NSF 2002 Summer School (Urbana-Champaign)
Microfluidics

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• Basic Concepts and Applications
• Gas Flows
• Liquid Flows
• Particulate Flows
• Moving Domains and Applications

Reference: G.E. Karniadakis & A. Beskok
Micro Flows: Fundamentals and Simulation,
**Microfluidics:** 
*Emerging technology* that allows development of new approaches to synthesize, purify, and rapidly screen chemicals, biologicals, and materials using integrated, massively parallel miniaturized platforms.

- **Microfluidics is Interdisciplinary:**
  - Micro-Fabrication
  - Chemistry
  - Biology
  - Mechanics
  - Control Systems
  - Micro-Scale Physics and Thermal/Fluidic Transport
  - Numerical Modeling
  - Material Science
  - System Integration and Packaging
  - Validation & Experimentation
  - Reliability Engineering
  - ...
Microfluidic Devices

**Sensors & Actuators:**
Pressure, Temperature, Shear Stress, Biological & Chemical Sensors

**Fluidic Components:**
Channels, Pumps, Membranes, Valves, Nozzles, Diffusers and Mixers

**Motion Generation:**
Micro-Motors, Turbines, Steam Engines, Gears, Pistons, Links

Micro-Total-Analysis-Systems (μ-TAS) seamlessly integrate sample collection and separation units, biological and chemical sensors, fluid pumping and flow control elements, and electronics on a single microchip.

Microfluidic Applications:

**Defense Applications:**
- Lab on a chip: μ-TAS

**Bio-Medical Applications:**
- Drug Delivery Systems
- DNA Analyzers
- Human Health Monitoring
- Artificial Organs

**Environmental Monitoring:**
- Water & Air Pollution Sensing
- Gas/Liquid Filtration Systems

**Microelectronics:**
- Thermal Management
- Bubble-Jet Printers

**Aerospace Industry:**
- Drag & Stall Control
Scientific & Technological Challenges

• Development of *new* concepts that are *specifically designed* to take advantage of the small scale of microfluidic devices,

• To impart unique new functions that are not simply miniaturized versions of existing systems and components.
Mass Flow Rate versus Pressure Drop

- Pipe Flow (2mm x 200 mm; gas at low pressure)

- Linear Scaling

- Quadratic Scaling
Deviations from Continuum - Gases

**Microchannel**: 0.51 microns (Bau et al., U Penn, 1988)

- $C^* = \frac{P_{ex}}{P_{th}}$ where $P_{o} = C_f R_e$
- $P_{o} = 64$ (pipe)
- $P_{o} = 96$ (2D channel)
Deviations from Continuum - Liquids

- Microducts (Bau & Pfahler, 2001)
- Silicone oil

**Question:** Anomalous Diffusion or something else?
Interface Inside Carbon Nano-Tubes

(transmission electron micrographs)

Courtesy of Megaridis & Gogotsi, UIC
Reverse Micelle Formation in Microchannels Containing Hexadecane/2% Span80

* Quake, Caltech

T-junction

13.2/125 psi w/o-s
12.8/125 psi w/o-s
12.4/125 psi w/o-s
12.0/125 psi w/o-s
11.5/125 psi w/o-s
11.1/125 psi w/o-s

in
out
Applications of Particulate Microflows

- Sorting
- Analyzing
- Removal

Liquids + Gas

- Cells
- Particles
- Embryos

Micro fluorescent activated cell sorting
μFACS

Micro magnetic activated cell sorting
μMACS

* Telleman et al.*
Characterization of Airborne Particles

Anthrax Spores

Anthrax Bacteria

Size, Shape & Orientation
Active Control of Supraparticle Structures Microchannels

Entropic Trapping and Seiving of DNA in Nanofluidic Channels

Digital Micro-Mirror Device™

Digital Light Processing™:
848 x 600 pixels
1280 x 1024 pixels
16µm x 16µm w/ 1 µm separation

Courtesy of Texas Instruments
DMD™ Air Damping Effects & Transient Response
Courtesy of Texas Instruments

DMD 840 X 1 DMD
19 µm mirrors

Atm.
85
25
1

Address Pulse
Optical Response

13.6 µS
11.6 µS
20 µS
11.6 µS

Pressure (mm Hg)
85
25
1

Time (µS)
Simulation of Micro-Pulse-Plasma Thrusters (micro-PPT)

- New issues arise in simulating plasma microthrusters that are an order of magnitude smaller than the existing state-of-the-art.
  - Current simulation technologies are based on mathematical models and assumptions that break down in microscales and, therefore, cannot treat these microflows comprehensively.

- Microspacercraft are currently considered by Air Force, NASA and industry for a variety of applications.
  - L<10 cm, W< 1 kg, and P< 10 W.
  - Need for micropropulsion.
  - Plasma microthrusters introduce an additional complexity in their analysis due to the overlap of electrodynamic and gasdynamic scales.
Physical Processes in a micro-PPT

- Gas Discharge Processes
- Teflon Ablation
- Magnetogasdynamic Acceleration
- Coupling with External Circuit

AFRL micro-PPTs

Igniter Plug
Cathode

Arc and Plasma

Energy Source
Power Processor

Teflon Bar

Anode

cathode

anode

anode
Gas Microflows: Typical Applications

\[ Kn = \frac{\lambda}{L} = \sqrt{\frac{\gamma \pi}{2}} \frac{M}{Re} \]

**Knudsen number**
The Continuum Hypothesis

• How small should a volume of fluid be so that we can assign it mean properties?
• At what scales will the statistical fluctuations be significant?
• Are the low-pressure rarefied gas flows dynamically similar to the gas micro-flows?
The Continuum Hypothesis

The Continuum Hypothesis
LIQUIDS: Nano-Scale Behavior

MD Simulations (Koplik & Banavar, ARFM 1995)

- Density fluctuations across a nano-channel.
- Layering of Lennard-Jones molecules near a smooth surface.

- 3D periodic channel 51.30x29.7x25.65 (molecular units)
- 27,000 number of atoms
- 2,592 atoms of each wall (FCC lattice type)
- 1 atom = 1 unit
The Continuum Hypothesis

\((Batchelor’s \ book)\)

<table>
<thead>
<tr>
<th>Type</th>
<th>Force (molec)</th>
<th>Motion ((d_0))</th>
<th>Structure (molec)</th>
<th>statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Strong</td>
<td>&lt;&lt;1</td>
<td>ordered</td>
<td>quantum</td>
</tr>
<tr>
<td>Liquid</td>
<td>Medium</td>
<td>(O(1))</td>
<td>Semi-order</td>
<td>quantum+ classical</td>
</tr>
<tr>
<td>gas</td>
<td>weak</td>
<td>&gt;&gt;1</td>
<td>disordered</td>
<td>classical</td>
</tr>
</tbody>
</table>
Slip Length in Complex Liquids

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

- 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\( \sigma \): strong nonlinear response?

**Question:** At high shear rates, is the liquid behavior near the wall non-Newtonian?
Physical Challenges of Micro-Scale Transport

- **Gas Flows**
  - Compressibility
  - Rarefaction
    - Slip
    - Transition
    - Free Molecular
    - Thermally Induced Motion
  - Surface & Roughness
  - Viscous Heating
  - Incomplete Similitude
  -...

- **Liquid Flows**
  - Wetting
  - Adsorption
  - Slip
  - Electrokinetics
  - Polarity
  - Coulomb & van der Waals Forces
  - Capillary Forces
  - Roughness
  -...

**Micro Flows: Fundamentals & Simulation**
ISBN 0-387-95324-8
Numerical Modeling Challenges

- Multi Physical Phenomenon (Thermal, Fluidic, Mechanical, Biological, Chemical, Electrical)
- Multi Scale (Atomistic, Continuum)
- Complex Geometry

Numerical Simulation Strategies

- **Scientific Simulations:**
  - Multi Scale
  - Simpler Geometry
  - Accurate (error < 1 %)

- **Engineering Simulations:**
  - Multi Scale
  - Multi Physics
  - Complex Geometry
  - Accurate (error < 5~10 %)

- **Low Order Models:**
  - Multi Physics
  - Full Device Simulation
  - Lower Accuracy, but Fast (error ~10 %)
Challenges of Microscale Research

• Small Scale Physics
  – Governing Equations Breakdown
    • Constitutive Laws
    • Boundary Conditions
  – Microscopic Effects
    • Dominance of Surface Forces
    • Coulomb Forces
    • Van der Waals Forces
    • Capillary Forces
    • Importance of Molecular Structure

• Detection & Experimental Verification
  • Micro Particle Image Velocimetry
  • Molecular Fluorescence Velocimetry
Numerical Modeling Methods

LIQUID FLOWS
- ATOMISTIC
  - MD
  - Lattice Boltzmann

GAS FLOWS
- CONTINUUM
  - Spectral Elements
  - Finite Elements
  - Finite Volume
  - Boundary Elements
  - Meshless
  - Force Coupling
- ATOMISTIC
  - DSMC
  - Boltzmann
  - Lattice Boltzmann
Experimental Limitations

- Micro-Particle-Image-Velocimetry (*Meinhart et al.*)

- 30 x 300 microns channel
- Resolution: 450 nm in the wall-normal
- Overlapped windows
- Specialized interrogation algorithms
Prototype Flows

• Pressure-Driven Flows
  – Poiseuille flow
• Shear-Driven Flows
  – Couette flow
  – Cavity flow
• Squeezed Film – Lubrication
  – Reynolds equation
• Electrokinetically-Driven Flows
  – Dielectrophoresis
• Thermal Creep
  – Knudsen compressors
• Surface-Tension-Driven Flows
  - routing of droplets
Microfluidics:
The path and link to nanotechnology

The wet circuit → liquid circuit + element

Fluidic Self Assembly — Massively Parallel VLSI-like, programmable fluidic networks with logic

Fluids with more than Viscosity – MOEMS

Complex Fluids
  • Magnetorheological fluids
  • Magnetic (high-frequency) microfluidics
  • Dynamic reconfiguration, use $E$ to change properties

Wall-less fluidics/interfaces (Bebe, Whitesides)

Smart dust — Biomimetic sensors