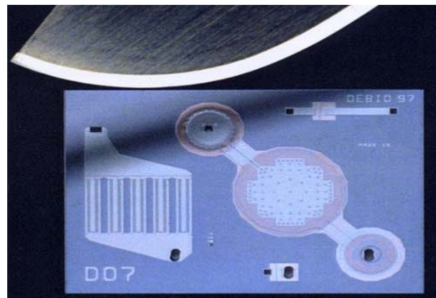
Contents

1. Introduction
2. Fluids
3. Physics of Microfluidic Systems
4. Microfabrication Technologies
5. Flow Control
6. **Micropumps**
7. Sensors
8. Ink-Jet Technology
9. Liquid Handling
10. Microarrays
11. Microreactors
12. Analytical Chips
13. Particle-Laden Fluids

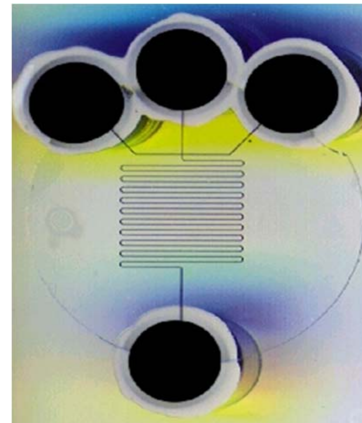
a. Measurement Techniques
b. Fundamentals of Biotechnology
c. High-Throughput Screening

6. Micropumps

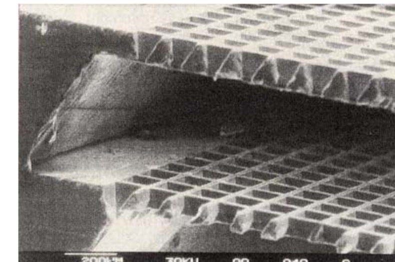
1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous



Micromembrane pump
(Debiotech
Lausanne, CH)



Electroosmotic Pump)
(M. Ramsey, ORNL, USA)



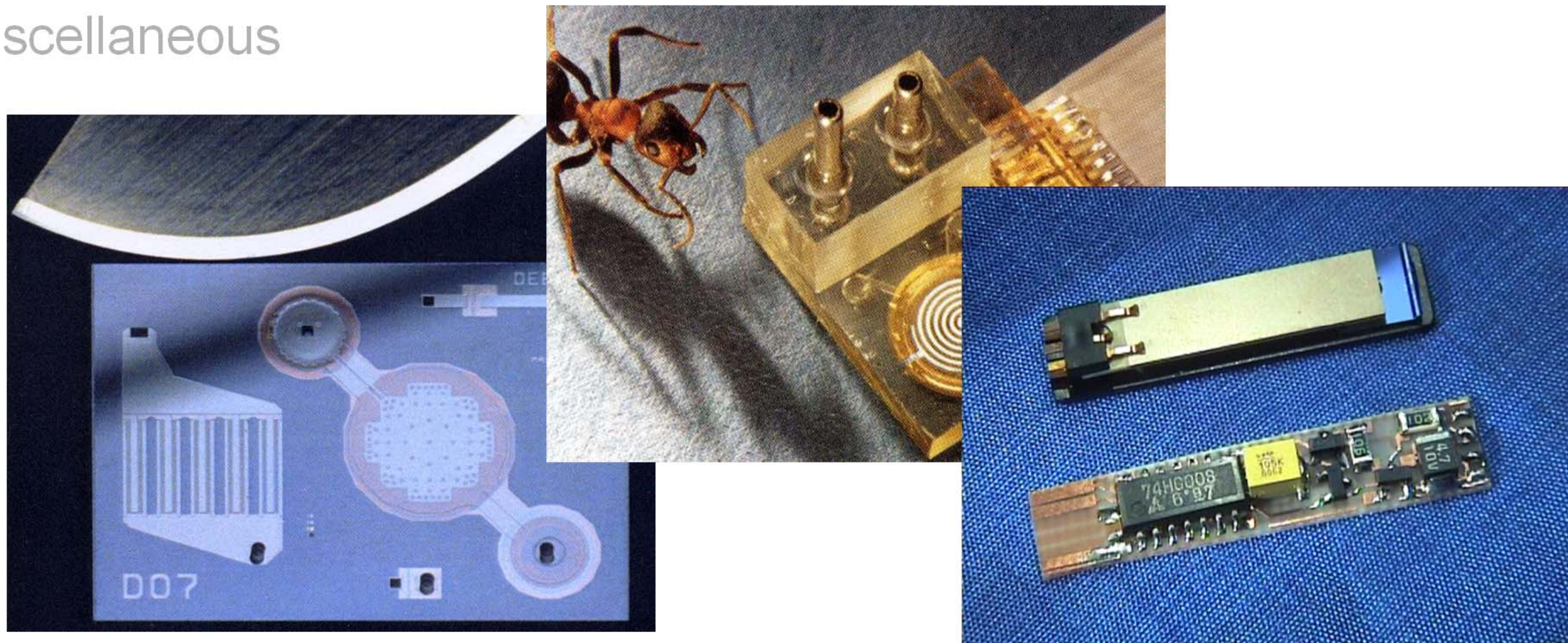
Electrohydrodynamic
Micropump
(FhG-IFT, Munich)

6. Micropumps

- Pumping
  - Transport of fluid
- Against „external forces / fields
  - Gravity
  - Pressure gradient
  - Viscosity
  - Etc.
- Micropumps
  - Peculiar scaling of forces in microworld
  - Fabrication issues
  - Novel pumping principles

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous



6.1. Microdisplacement Pumps

- Constituents
  - Pump chamber
  - Actuation
  - Flow rectifiers
    - Check valves
    - Fixed-geometry valves
    - Active valves
      - Peristaltic
      - Thermoviscous

Actuation principles
- Mechanical
- Pneumatic
- Thermomechanical
- Thermopneumatic
- Piezoelectric
- Electrostatic
- Electromagnetic
- ...

- Pumping cycle
  - Supply phase
    - Underpressure
  - Pump phase
    - Overpressure

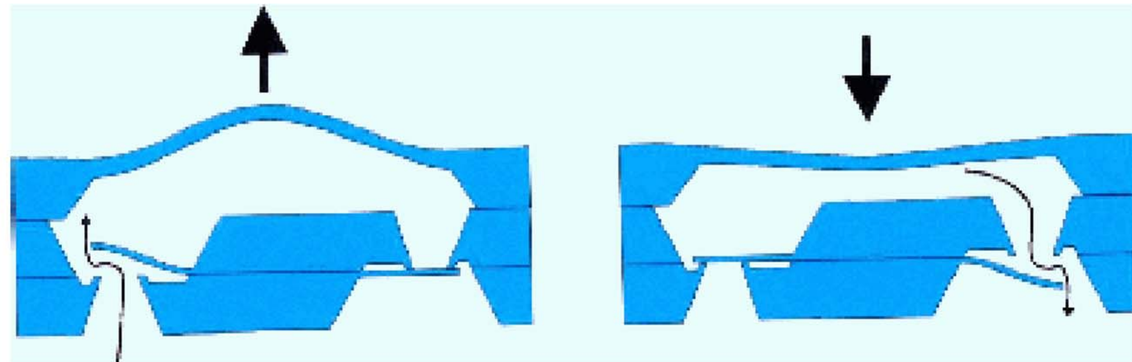


Fig. 6.1. Working principle of displacement pumps, in this case with two check valve rectifiers

6.1. Microdisplacement Pumps

1. Modeling
2. Design Issues
3. Integrated Check Valves
4. Fixed-Geometry Valves
5. Pumping Valve

6.1.1. Modeling

- Differential equations
  - Physics
- *pV*-diagram
  - Mechanical engineering
- Lumped element
  - Electronic engineering

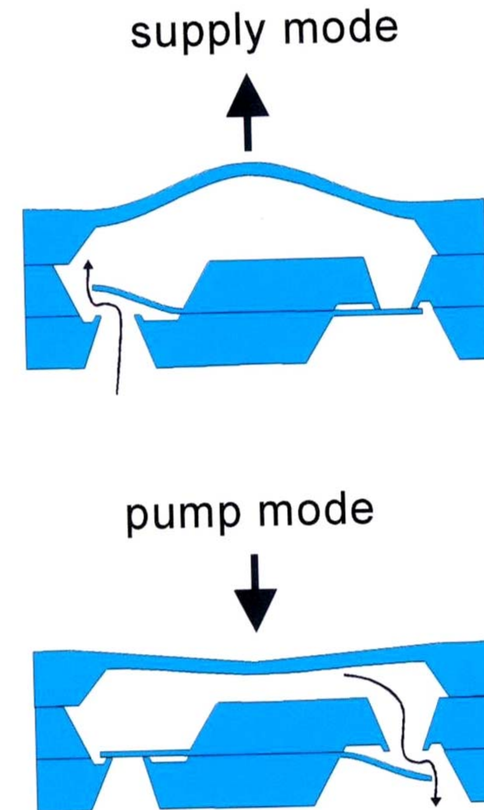
6.1.1. Dynamics

- Dynamics results from complex coupling
  - ➢ Mechanical displacer
  - ➢ Rectifier
    - E.g. valve

- Actuation of check valves by pressure within pump chamber

- External control only by actuation of membrane

- Motion of displacer governed by
  - ➢ Actuator
  - ➢ Inner pressure
  - ➢ Etc.



6.1.1. Dynamics

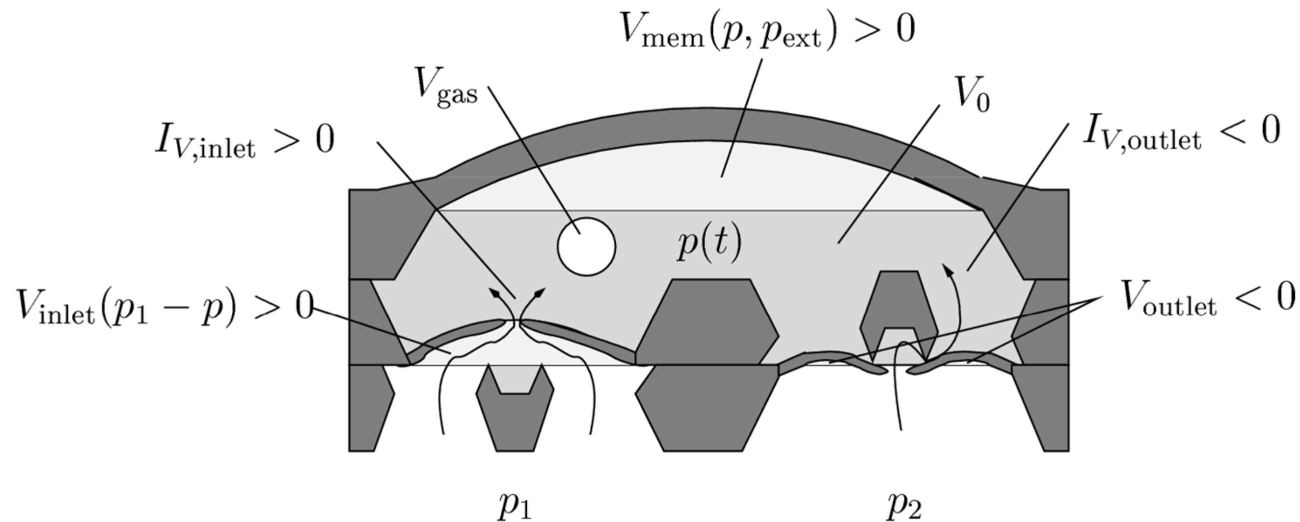


Fig. 6.3. Partial volumes and flows in the compression chamber of a microdisplacement pump with an internal pressure $p(t)$

- Pressures
  - In pump chamber $p(t)$
  - Inlet pressure p_1
  - Outlet pressure p_2

- Volumes
  - Pump chamber V_0
  - Membrane
  - Inlet
  - Outlet
  - Gas bubbles

6.1.1. Differential Equations

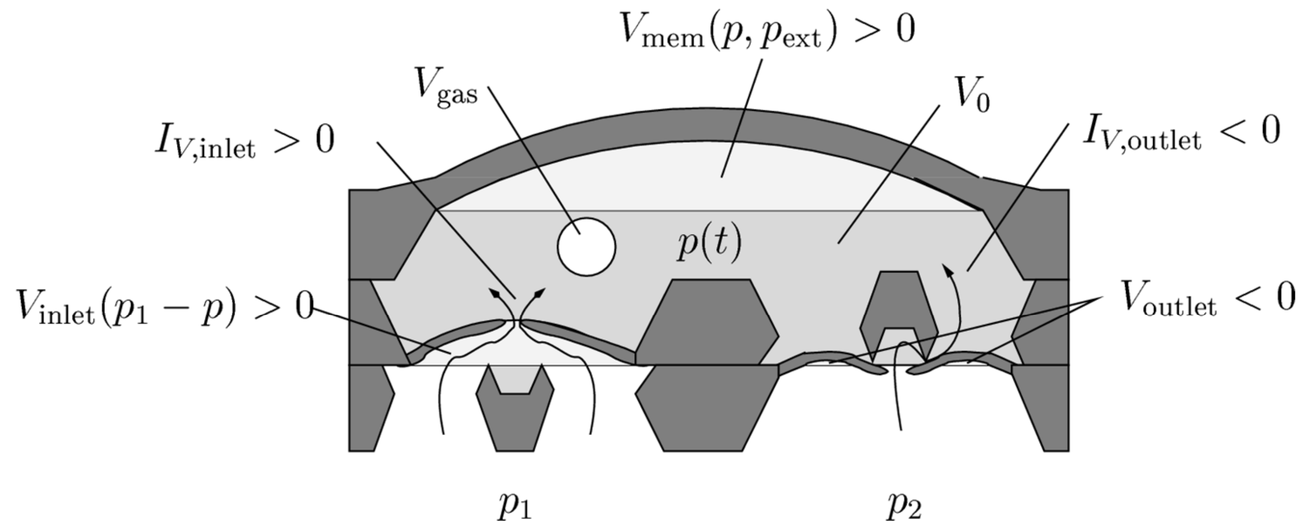


Fig. 6.3. Partial volumes and flows in the compression chamber of a microdisplacement pump with an internal pressure $p(t)$

- Volumes

$$V_{\mathrm{liquid}} = V_0 + V_{\mathrm{mem}} - V_{\mathrm{inlet}} + V_{\mathrm{outlet}} - V_{\mathrm{gas}}$$

- Continuity of volumes (mass)

$$I_m = \frac{\mathrm{d}m}{\mathrm{d}t} = -\int_{\partial A_{\mathrm{inlet}}, \partial A_{\mathrm{outlet}}} \boldsymbol{j}_m \mathbf{d}\boldsymbol{A}$$

6.1.1. Mass Currents

$$I_m = \varrho\left[I_{V,\text{inlet}}(p_1 - p) - I_{V,\text{outlet}}(p - p_2)\right]$$

$$I_m = \frac{\mathrm{d}m_{\text{liquid}}}{\mathrm{d}t} + \frac{\mathrm{d}m_{\text{gas}}}{\mathrm{d}t} \simeq \frac{\mathrm{d}m_{\text{liquid}}}{\mathrm{d}t} = I_{m,\text{liquid}}$$

$$I_{m,\text{liquid}} = \varrho\left[I_{V,\text{inlet}}(p_1 - p) - I_{V,\text{outlet}}(p - p_2)\right]$$

$$\frac{\mathrm{d}m_{\text{liquid}}}{\mathrm{d}t} =$$

$$\varrho\,\frac{\mathrm{d}}{\mathrm{d}t}\left[V_0 + V_{\text{mem}}(p, p_{\text{ext}}) - V_{\text{inlet}}(p_1 - p) + V_{\text{outlet}}(p - p_2) - V_{\text{gas}}(p)\right]$$

$$\frac{\mathrm{d}m_{\text{liquid}}}{\mathrm{d}t} = \varrho\left\{\left.\frac{\partial V_{\text{mem}}}{\partial p_{\text{ext}}}\right|_p \frac{\mathrm{d}p_{\text{ext}}}{\mathrm{d}t} + \left[\left.\frac{\partial V_{\text{mem}}}{\partial p}\right|_{p_{\text{ext}}} - \left.\frac{\partial V_{\text{inlet}}(p_1 - p)}{\partial p}\right|_{p_1} + \left.\frac{\partial V_{\text{outlet}}(p - p_2)}{\partial p}\right|_{p_2} - \left.\frac{\partial V_{\text{gas}}(p)}{\partial p}\right|_t\right]\frac{\mathrm{d}p}{\mathrm{d}t}\right\}$$

6.1.1. Numerical Simulation

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{I_{V,\mathrm{inlet}}(p_1 - p) - I_{V,\mathrm{outlet}}(p - p_2) - \left.\frac{\partial V_{\mathrm{mem}}}{\partial p_{\mathrm{ext}}}\right|_p \frac{\mathrm{d}p_{\mathrm{ext}}}{\mathrm{d}t}}{\left.\frac{\partial V_{\mathrm{mem}}}{\partial p}\right|_{p_{\mathrm{ext}}} - \frac{\partial V_{\mathrm{inlet}}(p_1 - p)}{\partial p} + \frac{\partial V_{\mathrm{outlet}}(p - p_2)}{\partial p} - \frac{\partial V_{\mathrm{gas}}(p)}{\partial p}}$$

- Final differential equation
  - ➢ Solved numerically

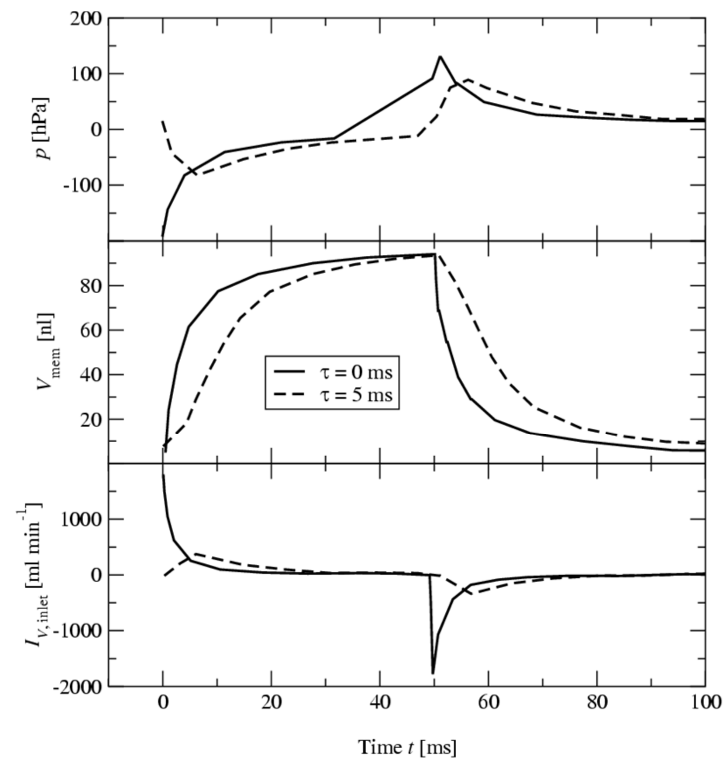


Fig. 6.4. Simulation

6.1.1. *pV*-Diagrams

- Mechanical engineer

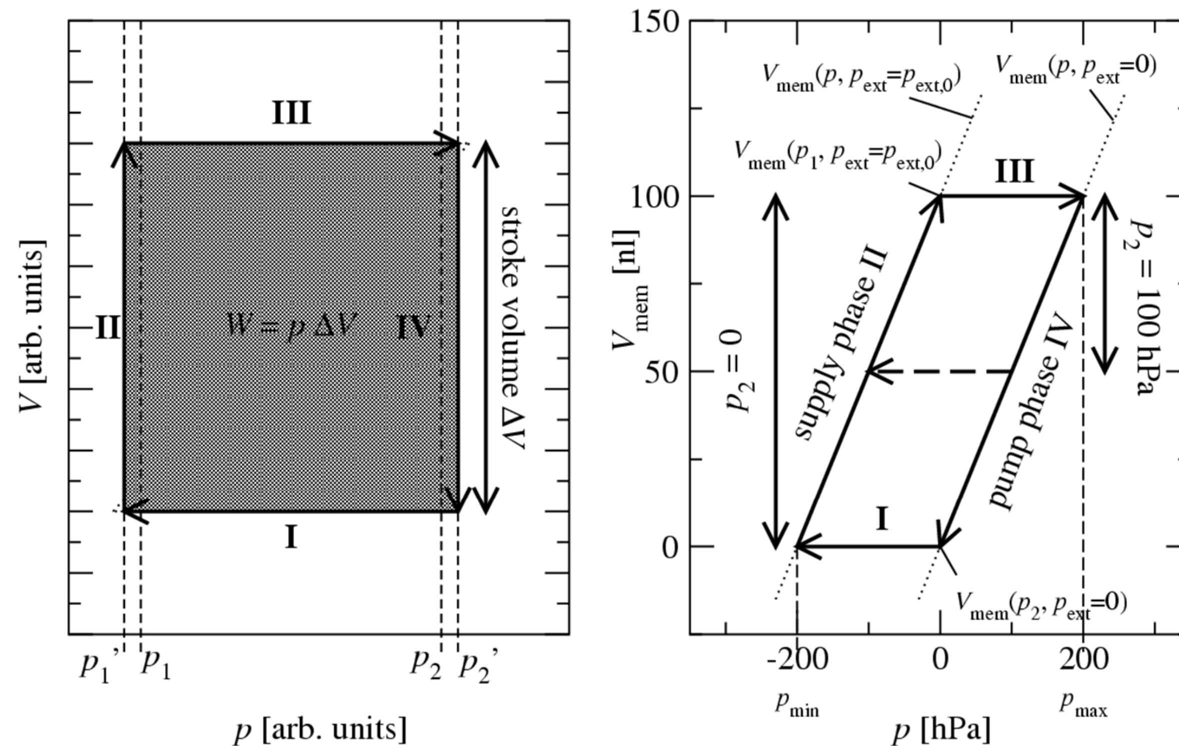
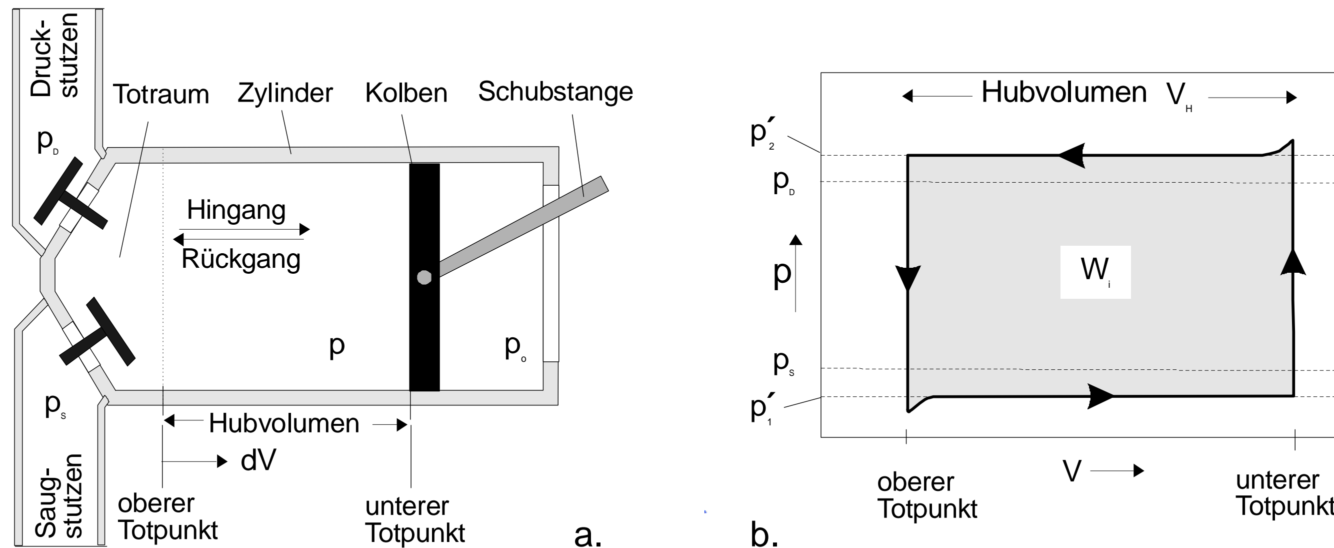


Fig. 6.5. pV-diagrams for a macroscopic displacement (left) and a microdisplacement pump (right). The motion of the displacement element is imposed by the strong external driving force of the macropump. For the micropump, the pumping dynamics results from the interplay between internal pressure and the external driving force

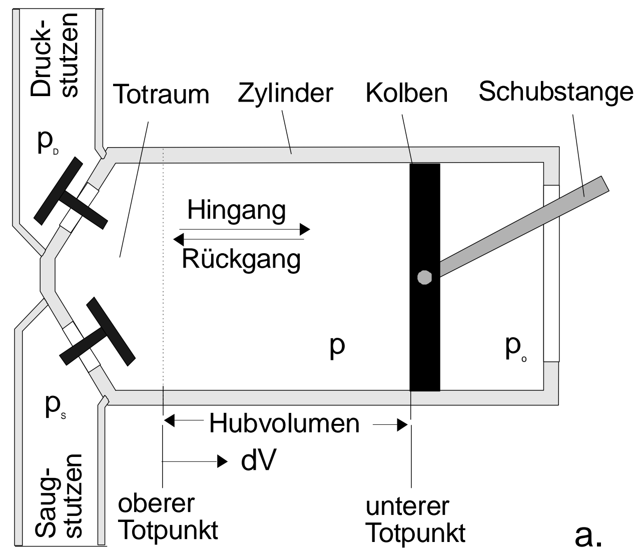
6.1.1. *pV*-Diagrams

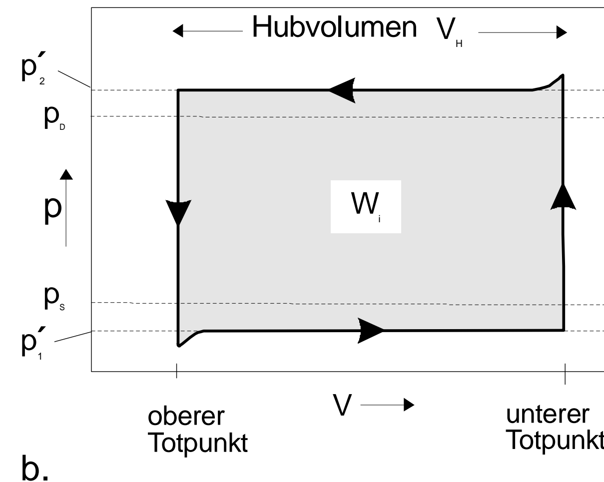


<u>Macroscopic displacement pump</u>

- Strong engines drive displacer
  - Negligible feedback of pressure in pump chamber on motion
- Pressure-controlled valves
- Displacer merely *transmits* motion

6.1.1. *pV*-Diagrams





Macroscopic displacement pump

- Pump rate
  - Actuation frequency ν
  - Stroke volume V

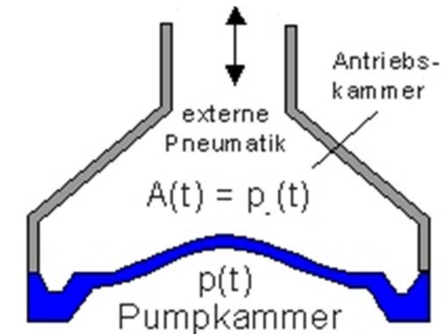
$$I_V = \nu V$$

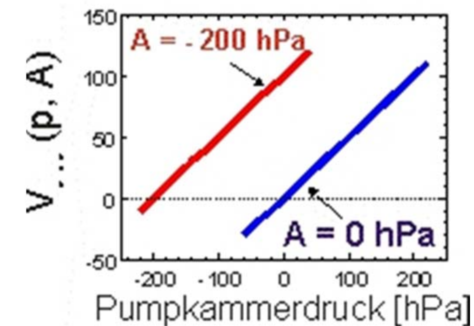
6.1.1. *pV*-Diagrams

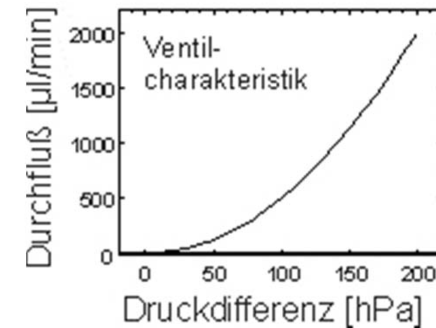
Micro-displacement pump

- Elastic membranes as displacers
- Actuation principles
  - Piezo-electrical
  - Electrostatic
  - Pneumatic
  - Thermopneumatic, etc.
- Properties of membrane govern dynamics
  - Rigidity
  - Restoring force, etc.
- Pressure-controlled valves

- Pressure in pump chamber governed by complicated interplay between
  - Flow dynamics
  - Mechanical motion
  - Motion of displacer



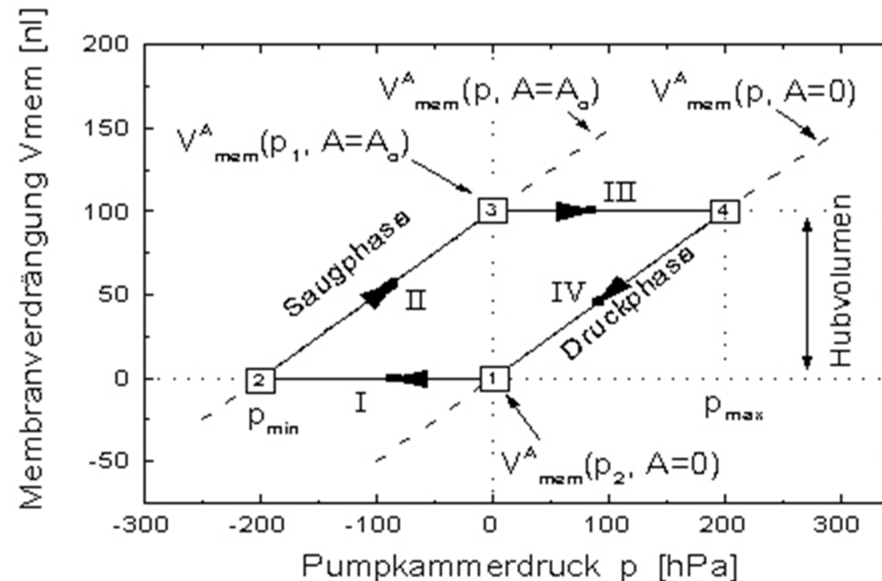




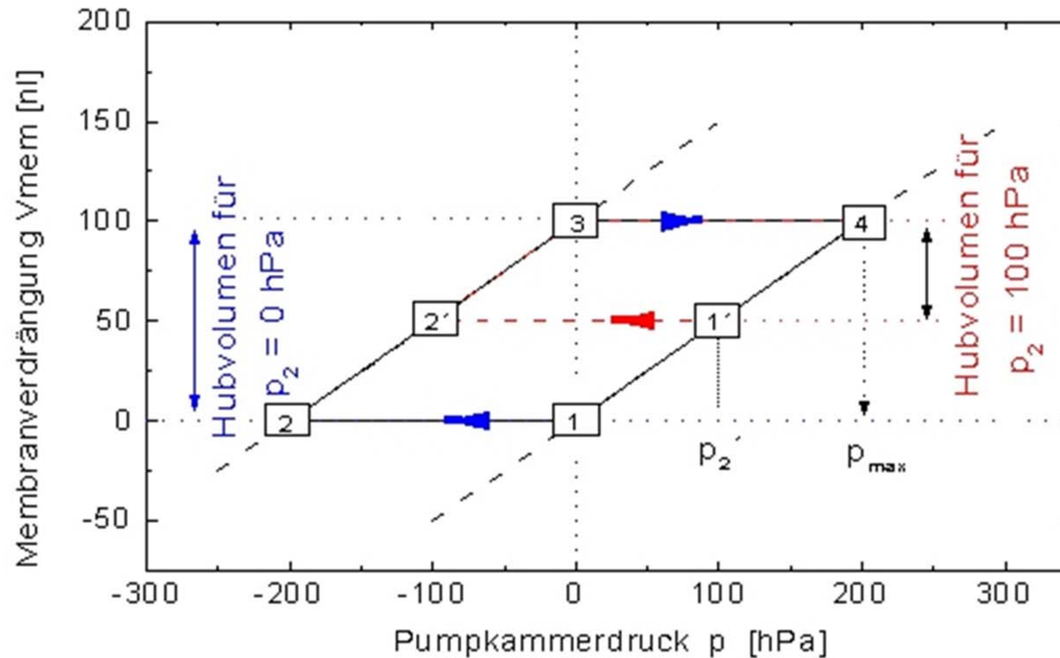
6.1.1. *pV*-Diagrams

Example: displacement pump actuated by underpressure

- Characteristic curve of MDP at A=0 (underpressure off) and $A = A_o$ (underpressure on) govern supply and pump phase
- Assumption: switch-on (section I) and switch-off (section III) of actuation (underpressure) faster than liquid can react;
  - Change in pressure w/o change in volume



6.1.1. *pV*-Diagrams



- *pV*-Diagram
  - Amplitude decreases with pressure head p_2
  - Minimum pressure in pump chamber increases with pressure head p_2

6.1.1. *pV*-Diagrams

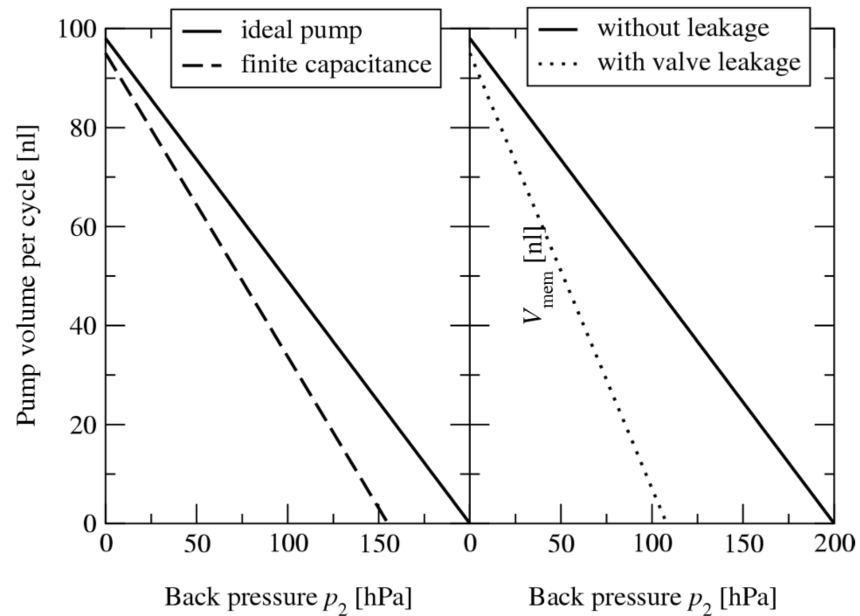
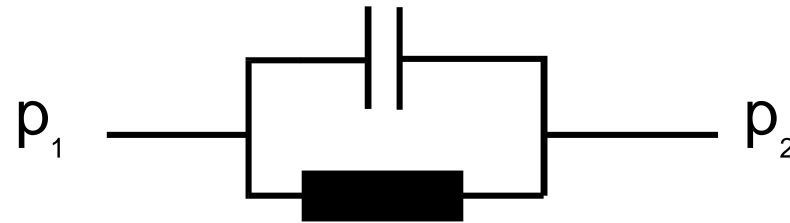


Fig. 6.6. Pump volume per cycle as a function of the back pressure p_2

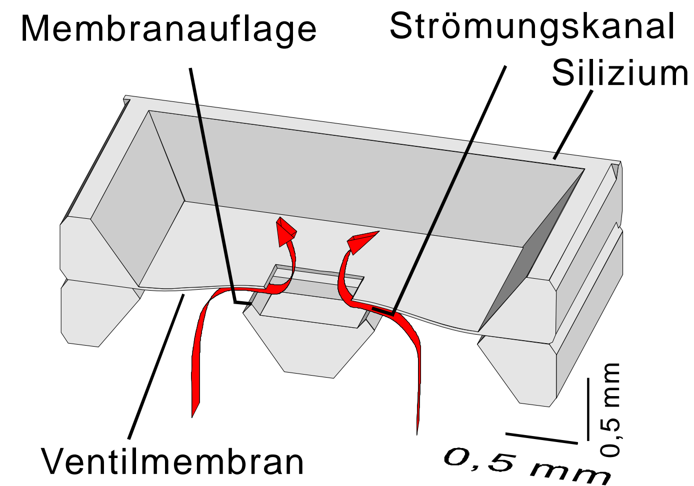
- *pV*-Diagram
  - Fluidic capacitance of valves decreases amplitude
  - Leak rate of valves decreases maximum back pressure

6.1.1. Electric Equivalent



Conclusions

- Valve with capacitance acts as low-pass filter
- At high frequencies, whole current goes into capacitive branch
  - Only motion of valve membrane
  - No net pumping of current



6.1.1. Electric Equivalent: Passive Valve System

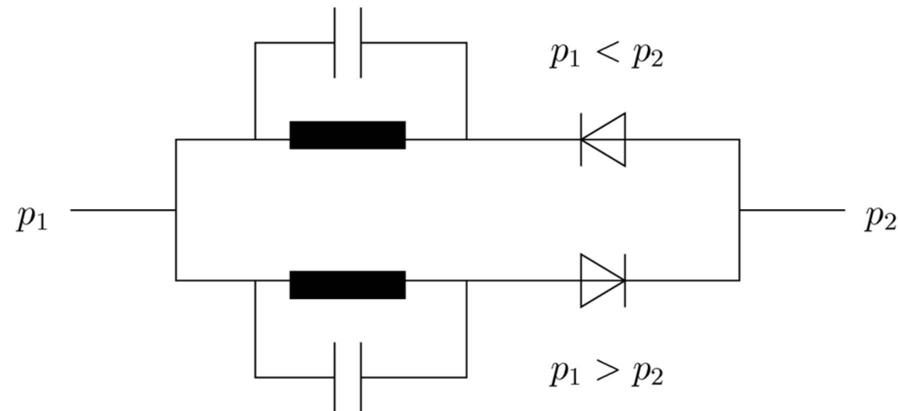


Fig. 6.2. Two current rectifiers in parallel, each of them characterized by a fluidic capacitance and a fluidic resistance, are the electric circuit equivalent of the pump chamber confined by two check valves. The pump is driven by the pressure difference $\Delta p = p_1 - p_2$ between its ends, opening the upper channel for $\Delta p < 0$ and the lower for $\Delta p > 0$

- Lumped-element representation of two passive valves
  - Rectification of flow

6.1.1. Electric Equivalent: Passive Valve

$$I_{\text{channel}} = I_{\text{valve}} + \frac{\mathrm{d}V_{\text{valve}}}{\mathrm{d}t} = I_{\text{valve}} + C_{\text{hd}} \frac{\mathrm{d}p}{\mathrm{d}t}$$

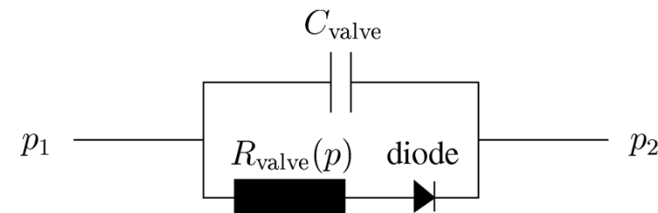


Fig. 5.1. The electric circuit equivalent of a passive valve is a resistance $R_{\text{valve}}(p)$ and a diode in parallel to a fluidic capacitance C_{valve}

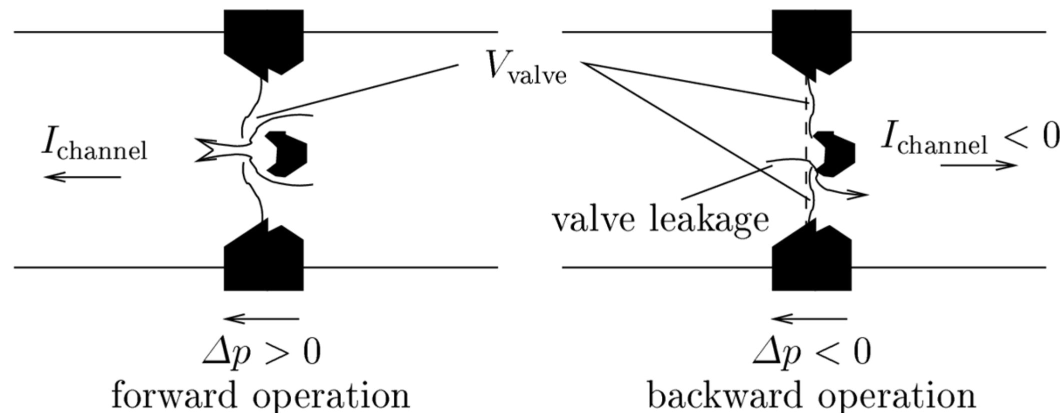


Fig. 5.4. Hydraulic capacitance C_{hd} of a membrane valve in forward and backward operation

6.1.1. Electric Equivalent: Pump

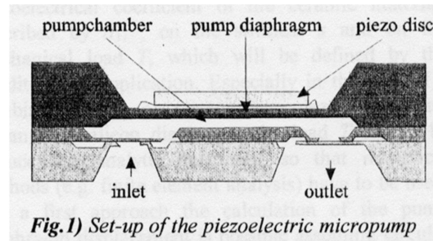


Fig. 1) Set-up of the piezoelectric micropump

Martin Richter
„Modellierung und experimentelle Charakterisierung von Mikrofluidsystemen“
Dissertation, München 1998;

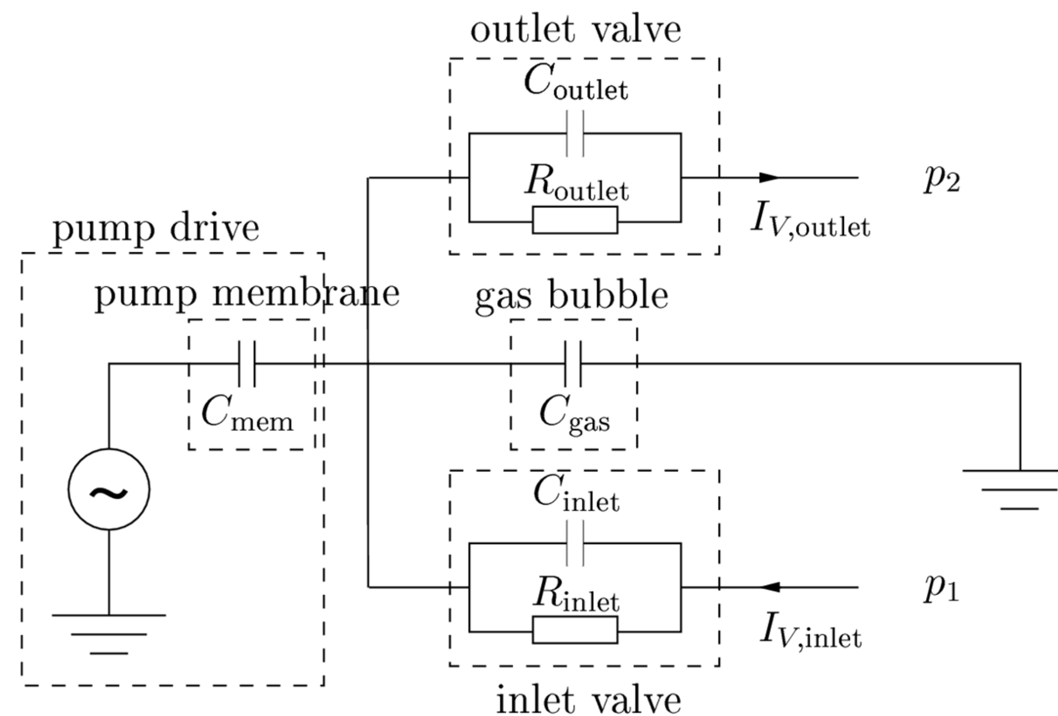


Fig. 6.7. Electric circuit representation of a membrane displacement micropump

6.1. Microdisplacement Pumps

1. Modeling
2. Design Issues
3. Integrated Check Valves
4. Fixed-Geometry Valves
5. Pumping Valve

6.1.2. Design Issues

- Market requirement
  - Fail-safe pump
- Bubble-tolerant pumping of liquids
  - Trapped gas bubbles in pump chamber
  - Highly compressible
  - Malfunctioning of displacement principle
  - Solution: High compression ratios
- Clogging
  - Particles carried by liquid
  - Solution: Prefiltering of liquids

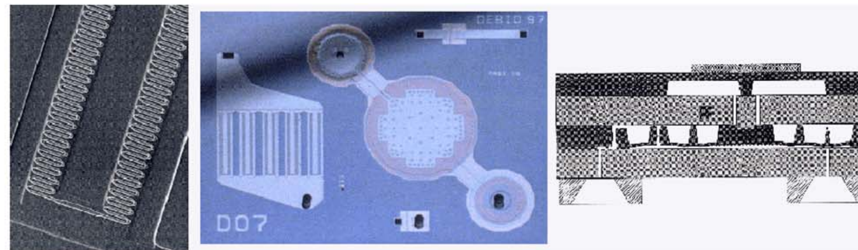


Fig. 6.15. High-performance silicon micropump for an implantable drug delivery system by Debiotech SA, Lausanne, CH . The planar particle filter (magnified view on the left) with asymmetrically offset inlet and outlet. The zig-zag barrier reduces the flow resistance with respect to a straight structure . A schematic cross-section is shown on the right

6.1.2. Fixed-Stroke MDP

Debiotech; Switzerland; 1998

- Based in pump design by Harald van Lintel
- Integrated particle filter
- Membrane moves between two mechanical stops
- Drawback: expensive concept

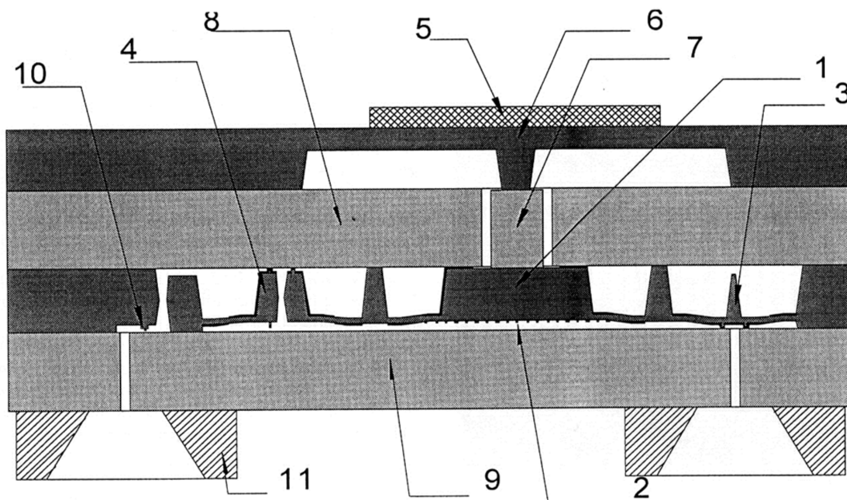
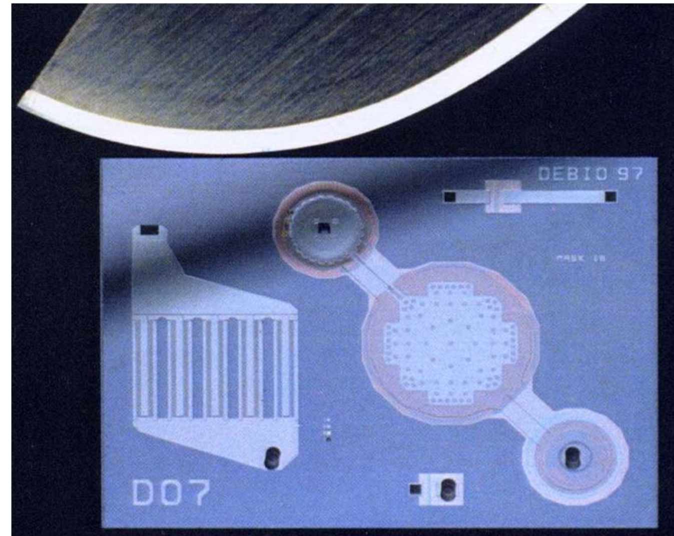
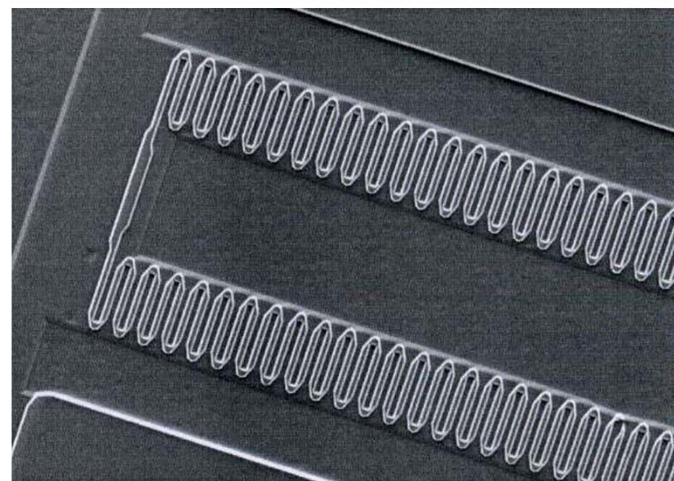


Figure 2: Schematic cross section of the pump (not to scale)

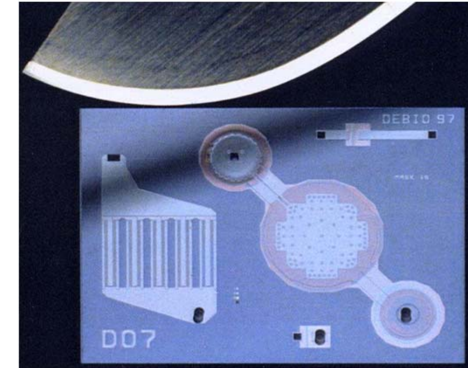


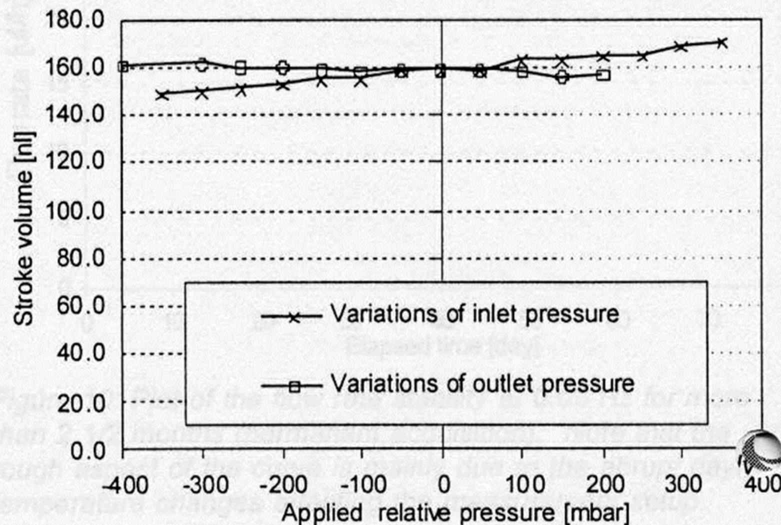


6.1.2. Fixed-Stroke MDP

Debiotech; Switzerland; 1998

- Membrane moves between 2 mechanical strops
  → fixed amplitude
  - Independent of pressure on inlet and outlet port





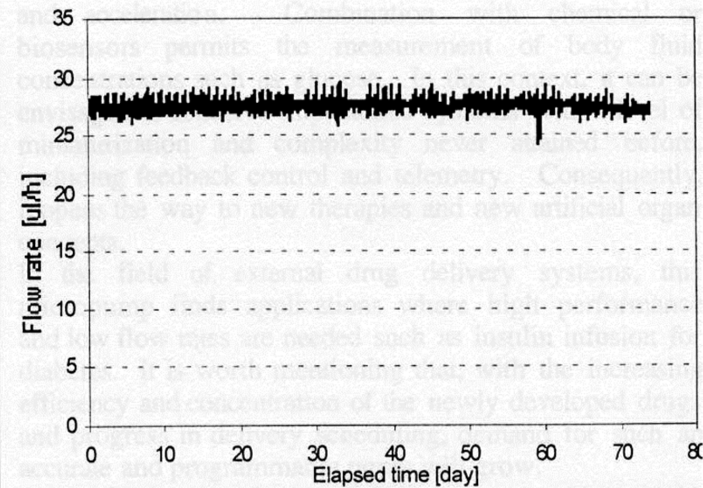


Figure 10: Plot of the flow rate stability at 0.05 Hz for more than 2 1/2 months (permanent acquisition). Note that the rough aspect of the curve is mainly due to the abrupt dayly temperature changes affecting the measurement setup.

6.1. Microdisplacement Pumps

1. Modeling
2. Design Issues
3. Integrated Check Valves
4. Fixed-Geometry Valves
5. Pumping Valve

6.1.3. Peristaltic Micromembrane Pump

- **J.G. Smits; MESA; 1983**
  „Piezoelectric micropump for peristaltic fluid displacement";
  Patent NL 8302860

- 3 active displacers (microvalves)
- Piezoelectric actuation

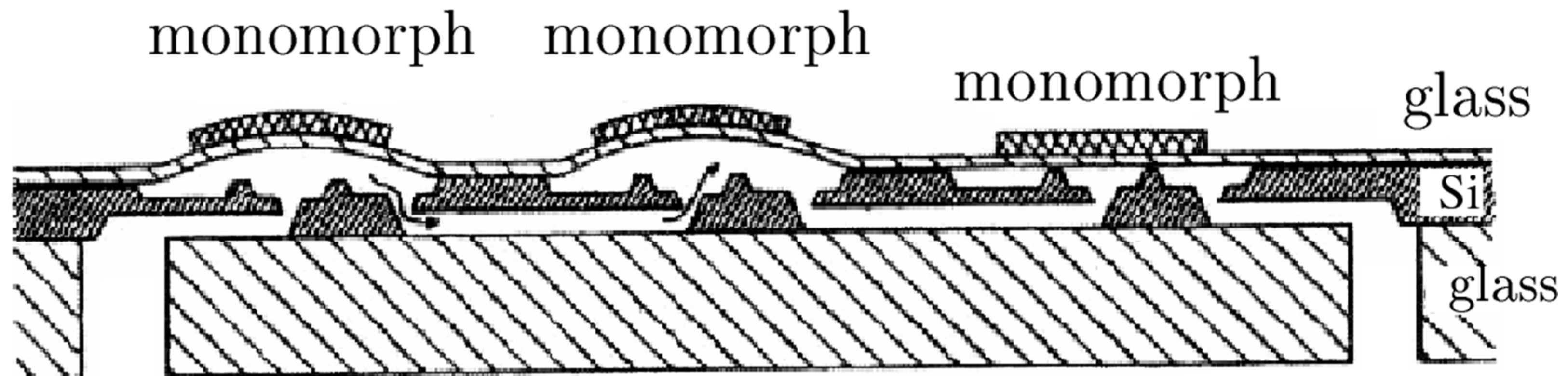
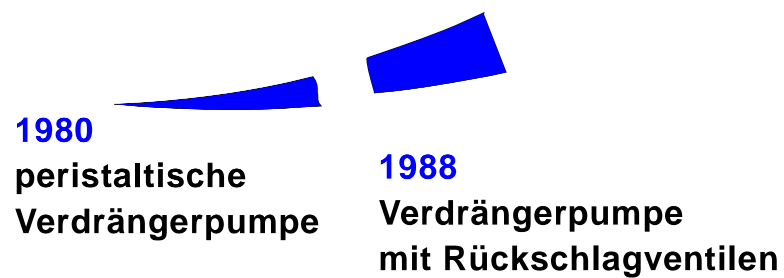


Fig. 6.8. Peristaltic, piezoelectrically actuated micropump

Milestones

Milestones in evolution of microdisplacement pumps



6.1.3. Displacement Pump with Check Valves

- **Harald van Lintel** et al.; MESA, 1988

  „A piezoelectric micropump based on micromachining of silicon“

- Piezoelectrically actuated displacer
- Two membrane valves

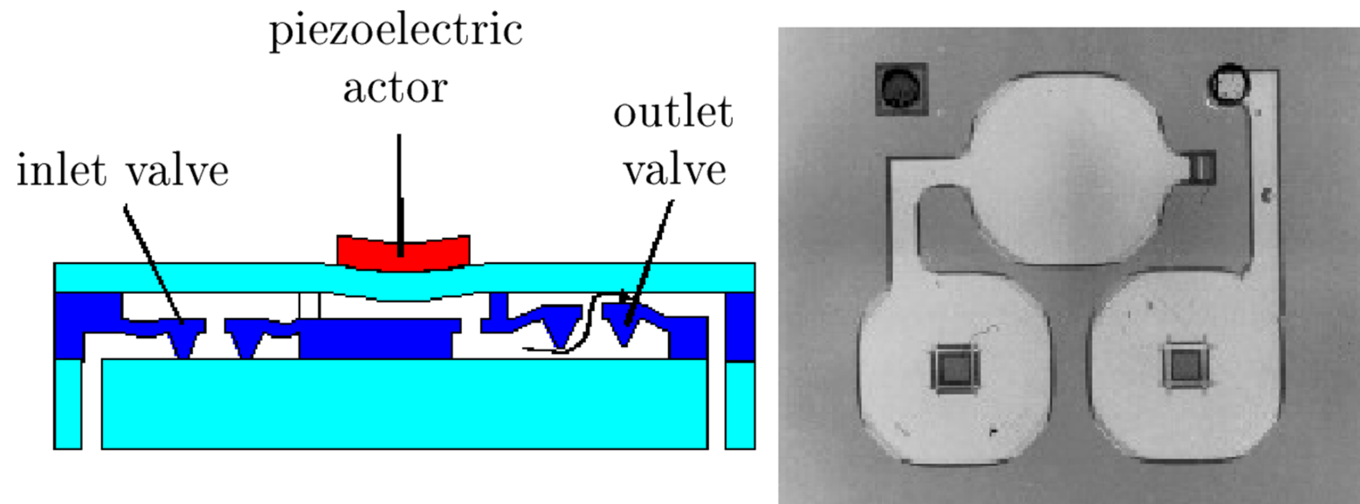


Fig. 6.9. Displacement pump with integrated membrane check valves

6.1.3. Pump Performance

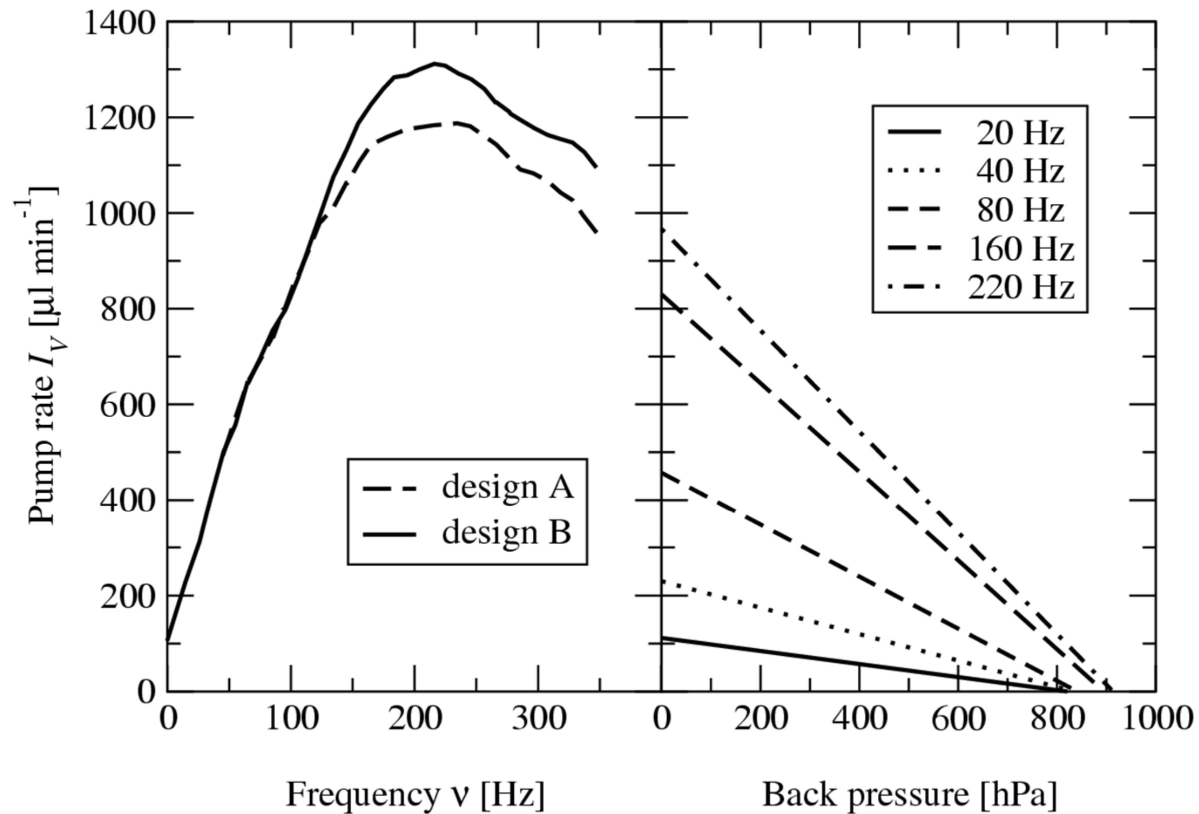


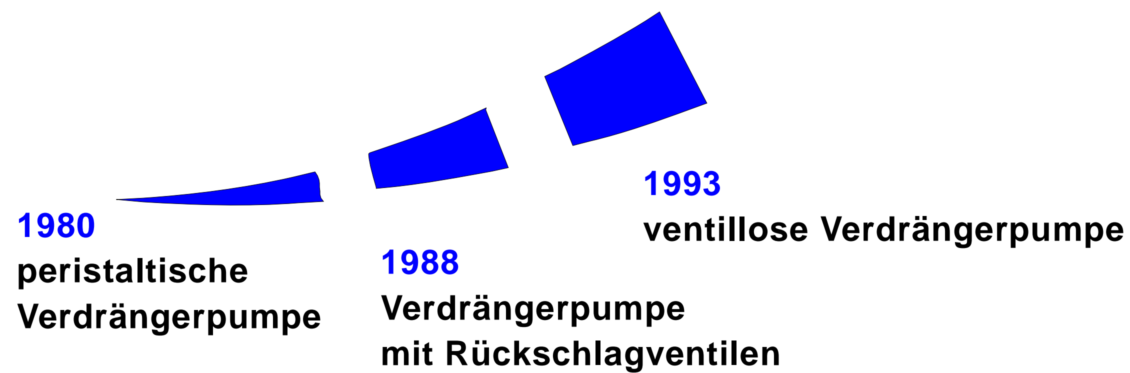
Fig. 6.10. Pump rate of the FhG–IFT micropump as a function of the driving frequency ν (left) and the back pressure with ν as parameter (right) . The pump medium is water

6.1. Microdisplacement Pumps

1. Modeling
2. Design Issues
3. Integrated Check Valves
4. Fixed-Geometry Valves
5. Pumping Valve

6.1. Milestones

Milestones in evolution of microdisplacement pumps



6.1.4. Fixed-Geometry Valves

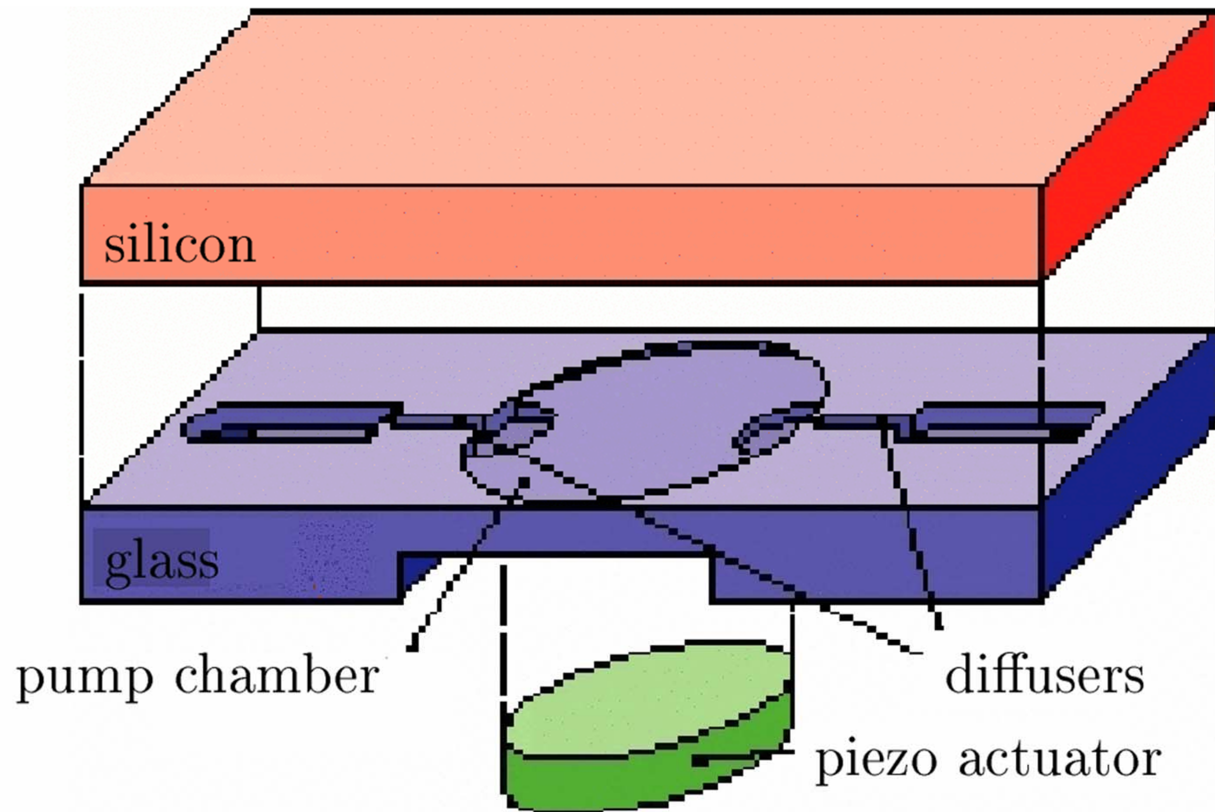


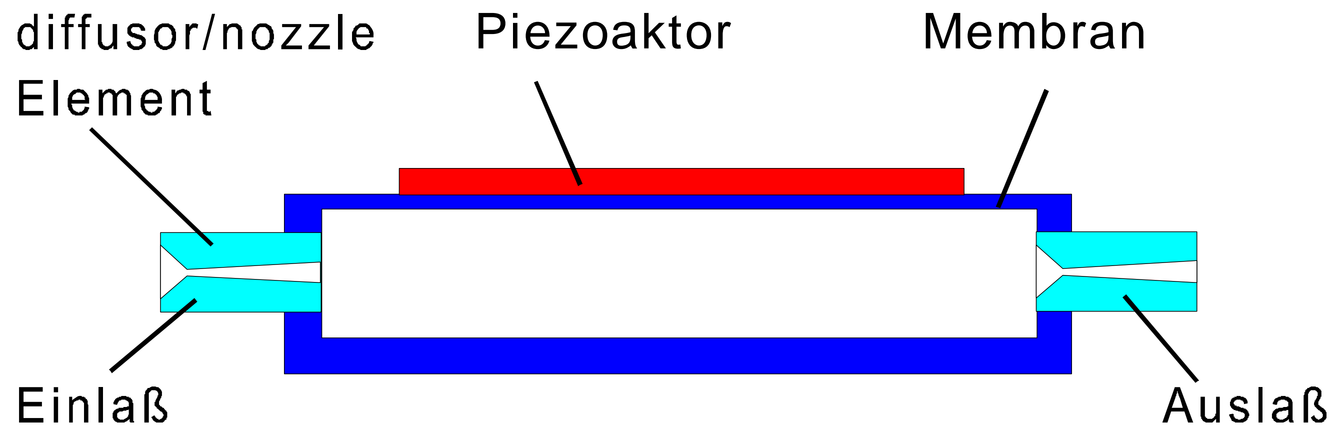
Fig. 6.16. Exploded view of the diffuser pump. The diameter of the pump chamber amounts to 6 mm. The height in the central shallow region measures 5 μm, only while the inlet sections and the nozzles are 30 μm deep

6.1.4. Fixed-Geometry Valves

- **Göran Stemme** et al.; KTH; Stockholm, 1993

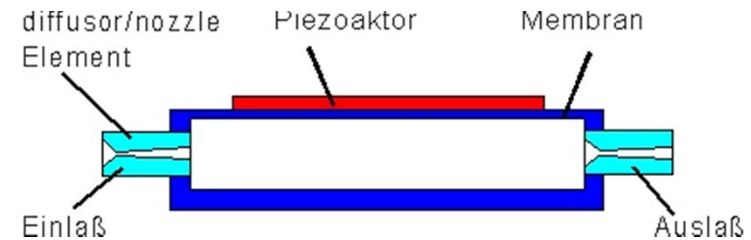
  „A novel piezoelectric valve-less fluid pump “

- Piezoelectrically actuated displacer
- Diffuser / nozzle as rectifier



6.1.4. Fixed-Geometry Valves

Anders Olson
„Valve-Less Diffuser Micropumps“
Dissertation, Stockholm 1998;



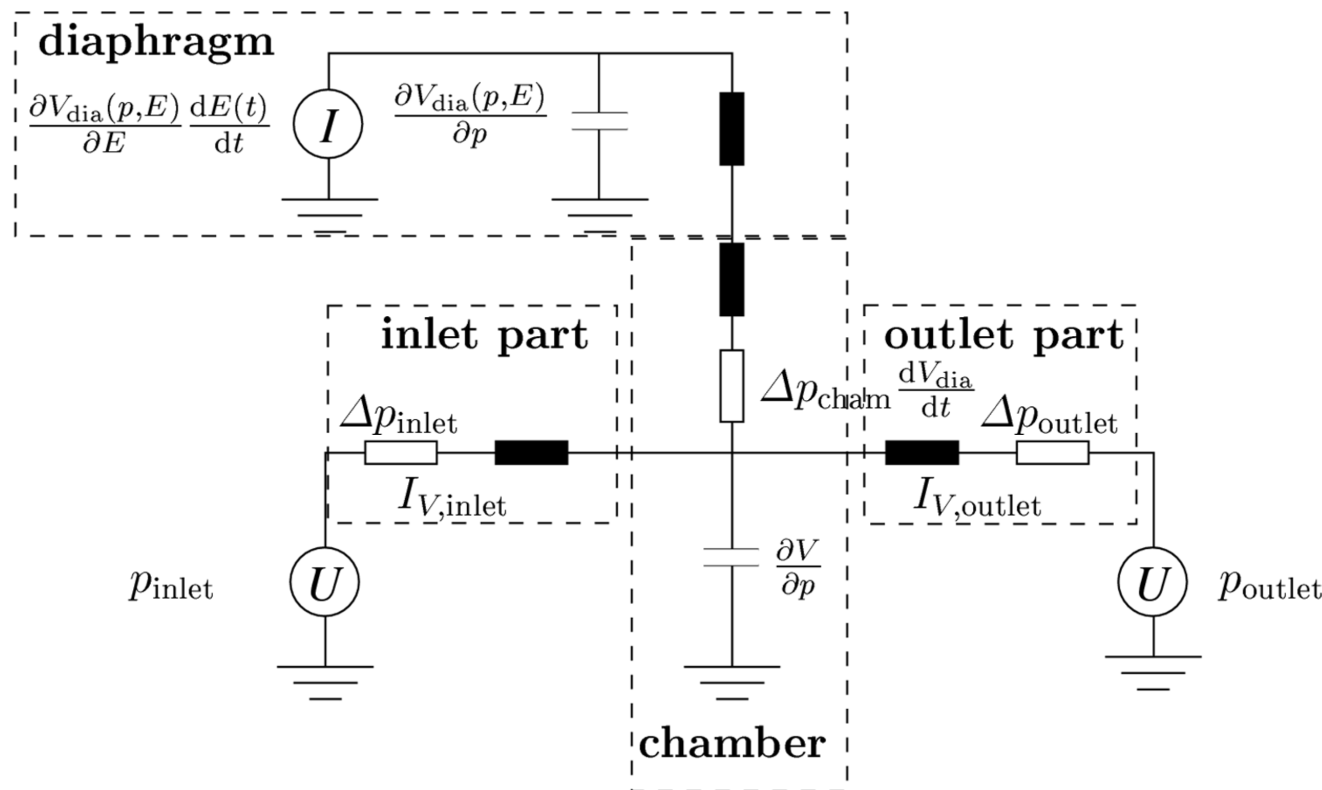
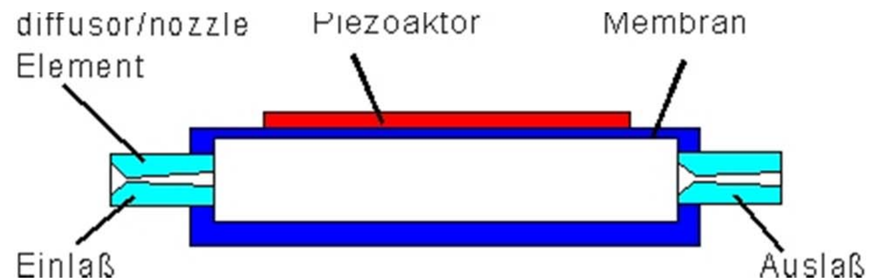


Fig. 6.19. Equivalent circuit model for a diffuser-nozzle pump

6.1.4. Fixed-Geometry Valves

Anders Olson
„Valve-Less Diffuser Micropumps“
Dissertation, Stockholm 1998;



Described by set of differential equations:

$$\frac{\partial V_{\mathrm{eq}}}{\partial p} \cdot \frac{dp}{dt} = \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} \Phi_{\mathrm{in}} \\ \Phi_{\mathrm{out}} \end{pmatrix} - \frac{\partial V_{\mathrm{dia}}}{\partial E} \frac{dE}{dt} \quad (31)$$

$$\rho_{\mathrm{liquid}} \cdot \begin{pmatrix} \alpha_{\mathrm{d}} + \alpha_{\mathrm{c}} & 0 \\ 0 & \alpha_{\mathrm{d}} + \alpha_{\mathrm{c}} \end{pmatrix} \frac{d}{dt} \begin{pmatrix} \Phi_{\mathrm{in}} \\ \Phi_{\mathrm{out}} \end{pmatrix} = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} p_{\mathrm{in}} \\ p \\ p_{\mathrm{out}} \end{pmatrix} - \begin{pmatrix} \Delta p_{\mathrm{loss}}(\Phi_{\mathrm{in}}) \\ \Delta p_{\mathrm{loss}}(\Phi_{\mathrm{out}}) \end{pmatrix} \quad (32)$$

$$\frac{\partial V_{\mathrm{eq}}}{\partial p} = \frac{\partial V_{\mathrm{dia}}}{\partial p} + \kappa_{\mathrm{liquid}} \cdot V_{\mathrm{ch}} + \left(\frac{1}{p + p_0} - \kappa_{\mathrm{liquid}} \right) \cdot \frac{x \cdot V_{\mathrm{ch}} \cdot p_0}{p + p_0} \quad (33)$$

6.1.4. Fixed-Geometry Valves

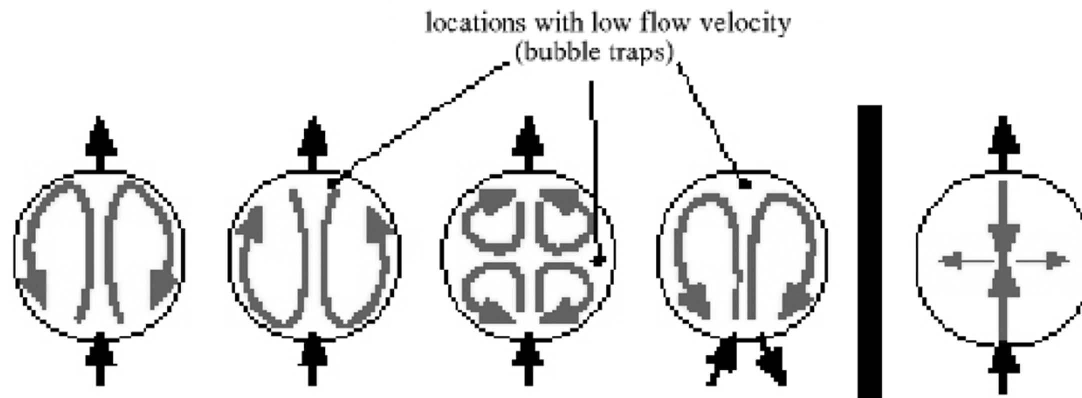


Fig. 6.18. Commonly observed flow patterns in the pump chamber with the black and grey arrows representing the diffusers and stream direction, respectively. Some locations with low flow velocities are indicated as potential bubble traps. On the right, a possible mechanism for vortex generation is shown. Fast fluid jets transfer their kinetic energy at the inlet onto the fluid resting in the chamber

6.1.4. Fixed-Geometry Valves

- **Thorsten Gerlach** et al.; TU-Illmenau; 1995

- Piezoelectrically actuated displacer
- KOH-etched diffuser / nozzle

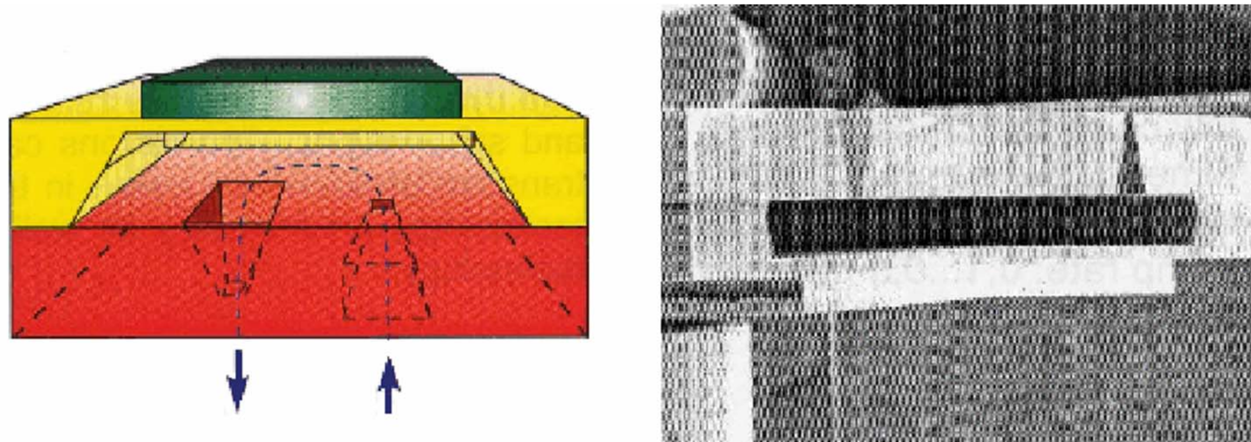


Fig. 6.17. Diffuser/nozzle pump developed at TU–Illmenau

6.1.4. Tesla Valve

Components:

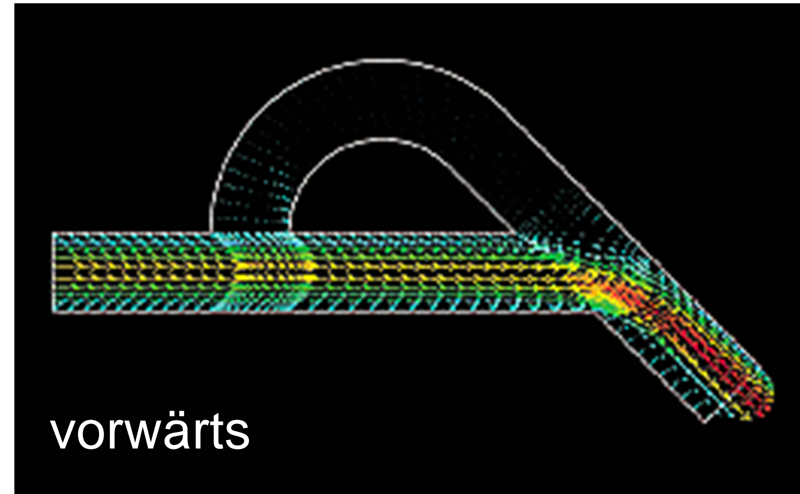
- Bypass at deviating angles

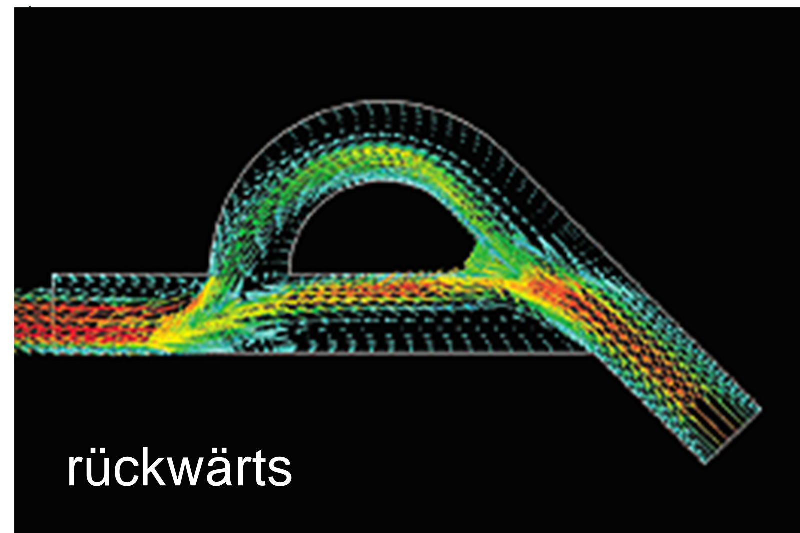
Pros:

- simple
- compact

Drawbacks:

- Low forward/backward ratio
- High „leak rate“





6.1.4. Tesla Valve

Components:

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Pros:

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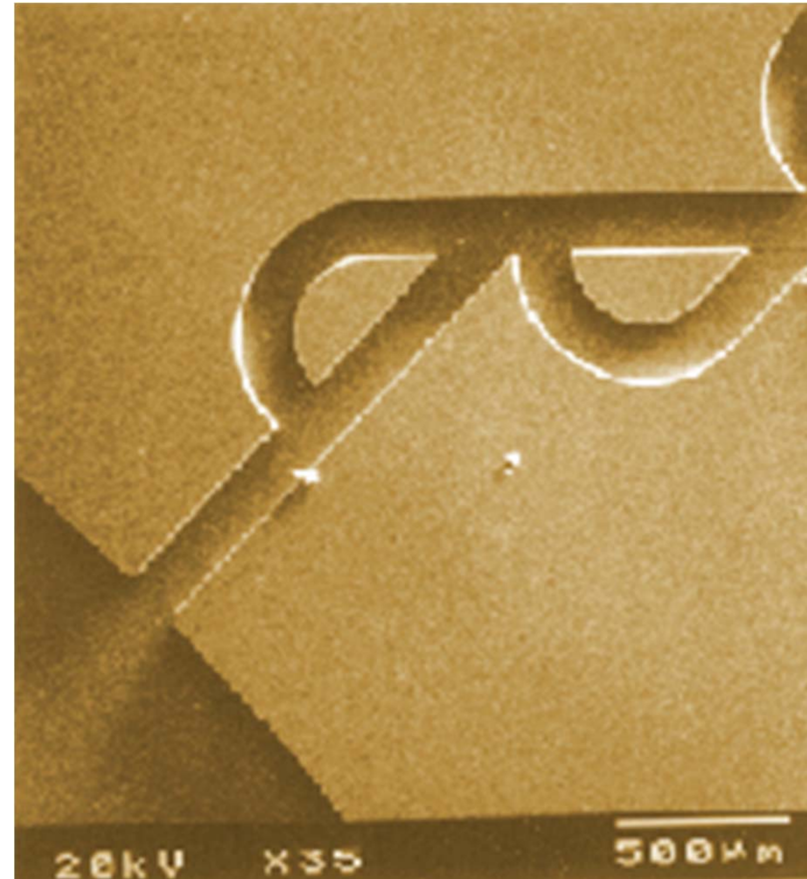
- compact

Drawbacks:

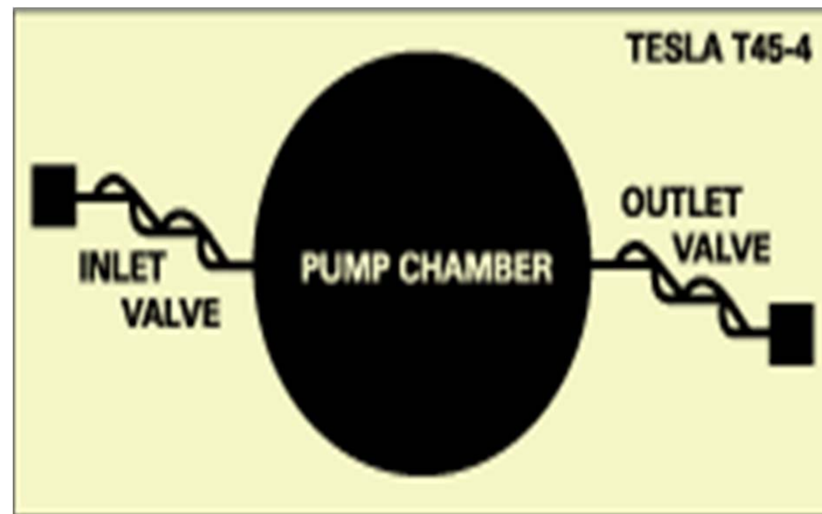
- Low forward/backward ratio
- High „leak rate“



6.1.4. Tesla Valve

- **Fred Forster** *et al.*; University of Washington; 1998

- Piezoelectrically actuated displacer
- Bypass-valves (TESLA-valve) as rectifier



6.1. Microdisplacement Pumps

1. Modeling
2. Design Issues
3. Integrated Check Valves
4. Fixed-Geometry Valves
5. Pumping Valve

6.1. Milestones

Milestones in evolution of microdisplacement pumps

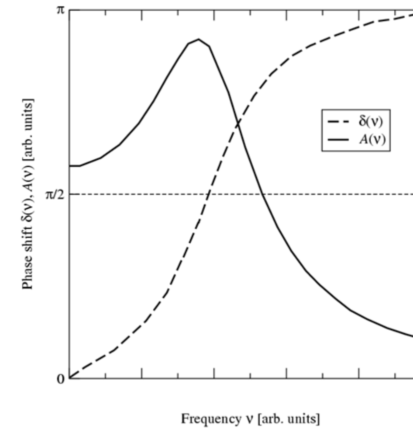


Fig. 6.13. Amplitude of the flap valve $A(\nu)$ and phase shift $\delta(\nu)$ as a function of the driving frequency ν

1980
peristaltische Verdrängerpumpe

1988
Verdrängerpumpe mit Rückschlagventilen

1993
ventillose Verdrängerpumpe

1995
Verdrängerpumpe mit Vorwärts- & Rückwärtsgang

6.1.5. Bidirectional MDP

- **R. Zengerle et al;** FhG-IFT, 1995

  „A bidirectional silicon micropump"
- Electrostatic actuation
- Flap valves

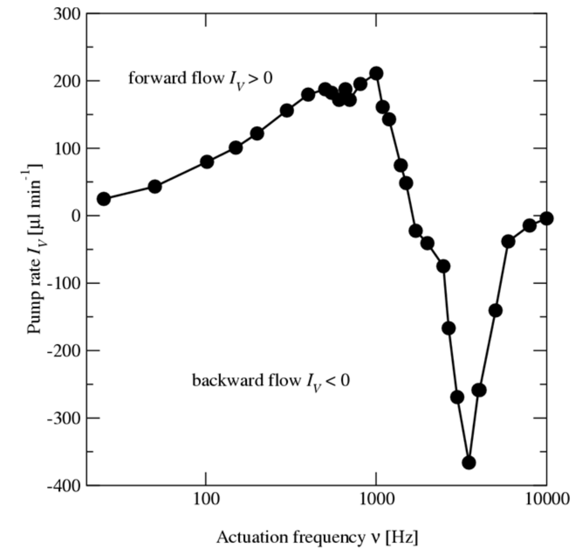
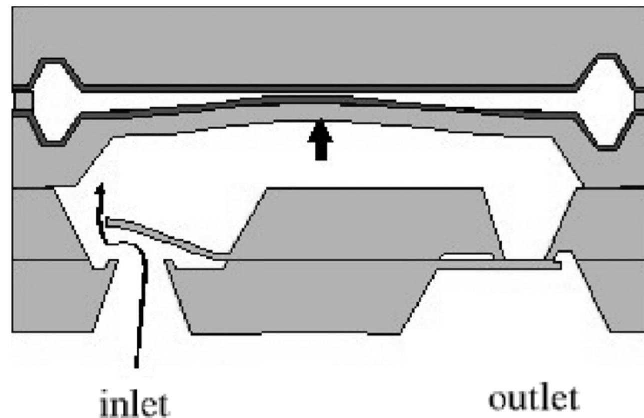


Fig. 6.14. Frequency dependence of the pump rate generated with the device

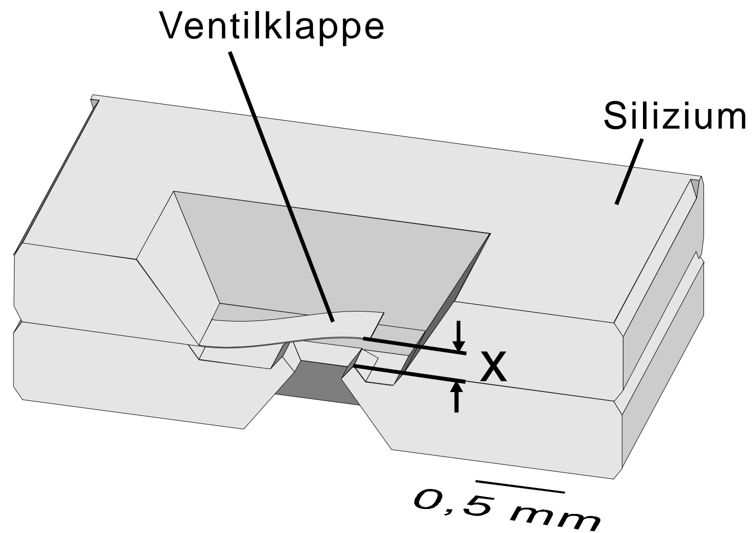


ig. 6.12. Bidirectional microdisplacement pump with electrostatic actuation

6.1.5. Bidirectional MDP

- **R. Zengerle et al;** FhG-IFT, 1995

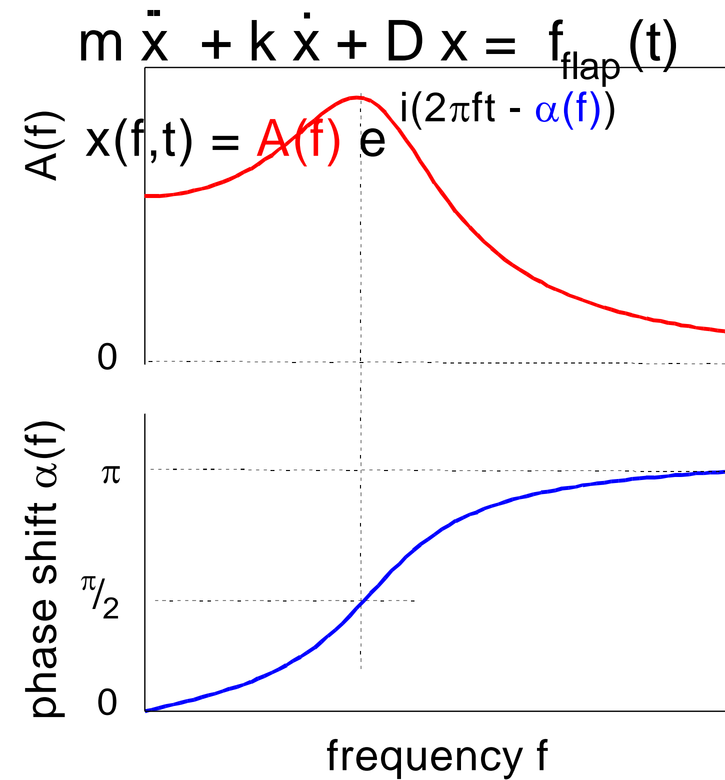
  „A bidirectional silicon micropump"



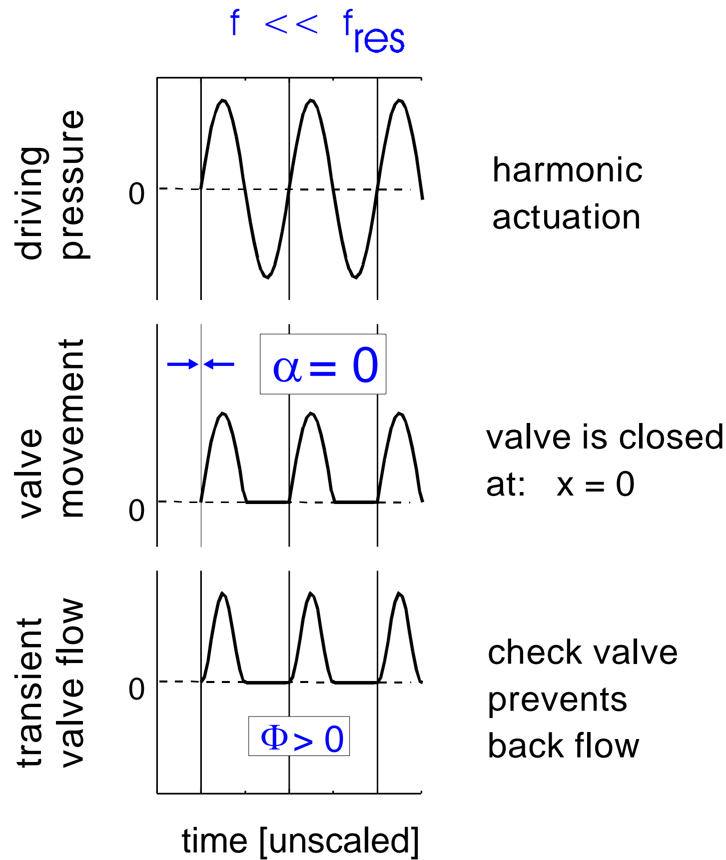
Motion of flap

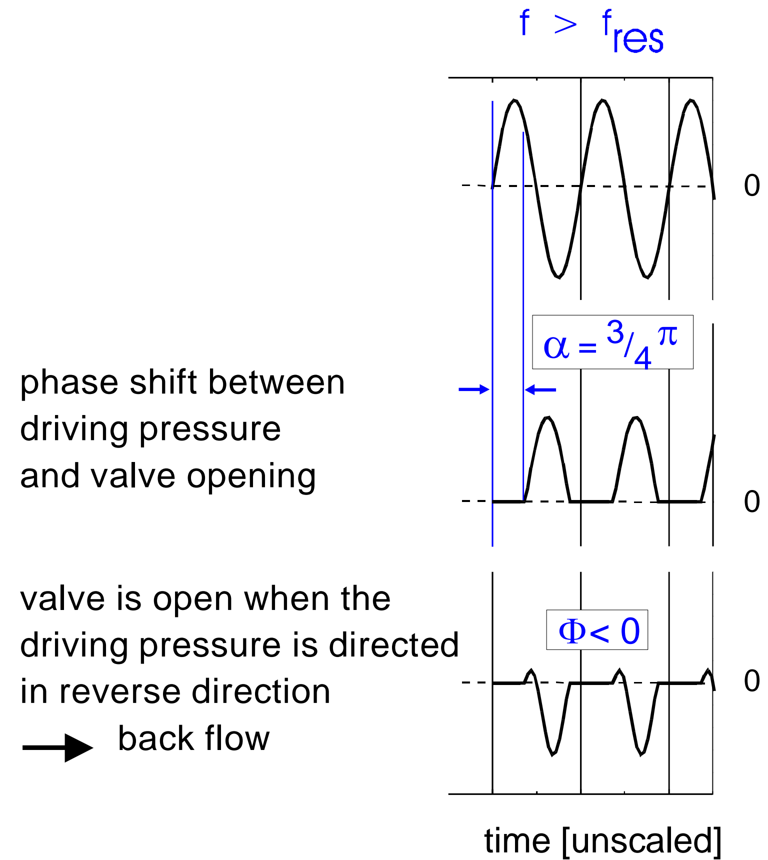
$$m\ddot{x} + k\dot{x} + Dx = f_{flap}(t)$$

$$x(f,t) = A(f)\, e^{i(2\pi ft - \alpha(f))}$$



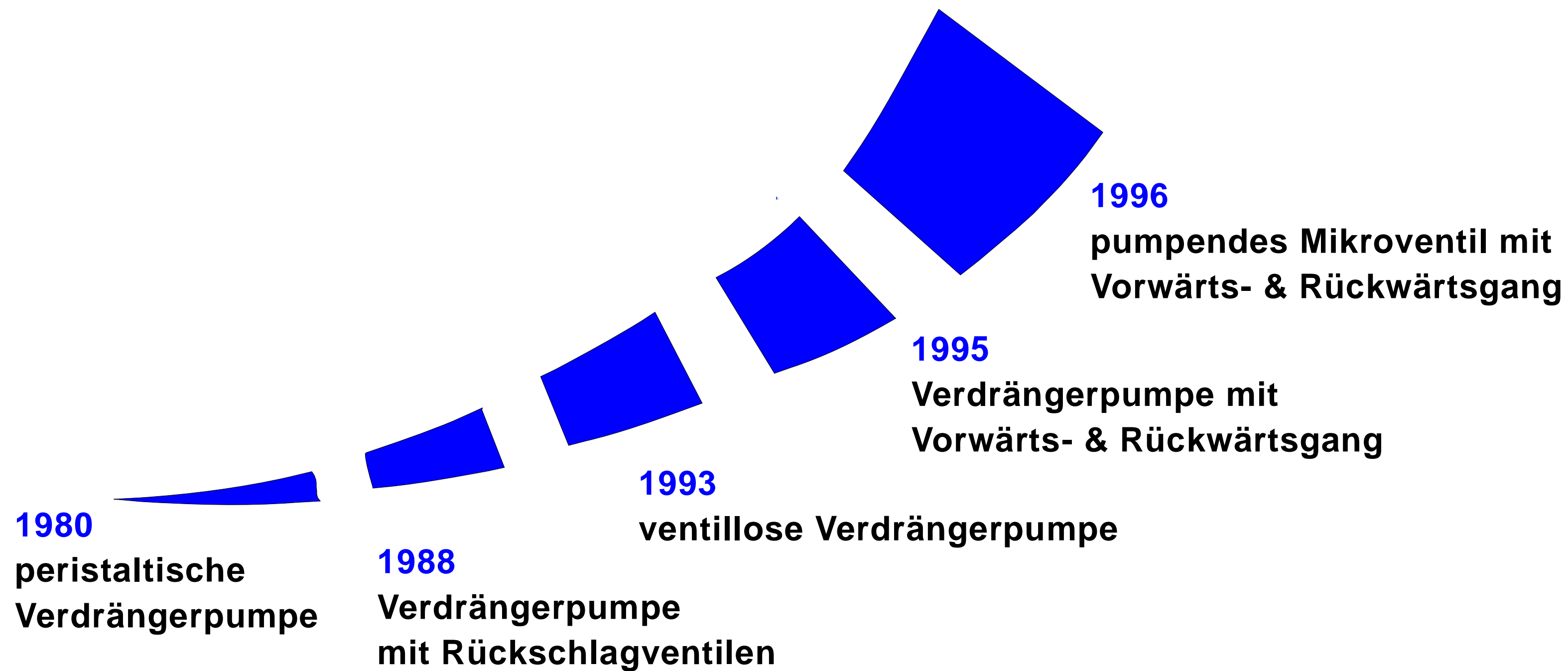
6.1.5. Bidirectional MDP





6.1.5. Milestones

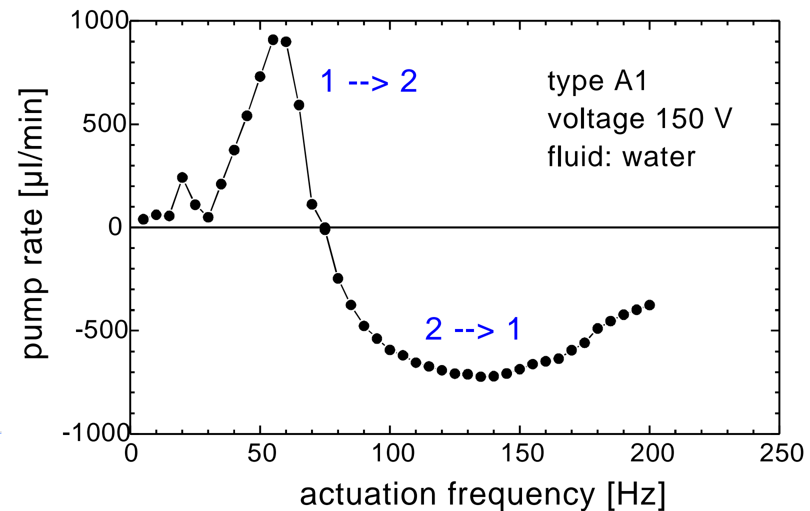
Milestones in evolution of microdisplacement pumps

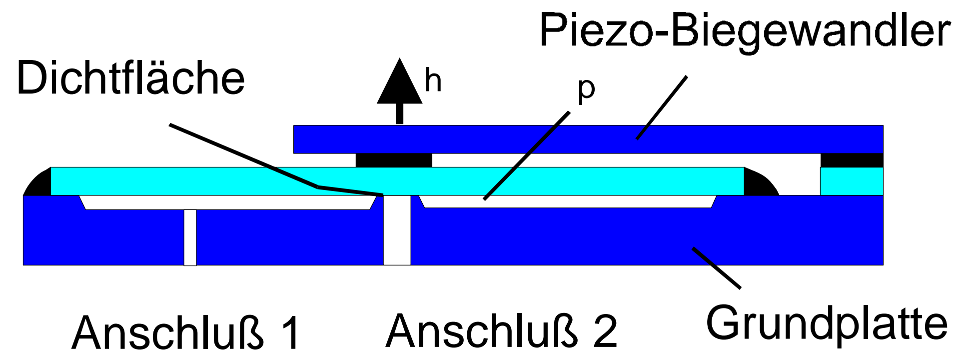


6.1.5. VAMP

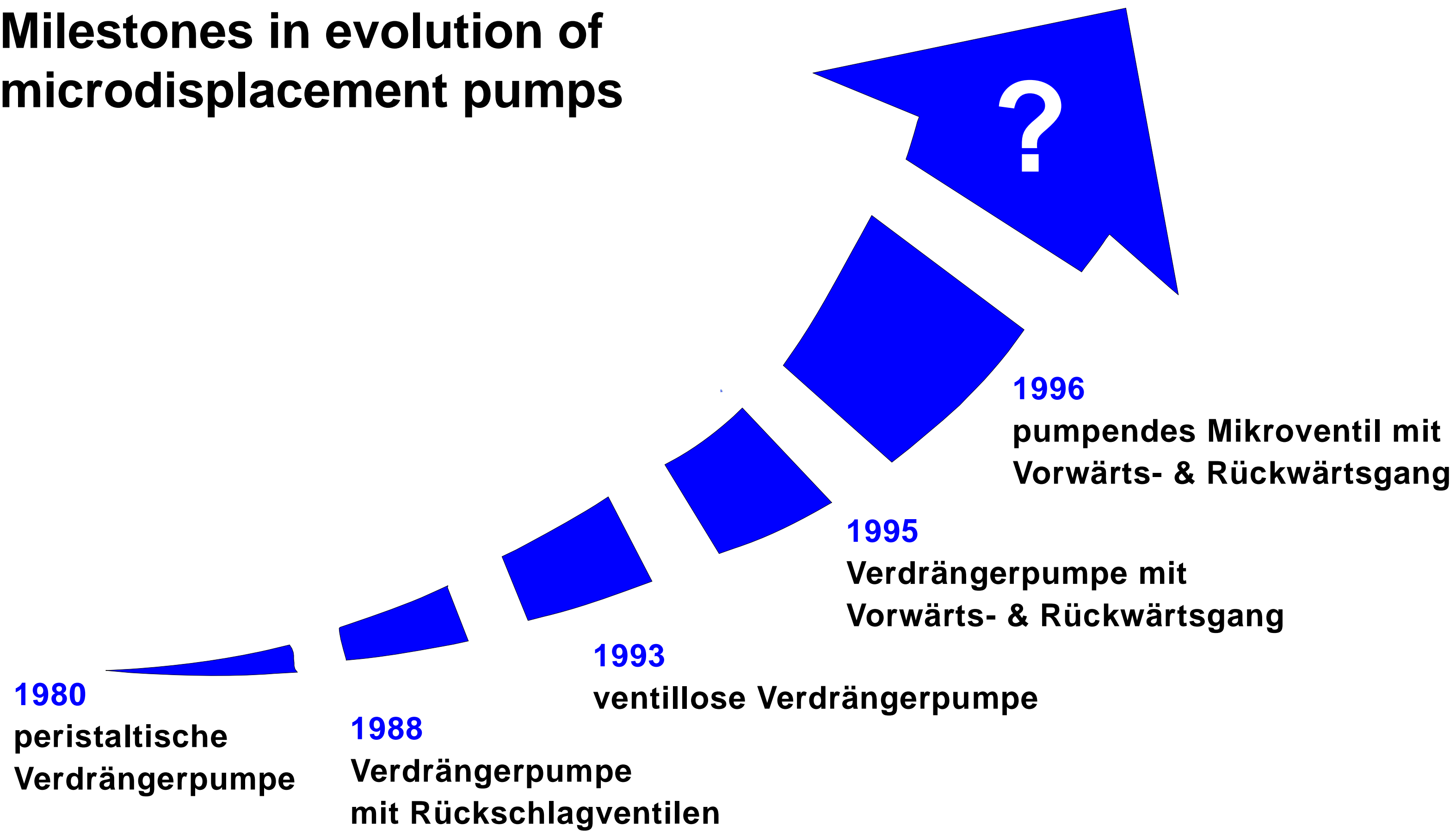
- **M. Stehr et al;** HSG-IMIT; 1996

  „The VAMP - A microvalve with bidirectional pump effect“

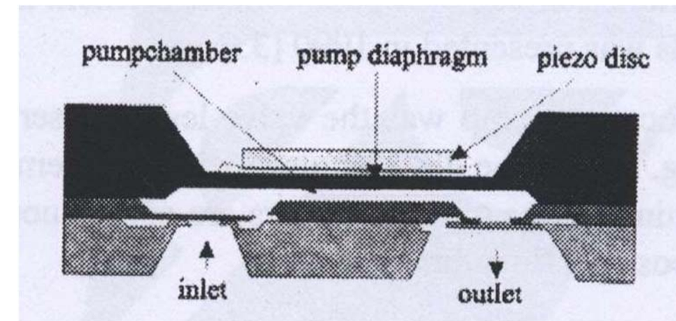




6.1. Milestones



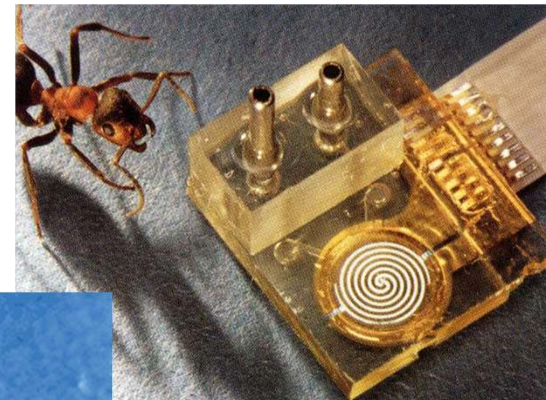
6.1. Check-Valved Microdisplacement Pumps



FhG-IFT: 1996

Common sources of failure

- Failure due to gas bubbles
  - Reduced volume of pump chamber
  - Higher compression ratio
- Leakage
  - External or integrated particle filters

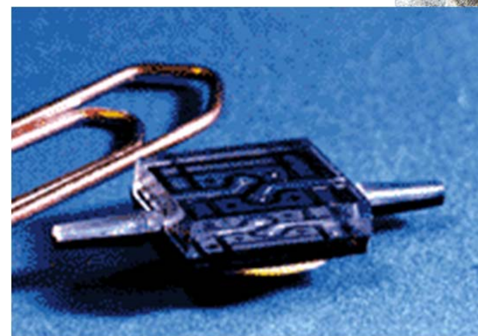


Forschungszentrum Karlsruhe

Economical

- High fabrication costs
- Low production numbers

IMM-Mainz

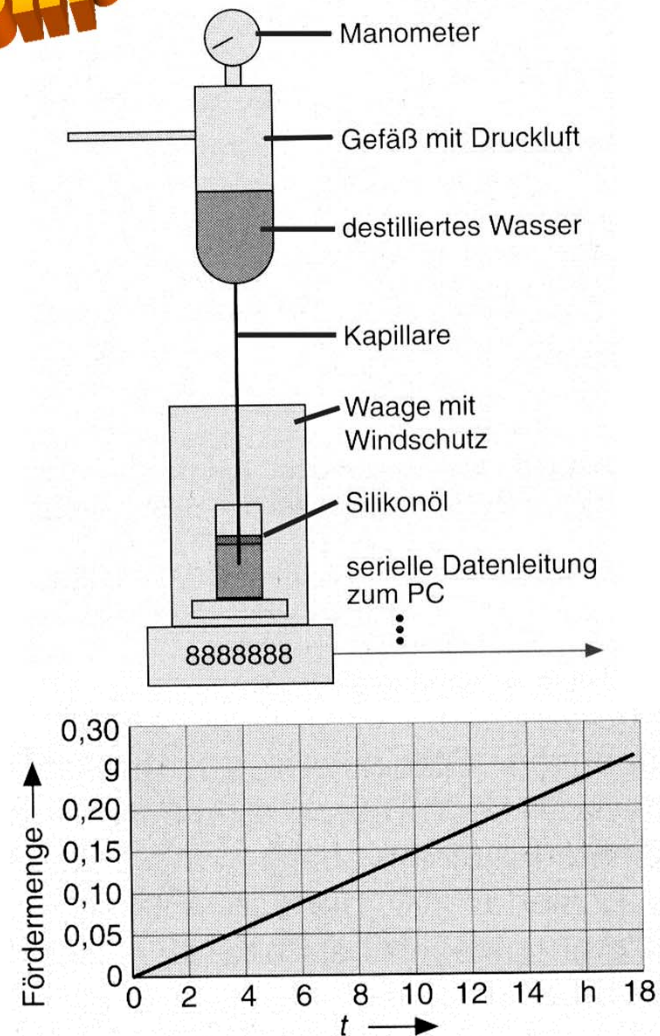


6.1. Pressure-Controlled Microdosage

Pumpen oder Dosieren?

Operating principles

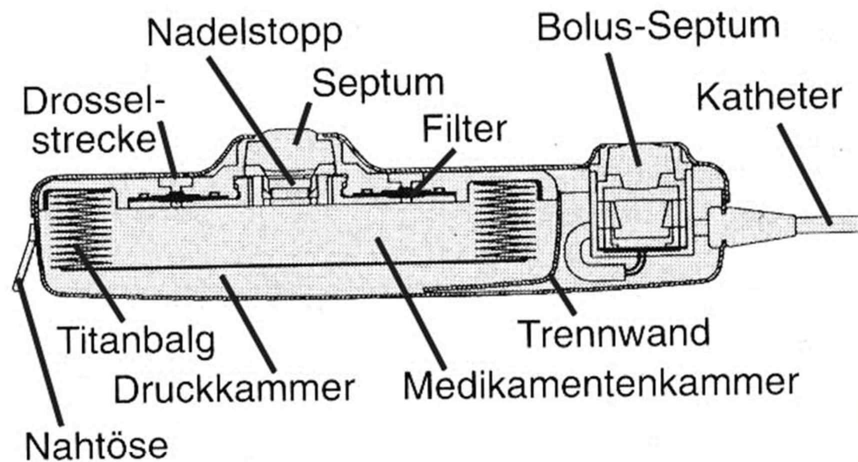
- Pressurized reservoir
- Capillary (glass, silicon-etched)
  - High hydrodynamic resistance
- Adjustment of resistance to desired flow rate
- Flow rate
  - Constant in time
  - Unchangeable

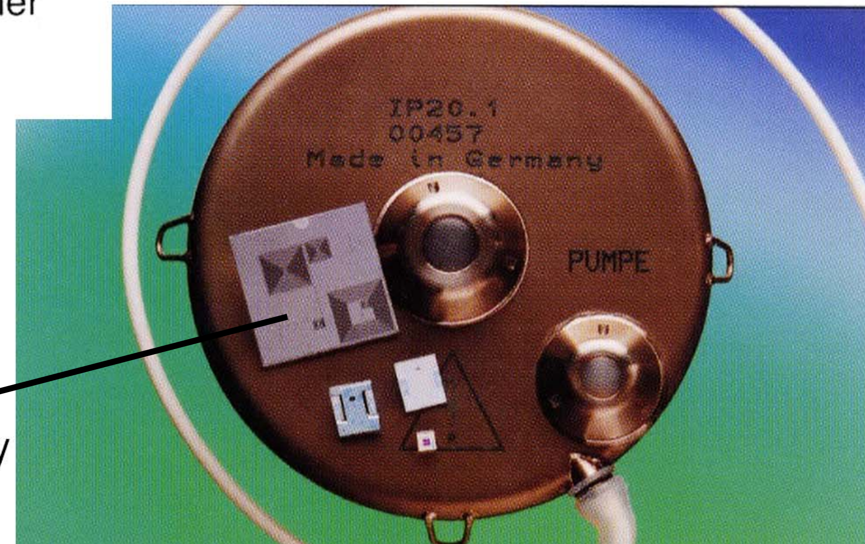


Optional

- Active valve to interrupt flow

6.1. Implantable Drug-Delivery System





Tricumed (Kiel)

- Spring mechanism exerts pressure on reservoir
- Resistance by long and tiny capillary etched in silicon

6.1. Extracorporal Drug-Delivery System

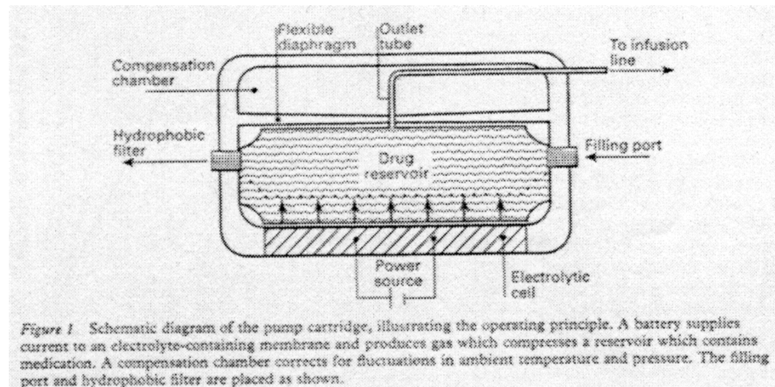


Figure 1 Schematic diagram of the pump cartridge, illusrating the operating principle. A battery supplies current to an electrolyte-containing membrane and produces gas which compresses a reservoir which contains medication. A compensation chamber corrects for fluctuations in ambient temperature and pressure. The filling port and hydrophobic filter are placed as shown.

Figure 2 The infusion pump showing the pump cartridge removed from the electronic control unit. There is a filter in the infusion line.

<u>Electrochemical Dosage</u>

- Pressure generated by electrochemical reaction
- No resistance required

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous

6.2. Electric-Field Mediated Pumping

- Advantages
  - No moving parts
  - Fabrication of electrodes well compatible with microtechnology
  - Planar flow profiles

- Two technological branches
  - Static fields
    - Charge carriers
      - Interfaces
      - Injected
  - Traveling fields
    - Gradient of electrical properties
      - Conductivity
      - Permittivity

6.2. Electric-Field Mediated Pumping

1. Electro-Osmotic Pumping
2. Static Electrohydrodynamic Pumping
3. Traveling-Wave EHD Pumping

6.2.1. Electro-Osmotic Pumping

- Electric field
- Electric double layer on wall of capillary
- Net motion of bulk fluid
- Characteristics
  - Flow controlled by electric potential
  - Pulseless pumping
  - Planar flow profile
  - No moving parts

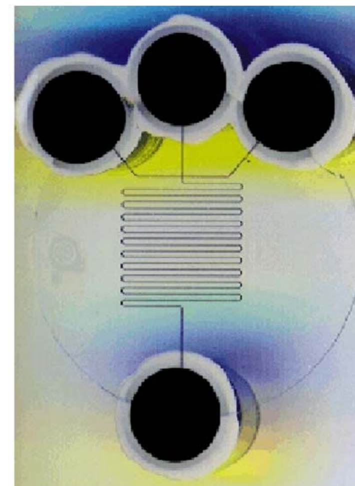


Fig. 6.25. Electroosmotic pumping in an electrophoresis chip developed at ORNL

6.2.1. Electro-Osmotic Pumping

- Speed of flow

$$v_\zeta = \mu_\zeta |\boldsymbol{E}|$$

$$\mu_\zeta = \frac{\varepsilon \varepsilon_0 \zeta}{\eta}$$

  - Speed on mm s^{-1} time scale
- Pump rate

$$I_V = 2\pi \int_0^{r_0} v_z(r) r \mathrm{d}r = \frac{\tilde{V} p \pi r_0^4}{8\eta l \tilde{l}} - k_\zeta \frac{\tilde{V} \varepsilon \varepsilon_0 \zeta U \pi r_0^2}{\eta l \tilde{l}}$$

  - Against back pressure *p*
  - Porosity
  - Tortuosity
  - Detailed treatment of potential

$$I_{V,\mathrm{max}} = k_\zeta \frac{\tilde{V} \varepsilon \varepsilon_0 \zeta U \pi r_0^2}{\eta \tilde{l} l}$$

$$k_\zeta = 1 - \frac{2 r_\mathrm{D} I_1(r_0/r_\mathrm{D})}{r_0 I_0(r_0/r_\mathrm{D})} \overset{r_0 \gg r_\mathrm{D}}{\approx} 1$$

6.2.1. Electro-Osmotic Pumping

- Equivalent pressure
  - Without back pressure
  - Equivalent flow rate of PDF

$$p_{\mathrm{equiv}} = k_\zeta \frac{8\tilde{V}\varepsilon\varepsilon_0\zeta U}{\tilde{l} r_0^2}$$

- Thermodynamic efficiency

$$\frac{\text{hydrodynamic power}}{\text{electric power}} = \frac{p I_V}{U I} \approx \frac{p I_V}{\sigma_E |\boldsymbol{E}|^2 V_{\mathrm{cap}}}$$

6.2.1. EOF-Induced Hydraulic Pumping

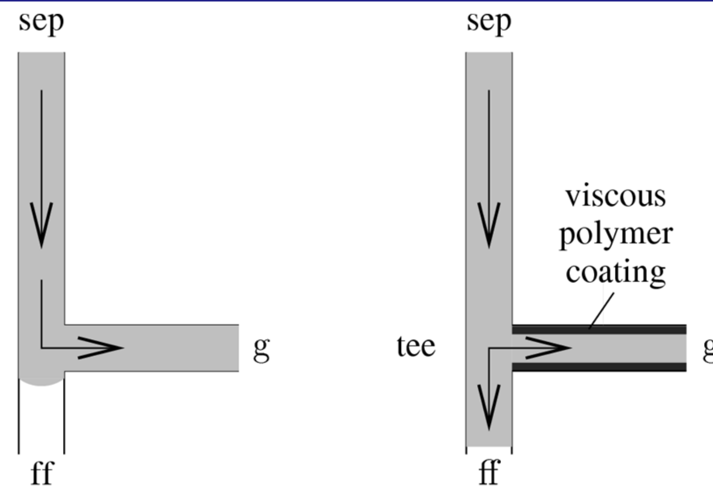


Fig. 6.26. Electroosmotically induced hydraulic pumping. In the uncoated tee intersection (left), an electric field draws the EOF from the high voltage on the top to the ground electrode (g). When the EOF is suppressed by a coating, a pressure is induced in the field-free channel (ff) as well (right)

- Tee section
- Potential drives flow from (sep) to (g)
- Coating of ground channel (g)
  - Continuity of mass
  - Pressure on liquid located in intersection
  - Pumping into free-floating channel (ff)

6.2. Electric-Field Mediated Pumping

1. Electro-Osmotic Pumping
2. Static Electrohydrodynamic Pumping
3. Traveling-Wave EHD Pumping

6.2.2. Static Electrohydrodynamic Pumping

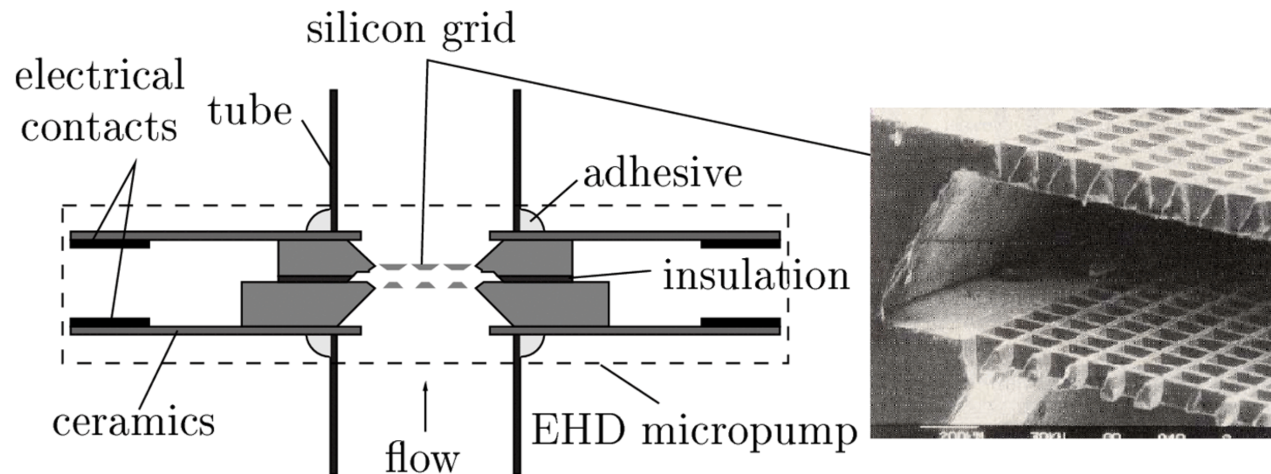


Fig. 6.27. Electrodynamic pump developed at FhG–IFT, Munich . Charge carriers in an insulating liquid are accelerated between the electrode grids

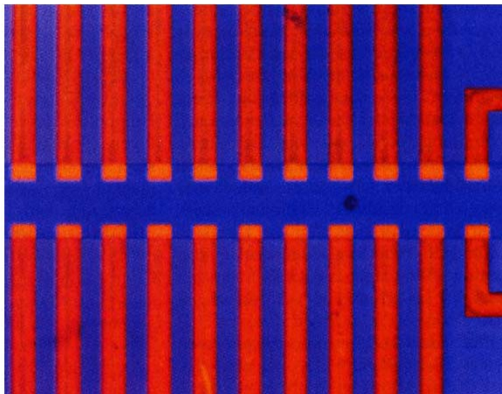
- Charge surplus in insulating liquid
- Pair of grid electrodes
- Coulomb force on bulk liquid in electric field
- Pump rate scales with field strength
- Direct conversion of electric into mechanical energy

6.2. Electric-Field Mediated Pumping

1. Electro-Osmotic Pumping
2. Static Electrohydrodynamic Pumping
3. Traveling-Wave EHD Pumping

6.2.3. Traveling-Wave EHD Pumping

- Gradient
  - Conductivity
  - Permittivity
- Traveling ***E***-field
- Net pumping action



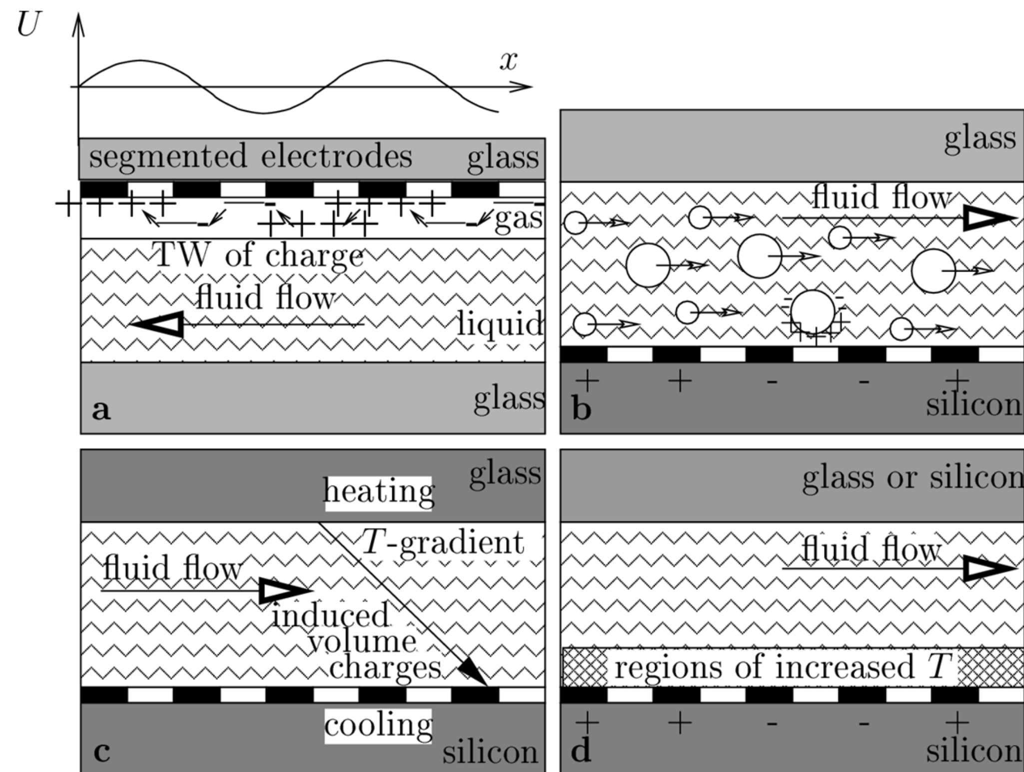


Fig. 6.28. Principles for generating travelling-wave EHD pumping

- •Layered fluids
- •Suspended particles
- •Externally generated fluid anisotropy
- •Self-generating fluid anisotropy

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous

6.2.3. Magneto-Hydrodynamic Pumping

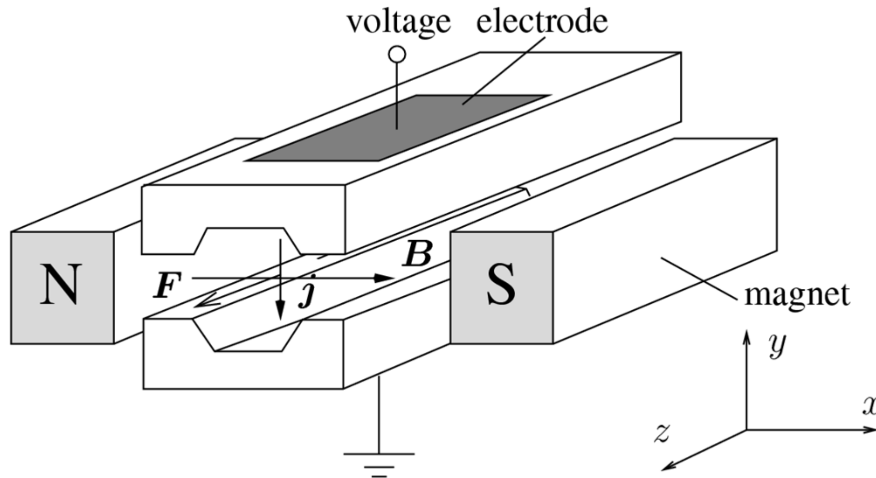


Fig. 6.30. Schematic of an MHD pump

Lorentz force

$$\boldsymbol{f} = \boldsymbol{j} \times \boldsymbol{B}$$

current

$$\boldsymbol{j} = \sigma_E \left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} \right)$$

- Pressure head

$$\Delta p = j_y B_x l$$

- Pump rate

$$I_V = j_y B_x \frac{\pi r_0^4}{8\eta}$$

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous

6.4. Acoustic Streaming

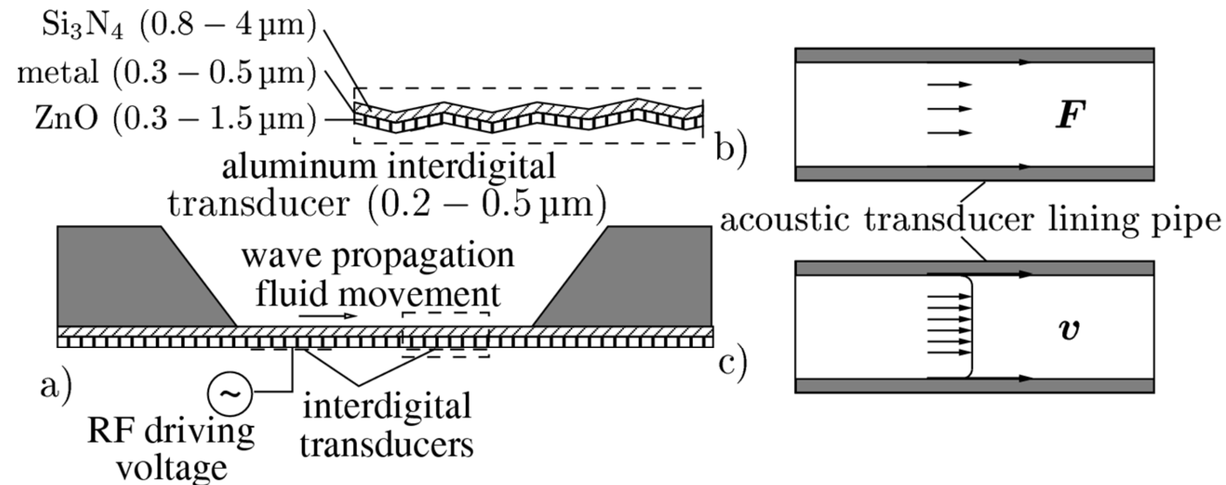


Fig. 6.31. Acoustic streaming device. a) cross-section displaying membrane composed of a silicon nitride, a metal ground plate and a piezoelectric zinc oxide layer. The membrane is actuated by interdigital electrodes. b) Streaming forces $\boldsymbol{F}$ generated by an axially directed, travelling acoustic wave grazing the walls of the tube. c) The resulting stationary velocity distribution $\boldsymbol{v}$

- Characteristics
  - Active-channel technique
  - Valve-less
  - Ultrasonic
- Momentum transfer from channel wall to fluid

6.4. Acoustic Streaming

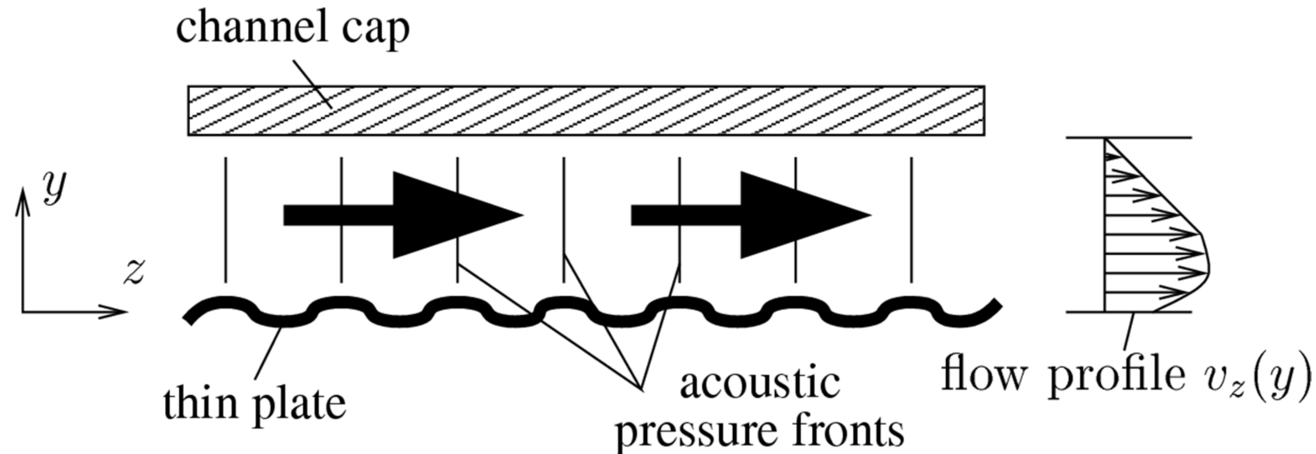


Fig. 6.32. Acoustic streaming by flexural-plate induced sound waves

- Flexural plate wave (FPW)
  - Traveling mechanical wave
  - Grazing channel wall
- Interdigital transducer
  - Thickness of few µm
  - Spacing of electrodes by about 100 µm
  - Frequencies of some MHz

6.4. Acoustic Streaming

- Velocity profile

$$v_z(y) = v_{\max} \exp\left\{-\left(\frac{y}{l_{\text{evan}}}\right)\right\}$$

  - Evanescent length

$$l_{\text{evan}} = \frac{\lambda}{2\pi\sqrt{1-(c_{\text{FPW}}/c_{\kappa})}}$$

  - Flow velocities ver small for $y > l_{evan}$
- For $y > l_{evan}$:
  - Flow rate widely independent of channel height

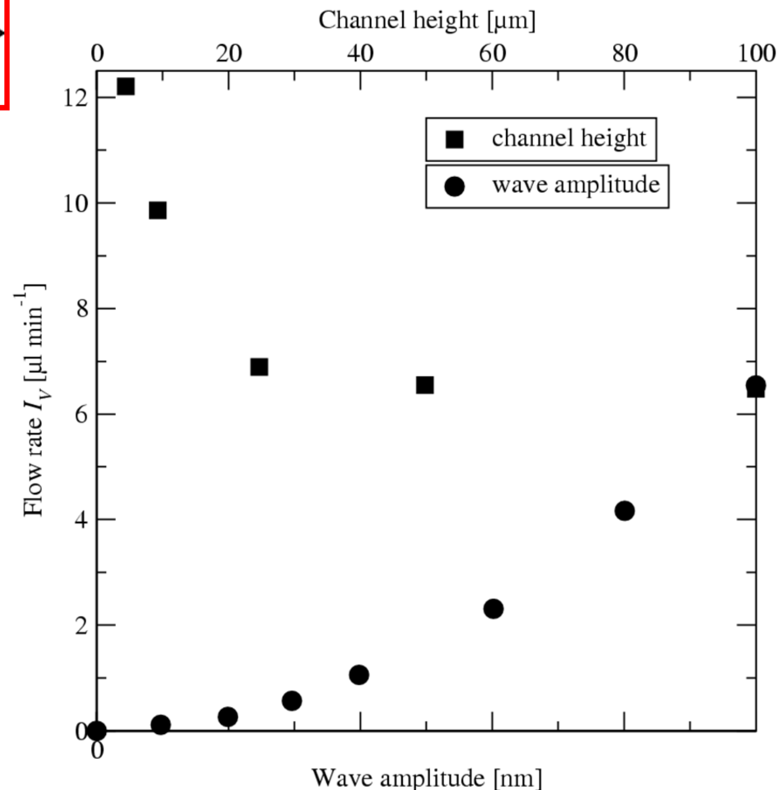


Fig. 6.33. Performance of acoustic streaming as a function of actuation amplitude and the channel height

6.4. Advalytix

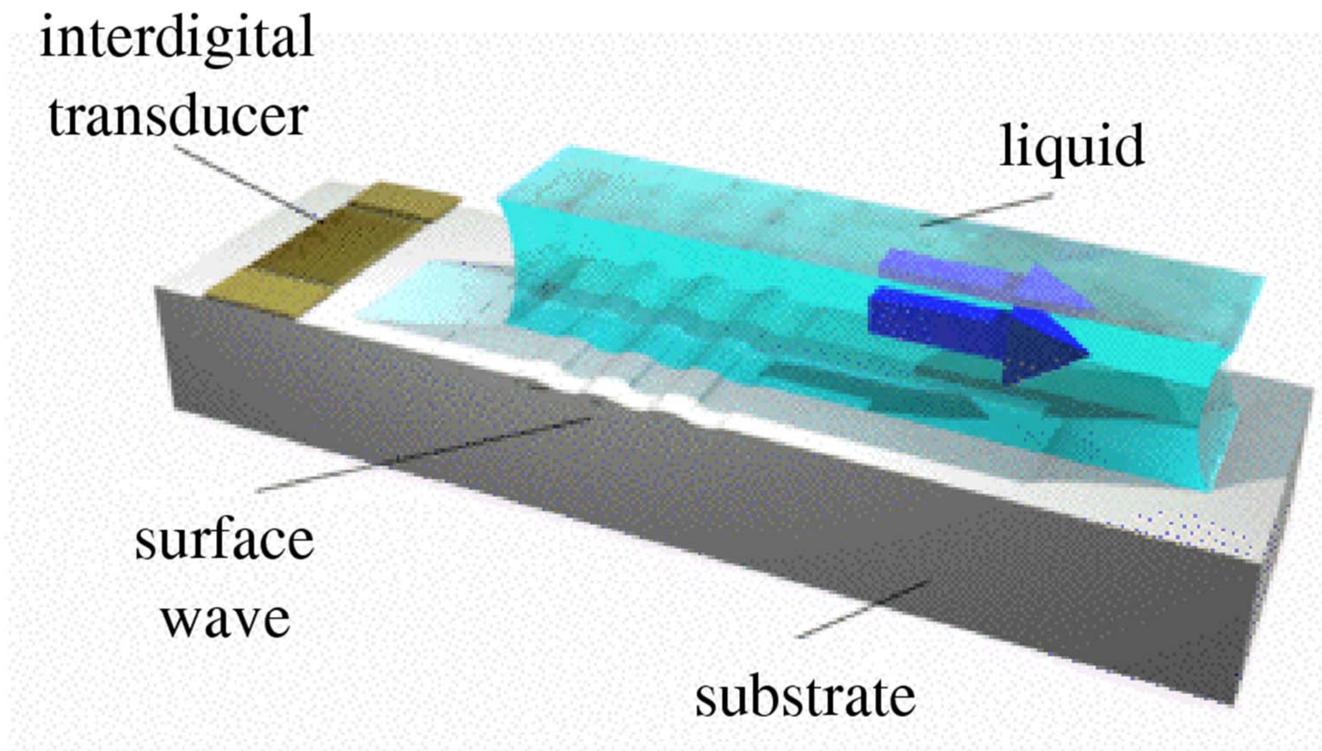


Fig. 12.19. Pumping by surface acoustic waves as a driving element for a microfluidic processor

- Flow control by surface acoustic waves (SAWs)

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous

6.5. Pumping by Interfacial Tension

- Capillary effects
- Variations in surface tension

$$\sigma = \frac{F_\sigma}{l}$$

- Variations in contact angle

$$p_\Theta = \frac{2\sigma}{r}\cos\Theta$$

- Contact between different phases
  - Transport of discrete sampels
    - Plugs
    - Droplets

6.5. Pumping by Interfacial Tension

1. Thermocapillary Pumping
2. TCF of Droplets on Free Surfaces
3. Electrowetting
4. Electrocapillary Pumping

6.5.1. Thermocapillary Pumping

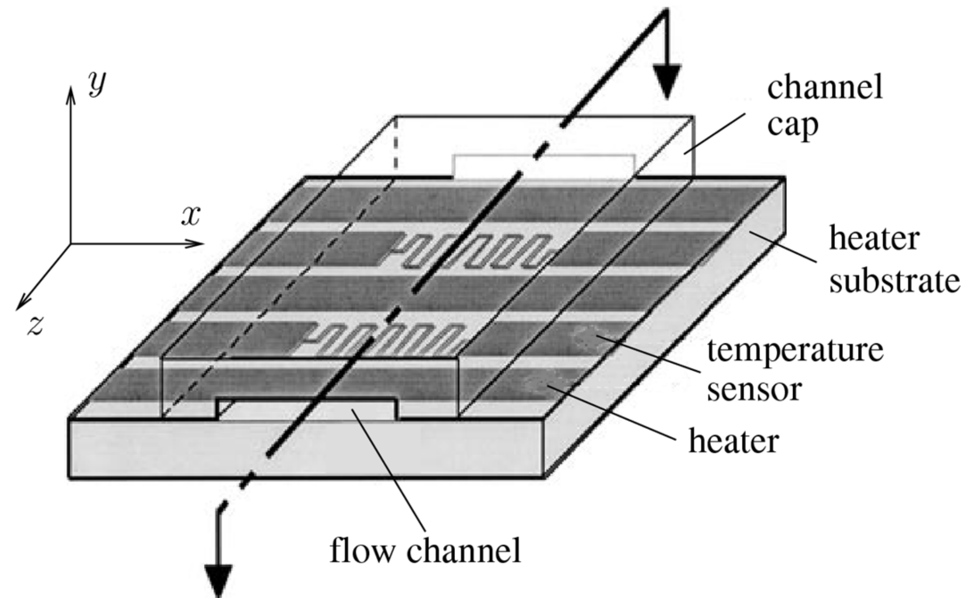


Fig. 6.34. Schematic of a thermocapillary pump

$$p_{\text{int}} = p_0 - \underbrace{\frac{k_{\text{geom}}\sigma}{d}\cos\Theta}_{p_\Theta}$$

$$\bar{v}_{\text{TCF}} = \frac{dk_{\text{geom}}k'_\sigma \cos\Theta^*_{\text{rec}}}{lk_{\text{shape}}\eta} \cdot \left[T_{\text{adv}} - T_{\text{rec}} - \left(\frac{k_\sigma}{k'_\sigma} - T_{\text{adv}}\right)\left(1 - \frac{\cos\Theta^*_{\text{adv}}}{\cos\Theta^*_{\text{rec}}}\right)\right]$$

- Thermocapillary flow (TCF)
  - Difference in surface tension
  - Thermal gradient
  - Difference in internal pressures at menisci of liquid plug
- Implementation by precisely controlled heaters

6.5. Pumping by Interfacial Tension

1. Thermocapillary Pumping
2. TCF of Droplets on Free Surfaces
3. Electrowetting
4. Electrocapillary Pumping

6.5.2. TCF of Droplets on Free Surfaces

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}\left[\frac{\mathrm{d}\sigma}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}x}\frac{h^2}{2\eta} + \frac{h^3}{3\eta}\frac{\partial}{\partial x}(\sigma\nabla^2 h)\right] + \frac{\partial}{\partial y}\left[\frac{h^3}{3\eta}\frac{\partial}{\partial y}(\sigma\nabla^2 h)\right] = 0$$

- TCF based delivery of droplets on free surface
  - Chemically patterned substrate
  - Hydrophilic stripes
- Equation of motion
  - Direction of flow x
  - Lateral coordinate y
  - Height profile $h(x)$
  - Temperature profile $T(x)$
  - Width of stripes w
- Flow speed of 600 μm s^{-1}
  - Viscosity of 5 mPa s
  - Width of 800 μm
  - Temperature gradient of 14.4 K cm^{-1}

6.5. Pumping by Interfacial Tension

1. Thermocapillary Pumping
2. TCF of Droplets on Free Surfaces
3. Electrowetting
4. Electrocapillary Pumping

6.5.3. Electrowetting

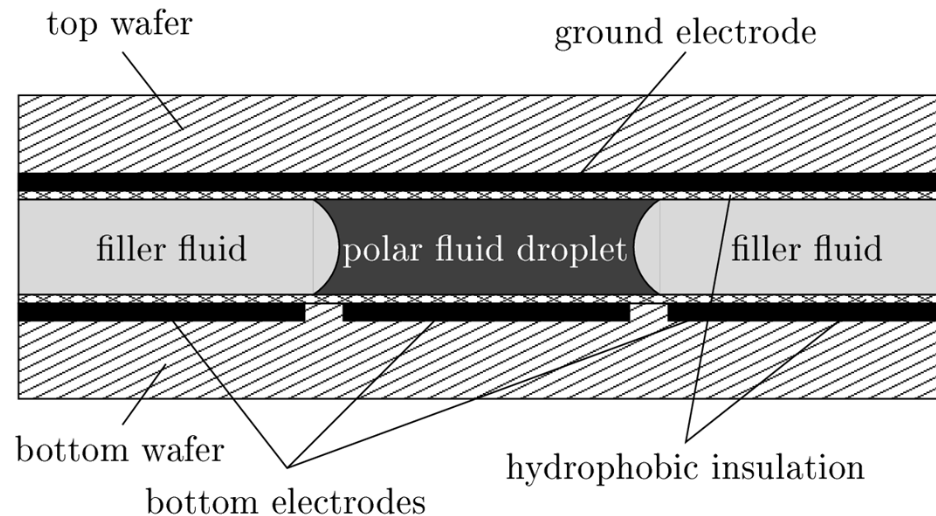


Fig. 6.35. Principle of electrowetting. By applying a voltage between adjacent electrodes, the surface becomes hydrophilic and a polar liquid droplet is drawn in the space between them

- Gradient in local cohesion energy
  - Controlled by voltage on electrodes
  - Voltage-induced surface charges
- Gradient in cohesion energy
- Net capillary pressure
- Pumping

$$\sigma_q(U) = \frac{\varepsilon\varepsilon_0}{d} U$$

$$\Delta\sigma = \frac{d\sigma_q^2}{2\varepsilon\varepsilon_0} \overset{\text{Gauss}}{=} \frac{\varepsilon\varepsilon_0}{2d} U^2$$

6.5. Pumping by Interfacial Tension

1. Thermocapillary Pumping
2. TCF of Droplets on Free Surfaces
3. Electrowetting
4. Electrocapillary Pumping

6.5.4. Electrocapillary Pumping

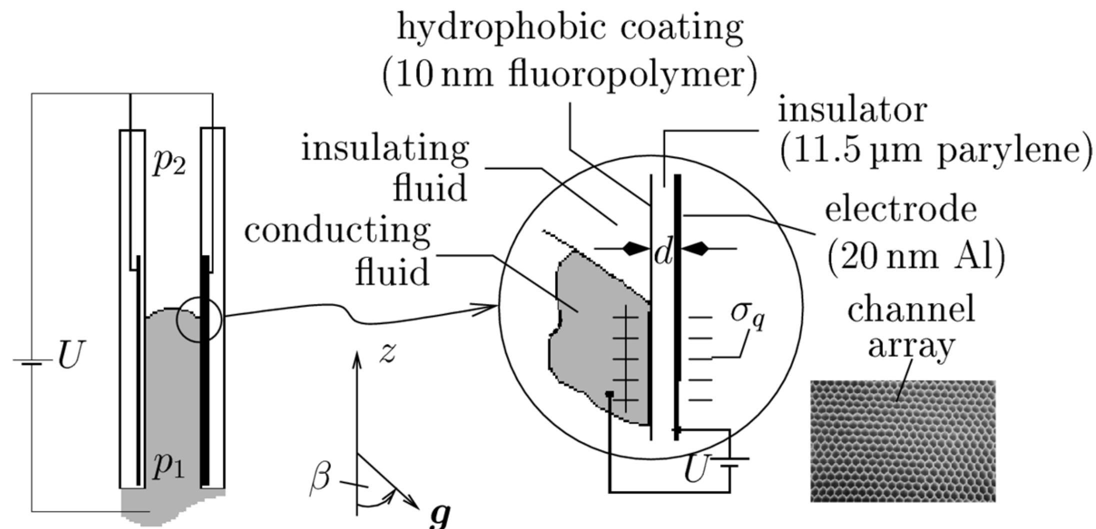


Fig. 6.36. Schematic of electrocapillary pumping

- Control of contact angle by voltage
- Array of 1000s of hydrophobically coated 3D microchannels
- Electrostatic control of interfacial tension
  - Induced image charges
  - Reversible fluid displacement
- Electrocapillary pressure

$$p_{\mathrm{ECP}}(U) = \frac{\Delta\sigma l}{A} = \underbrace{\frac{l}{A}}_{\text{geometry}} \underbrace{\frac{\varepsilon\varepsilon_0}{2d}}_{\text{wall}} U^2$$

6. Micropumps

1. Microdisplacement Pumps
2. Electric-Field Mediated Pumping
3. Magneto-Hydrodynamic Pumping
4. Acoustic Streaming
5. Pumping by Interfacial Tension
6. Miscellaneous

6.6. Miscellaneous

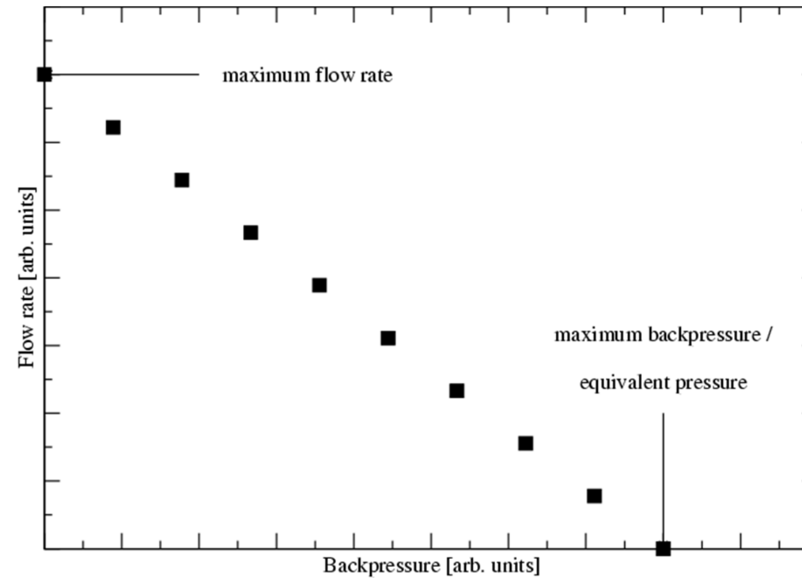


Fig. 6.37. Working diagram of a pump

- Working diagram
  - Flow rate
  - Backpressure
- Maximum flow rate ($p = 0$)
- Maximum backpressure ($I = 0$)
- Working point

6.6. Miscellaneous

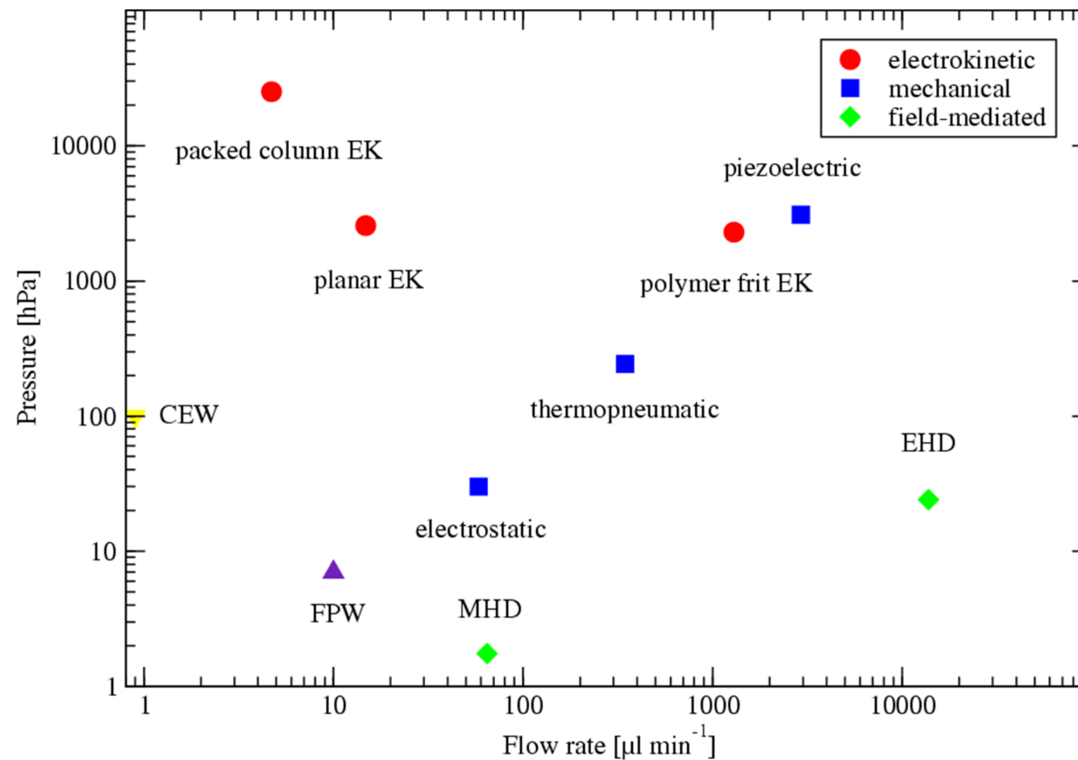


Fig. 6.38. Flow rates and pressures generated by various pumping principles

- Comparison of pump principles
  - Maximum backpressure
  - Maximum flow rate