Chapter 01:
Flows in microfluidic systems

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What is a microfluidic system?

• A system manipulating fluids in channels having cross section dimension on less than 100 micro-meters.

• The fluids in microfluidic system
  – Simple fluids: liquids and gases
  – Complex fluids: immersed structures, surfactants, polymers, DNA …
The objectives of microfluidic systems

- **Micro-Total-Analysis-Systems (µTAS)**
  - One system to provide all of the possible required analyses for a given type problem
  - All processing steps are performed on the chip
  - No user interaction required except for initialization
  - Portable bedside systems possible
- **Lab-on-a-chip**
- **Industrial production facilities**
Microfluidics is Interdisciplinary

- Micro-Fabrication
- Chemistry
- Biology
- Mechanics
- Control Systems
- Micro-Scale Physics and Thermal/Fluidic Transport
- **Numerical Modeling**
  - Simulation of microflows
- Material Science
- ...
Typical fluidic components

- Microchannels and channel-circuit
- Functional structures
  - Micro-pump and switches
  - Mixing and separating devices

![Typical functional structure](image)

![Electroosmotic Pumping](image)
Length scales in microfluidic systems

- **Micro-channel**
  - 1mm

- **Microstructure and micro-drops**
  - 100µm
  - 10µm
  - 1µm

- **Cellular scale**
  - 100nm
  - 10nm

- **Typical size of a chip**

- **Radius of Gyration of DNA**

- **Colloid and polymer molecular size**

- **Extended length of DNA**
Deviations from continuum hypothesis for microfluidics I: gas microflows
Deviations from continuum hypothesis for microfluidics
II: simple liquid microflows

• How small should a volume of fluid be so that we can assign it mean properties?
  – Nano-meter scale
• At what scales will the statistical fluctuations be significant?
  – Nano-meter scales

MD Simulations (Koplik & Banavar, ARFM 1995)

Density fluctuations across a nano-channel.

Layering of Lennard-Jones molecules near a smooth surface.
Deviations from continuum hypothesis for microfluidics

II: simple liquid microflows

- Slip at wall in nano-scale?
  - High shear rate
  - Hydrophobic surface

\[
\frac{L_s}{L^0_s} = [1 - \frac{\dot{\gamma}}{\dot{\gamma}_c}]^\alpha
\]

- MD of Couette flow
- Lennard-Jones
- \( H = 25.57 \sigma \)

- Slip length increases as wall-energy decreases or wall-density increases
- For slip length > 17\( \sigma \):
  strict nonlinear response?
Deviations from continuum hypothesis for microfluidics

III: microflows with complex fluids

- Detailed modeling can not use continuum model
  - Nano-Scale

- DNA molecule stretched by flow

- Nanowires deformed under shearing
Conclusion on continuum hypothesis for microfluidics

• Dependent on dimensional scales
  – Nano-meter scales: NO
  – Micro-meter scales: Yes, but NO for Gas

• Influence on numerical method
  – Nano-meter scales: non-continuum
    • Molecular Dynamics, Dissipative Particel Dynamics, Lattice Boltzmann method
  – Micro-meter scales: continuum
    • Finite volume/element method
  – Micro-meter scales for gas: non-continuum
    • Direct simulation Mont Carlo
  – Nano- to micro-meter scales: Multi-scale modeling needed
Other flow features for microfluidics

- Low Reynolds number flow
- Complex flow
  - Multi-phase and complex fluids
- Multi-physics
  - Surface tension and wetting effects
  - Phase changes
  - Electric field
  - Chemical reactions
- Transport phenomena
  - Disperse and diffusion
  - Chaotic mixing
  - Separation process: particle, polymer and DNA
Low Reynolds number flow

- Reynolds number is ratio between inertial force to viscous force
- In many cases $Re<1$, where the viscous force dominant the intertial force
- Intertial irrelevance

$R = \frac{av\rho}{\eta} \approx \frac{av}{\nu}$

$R = 10^4$ for a swimmer

$R = 10^2$ for a fish

$R \approx 10^{-4}$ for a drop

Figure 1: $R = \frac{av\rho}{\eta}$ for water

Purcell 1977
Complex flow

Multi-phase micro-flow

DNA in micro-flow
Complex flow

colloid suspension

protein and cells (Nano- and Micro-structures)
Multi-physics: Surface tension and wetting effects

- Capillary number $Ca$
  - Ratio between viscous force to surface force
  - Not small

Interface Inside Carbon Nano-Tubes
(transmission electron micrographs)
Transport phenomena: Dispersion and diffusion

- Peclet number: $Pe$
  - Relative importance of convection to diffusion: very large
  - Require length of channel (measured with number channel widths) for full mixing in a microchannel is very large
- Strategy for faster mixing: increase the length of mixing layer
Strategy for faster mixing

Taylor dispersion

- Stretching and folding the mixing layer by shearing flows
  - Geometric structure
  - Surface tension effects

Chaotic mixing
Transport phenomena: separating particle, polymer and DNA

- External force used to move the solute
- Separating particle
  - Large mass, small velocity
  - Dielectric properties
- Separating Polymer and DNA
  - Weissenberger and Deborah numbers: relaxation time to shear rate or flow time scale
  - Longer chain, longer relaxation time

Separating DNA
Numerical Modeling Challenges

• Multi Physical Phenomenon
  – Thermal, Fluidic, Mechanical, Biological, Chemical, Electrical

• Multi-scale
  – Continuum and atomistic modeling may coexist

• Multi-phase
  – Gas, liquid

• Complex fluids
  – Particle, nanostuctures, polymer, DNA

• Complex geometry