

Are flow and molecular transport in porous materials the same as in channel-based systems?

• *No* – flow is qualitatively different (in a good way)
• *No* – diffusion shows intriguing differences
The refined experiment

- Nitrocellulose used for most experiments
- Materials blocked to prevent adsorption
- Container humidified to reduce evaporation
- Inlet (top): free-flowing sources
- Outlet (bottom): absorbent pad

Flow control without pumps

network model

inlet resistances
(Darcy’s Law)

\[
R_y = \frac{\mu L_y}{\kappa H W_y}
\]
\[
R_b = \frac{\mu L_b}{\kappa H W_b}
\]

flowrate ratio in main leg

\[
\frac{I_b}{I_y} = \frac{R_y}{R_b}
\]

Flow control without pumps


multiple flowrates can be controlled by geometry
Hydrodynamic focusing

center stream thickness controlled by inlet resistances

Above: diffusion time ~1 min
Austin, PRL 1998: 10 microsec

control of multiple flows without pumps or instrument

Mixing: one of the major challenges in microfluidics 1.0

diffusion distance: 5000 microns
diffusion time: ~100 minutes

diffusion distance: 100 microns
diffusion time: ~3 seconds

continuous mixing: a hard problem made easy in paper

Mixing: geometrically-controlled mixing ratios


Important: requires attention to strip-strip contact. Higher mixing ratios possible (50x) in 2-stage circuits.
H-Filter: small molecule extraction

Small molecule extraction from a complex sample

Figure courtesy of Kristen Helton
H-Filter: small molecule extraction

large + small
buffer

Bovine serum albumin (large):
\[ D_{BSA} = 6 \times 10^{-7} \text{ cm}^2/\text{s} \]

Tartrazine (small):
\[ D_{tart} = 6 \times 10^{-6} \text{ cm}^2/\text{s} \]

Ratio of diffusion coefficients:
10-fold

**H-Filter:** small molecule extraction

Inlet

Tartrazine:BSA, 1:50

Left outlet (waste)

Tartrazine:BSA, 1:55

Right outlet (product)

Tartrazine:BSA, 1:3000


*clean extract could be sent to downstream paper analysis*
T-Sensor: diffusion immunoassay

Key point: requires measurement of the diffusion interface

Previous apps: pH (demo), detection of small molecules
T-sensor: pH measurement demo

Jen Osborn, Carly Holstein (see MicroTAS poster M3G)
T-sensor: pH measurement demo

Jen Osborn, Carly Holstein (see MicroTAS poster M3G)
T-sensor: pH measurement demo

Jen Osborn, Carly Holstein (see MicroTAS poster M3G)
T-sensor: an attempt at the diffusion immunoassay

- **Problems:** autofluorescence & bleaching, non-uniform illumination, evaporation
- **Solutions:** colorimetric detection, flat-field correction, device humidification

Measuring the diffusion interface with a web camera


*experiments cleaned up nicely, but intriguing phenomena remained*
Classic microfluidics in capillary-driven flows

How does flow differ in these devices? How does molecular transport differ?
Flow Visualization

electrode generates OH⁻ ions, pH indicator tracks fluid

Peter Kauffman, Jen Osborn

2D flow model (COMSOL)

- Stokes flow (low Reynolds #)
- Flow governing equation (Darcy)

\[ Q = \frac{kA}{\mu L} \left( \frac{\partial P}{\partial L} \right) \]

- Boundary conditions:
  - **Inlet**: free flow (zero pressure)
  - **Outlet**: capillary pressure (negative)
  - "walls": free slip (debatable)

Comsol model by Elain Fu and Jen Osborn
Flow in channels versus capillarity

Channels

Paul Yager

Capillarity

Comsol model by Elain Fu and Jen Osborn
Conclusions

Capillary-driven flow has appealing features

• No pumps, uniform velocity fields

Classic laminar flow processes can be recreated (qualitatively) in capillary-driven porous materials

• T-sensor, H-filter, hydrodynamic focusing, mixing

Diffusion processes can be quantitatively measured in wicking devices (with a webcam)
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Some References


