MEMS Applications in Propulsion: Problems and Possibilities

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Brief History

- MEMS (Micro electrical mechanical systems) or Microsystems (in use in Europe) is based on the use of microelectronic fabrication methods to make very small mechanical devices.
- MEMS devices began to emerge in the early 1980's and most early successes were sensors.
- Application areas are diverse and include sensors, fluid control and manipulation, optics, displays, printing, electrical switching, chemical analysis, biochemical fluid processing, precise motion control and data storage.

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Propulsion Applications

- There have been three major areas of attempted application in propulsion:
  - – Micro rocket propulsion systems
  - – Micro reciprocating/rotating engine systems
  - – Fuel Injection

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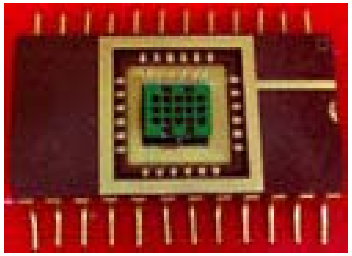
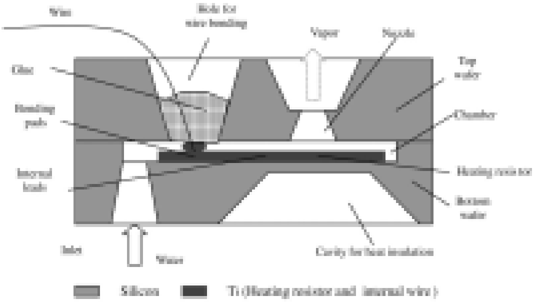
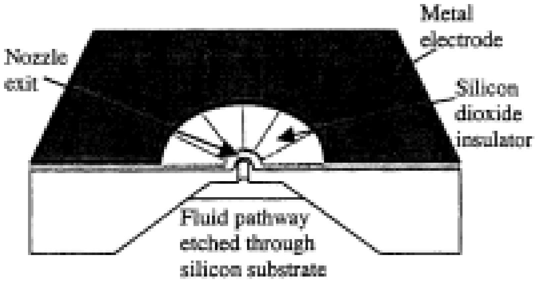
Rocket Propulsion



- Liquid
- Solid
- Gas
- Electric





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Reciprocating/Rotating Engines

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- Free piston engine
  - Honeywell
  - Georgia Tech
- Rotary engine
  - UC Berkeley
- Gas turbine
  - MIT

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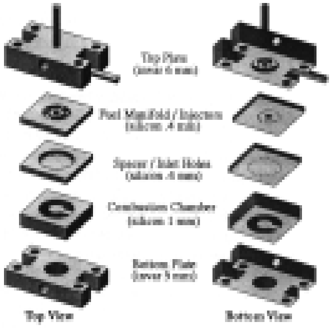

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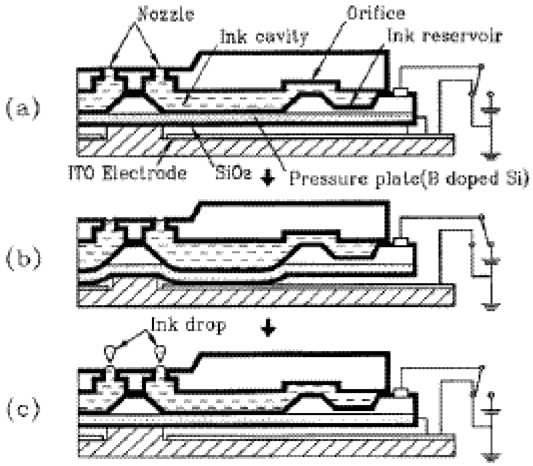
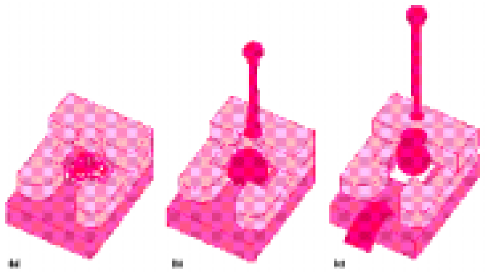
Fuel Injection

- Injet Based Concepts
  - Ho was the first to explore.





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Where Are (The Royal) We?

- We have made a lot of little gadgets that don’t work in the real world!
- Why?
  - Poorly understood physics
  - Material compatibility issues
  - Fabrication difficulties, including dimensional stability
  - Packaging difficulties
  - Reliability

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Physics

- Solid Mechanics
  - Do small scale systems behave like macro systems? Deformations/dynamics?
    - i.e. Can I use Roark?
- Fluid Mechanics
  - Boundary conditions/Surface effects
    - i.e. Is there slip?
- Electrostatics
  - Do continuum approaches work?
  - If aspect ratio large can I use simple theory?

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Material Compatibility

- Propulsion applications are often exposed to strong solvents, high temperatures and oxidizing atmospheres.
- Silicon, the master material of MEMS, is not so great in these environments.
- Adhesives are equally challenged.

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Fabrication/Packaging

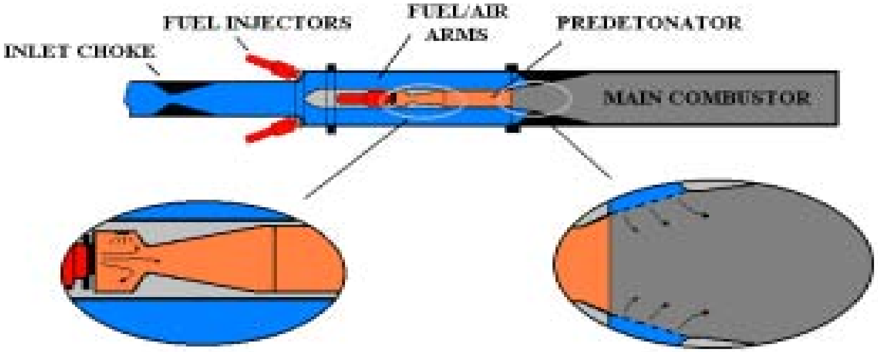
- Don’t let anyone tell you otherwise, fabrication and packaging are Black Magic!
- All steps are critical. Small differences in etching time, sputtering voltages, adhesive composition etc. can have profound effects.
- Any wise person will keep fabrication and packaging details as trade secrets!

Reliability

- This is a major issue for developing MEMS devices.
- Even raw supplies like wafers are often delivered with flaws or large variability in properties.
- Fabrication sensitive to procedures.

Our Case Example

- Goal - Develop a fuel injector in support of Navy air breathing PDE.
- Base design on inkjet technology.



$\Delta p < 50$ psid

SMD < 10 um

$T_{MAX} = 500$ F

100 Hz control authority

$\phi_f = 0.5$ lbm/s

No-drip

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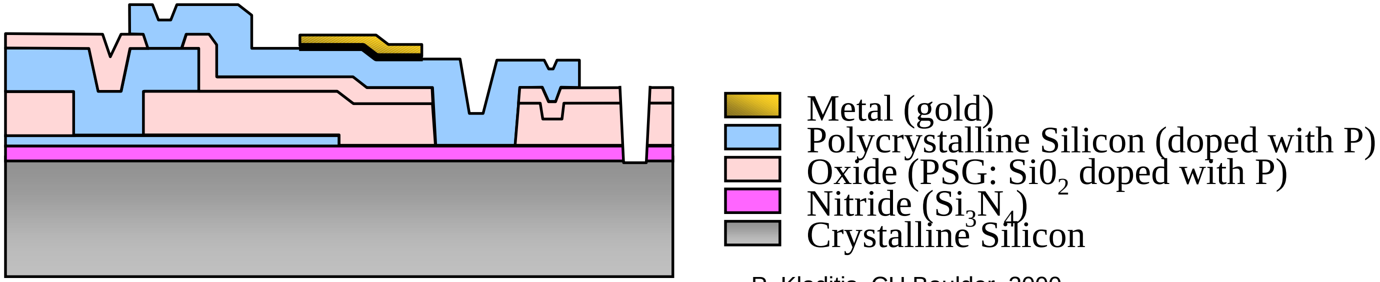
Technical Challenges

- Adapting inkjet technologies
  - 10µm SMD or less
  - high mass flow
  - JP-10 fuel compatibility
- Limitations of MEMS fabrication processes



P. Kladitis, CU Boulder, 2000

- Assembly/ Bonding
- Reliability and endurance (10^8 cycles)

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Meeting the Challenges

- Physics - Analytical and multi-physics numerical modeling.
- Materials - Experiments to establish compatibility.
- Fabrication and Packaging - Simple designs and find some good people.
- Time will tell!
  - i.e make and test.

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Early Assessment

- Are small droplets possible?
- Can conventional inkjet technology be used?
- What materials are compatible with JP-10? Are we left with materials that can be fabricated?
- What is most suitable configuration?

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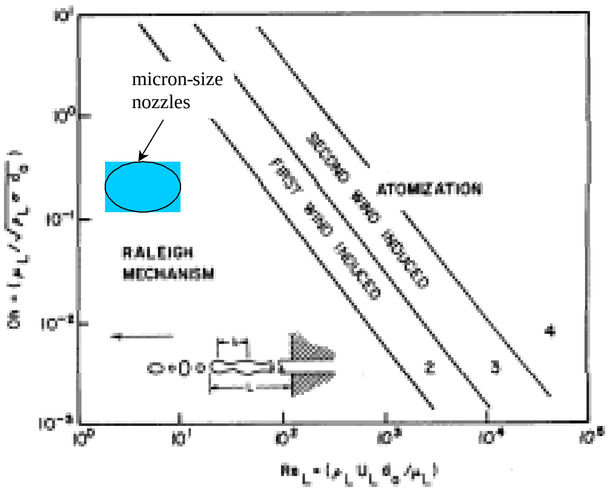
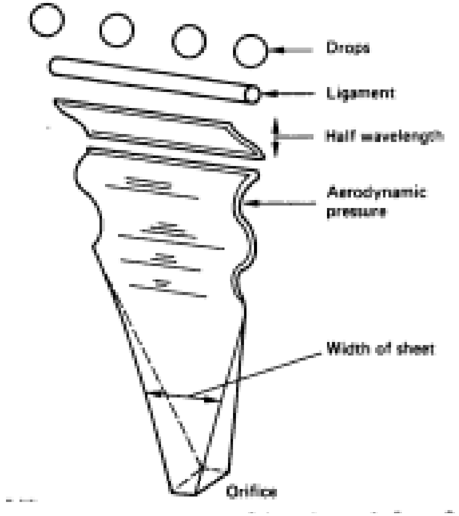
Small Drops?

JP-10 fluid properties not that dissimilar from inks and water.



micron-size nozzles



If the holes or slots are small enough, the droplets will be small enough

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Conventional Technology

- Early tests showed that adhesive and packaging materials are not compatible with JP-10.
- Not all actuation methods suitable. Thermal actuation, for example, requires far too much power.
- Fluidics not designed to operate with significant pressure drop.

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Material Compatibility

- There are materials that can handle JP-10.
- Thermal compatibility may be an issue, however, materials like SiN and SiCN can be used along with pure metals.
- There are adhesives and packaging materials that are tolerant to JP-10 and can handle thermal environment.

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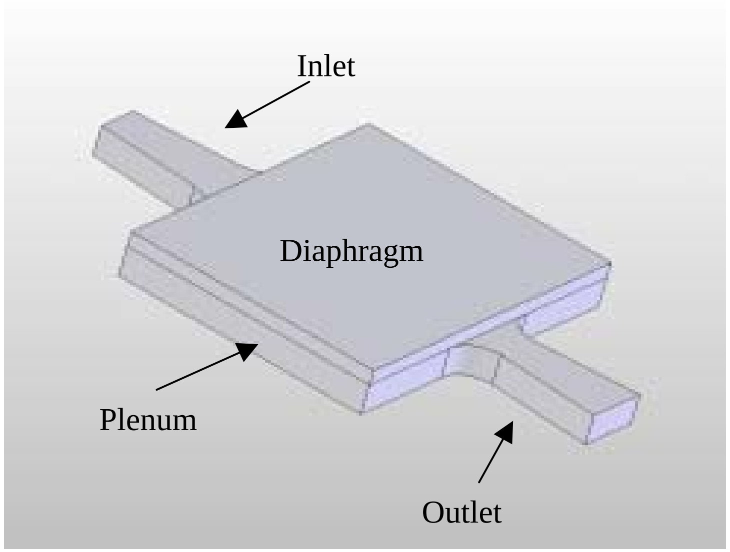
The Basic Design

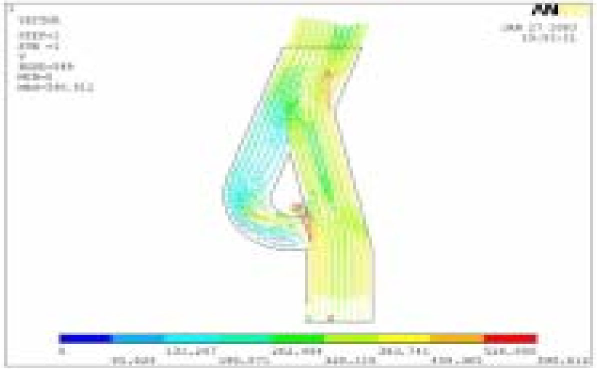
- Electrostatically actuated diaphragm pump with passive valves:

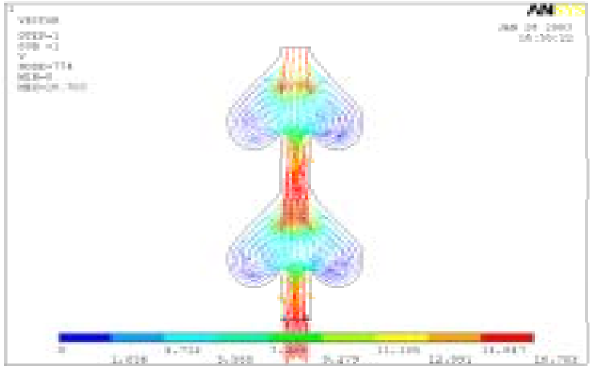
  - Electrostatic for high displacement/low power.
  - Passive valves for simplicity.



What is Important?

- Want high pump efficiency: $\eta = \dfrac{Q_{net}}{Q_{ideal}}$
- Valves are critical





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Analysis

- Electrostatic Force

$$P = \frac{\varepsilon_0 V_{app}^2}{g^2}$$

- Static Deflection

$$y_{\max} = \frac{3P(m^2 - 1)L^4}{16\pi E m^2 t}$$

- Natural Frequency

$$f_1 = \frac{13.49}{2\pi L^2}\sqrt{\frac{D}{\rho t}} \qquad D = \frac{Et^3}{12(1-\nu^2)} \qquad \frac{f_{1\,fluid}}{f_{1vac}} = \frac{1}{\left(1 + \frac{A_p}{M_p}\right)^{1/2}}$$

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Analysis

- Pressure Drop (Nozzle/Diffuser)

$$\Delta p_{N,D} = K_{N,D}\rho\frac{V^2}{2} \qquad \eta = \frac{K_N}{K_D}$$

- Net Flow Rate

$$Q_p = \frac{V_0\omega}{\pi}\left(\frac{\eta^{1/2}-1}{\eta^{1/2}+1}\right)$$

- Question: How well do these work?

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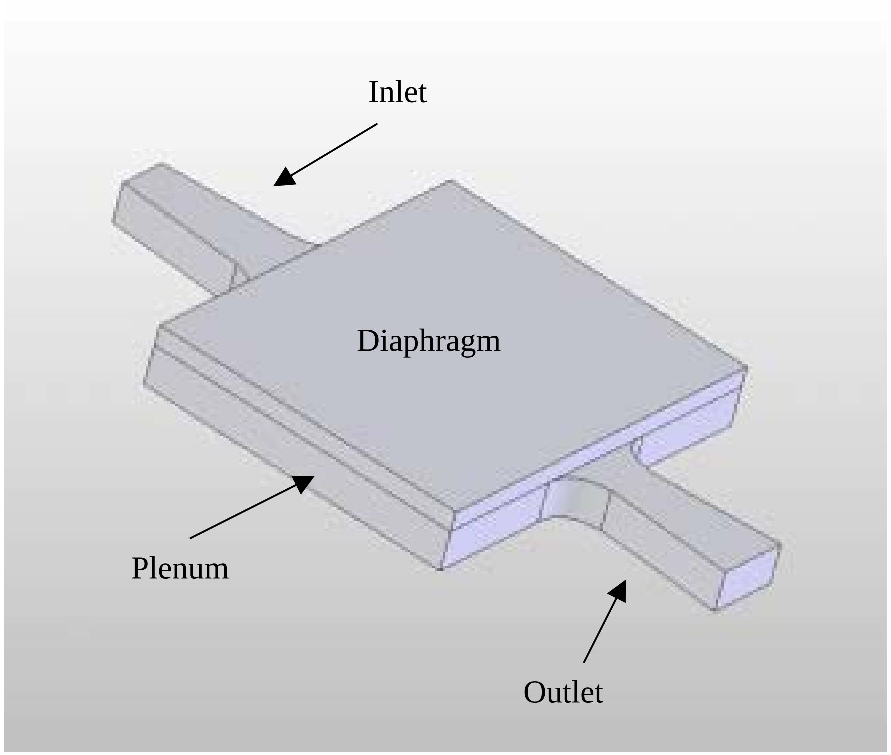
Numerical Methods

- ANSYS Multi-physics finite element code is used to carry out simulation:
  - Weak sequential algorithm to couple structural and fluid dynamics,
  - Arbitrary Langrangian-Eulerian formulation solves for the fluid flow with moving boundaries,
  - Fluid dynamics is solved using ANSYS FLOTRAN (Flow treated as incompressible.)

Example
Time Dependent 3-D Simulation



$L_{diaph} = 1\ \text{mm}$

$t_{diaph} = 50\ \mu\text{m}$

$t_{plenum} = 100\ \mu\text{m}$

$t_{passages} = 100\ \mu\text{m}$

$L_{passages} = 0.33\ \text{mm}$

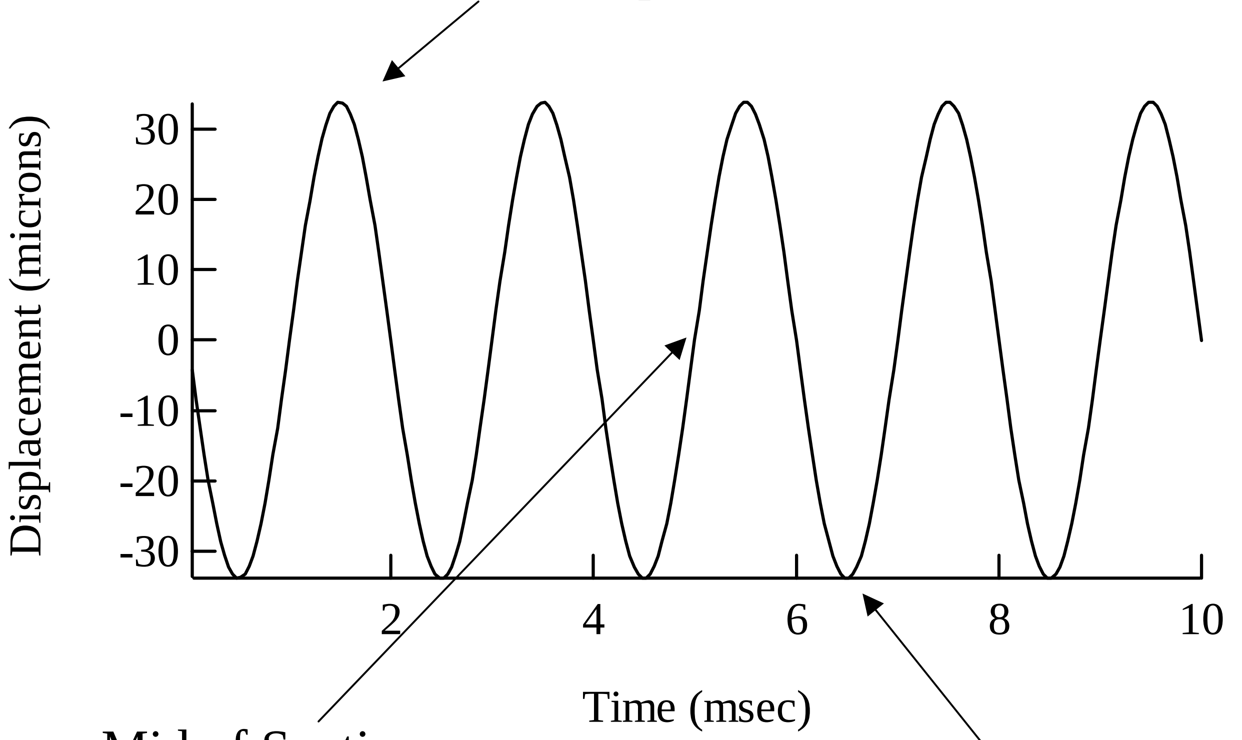
$W_{inpassages} = 66.7\ \mu\text{m}$

$\alpha_{valve} = 5$ degrees

Simulation uses vertical symmetry plane

Calculations for 100-900 Hz

Displacement
500 Hz



Top of Suction Stroke

Mid of Suction Stroke

Bottom of Pressure Stroke

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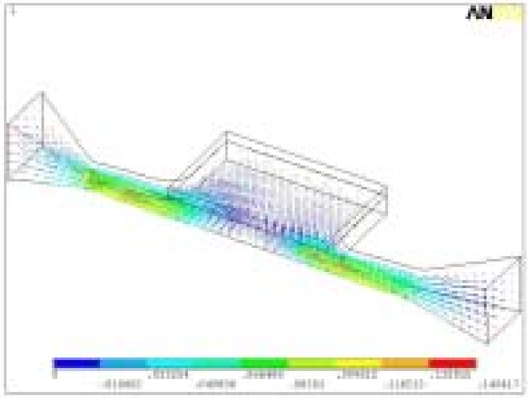
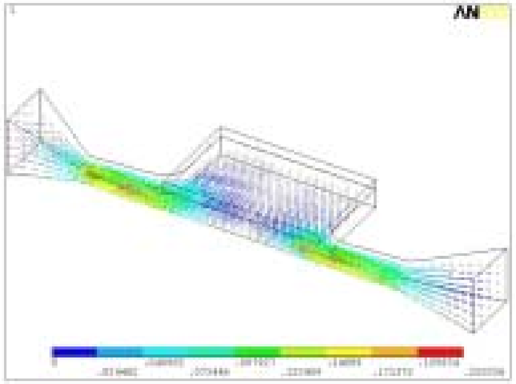
Flow Field

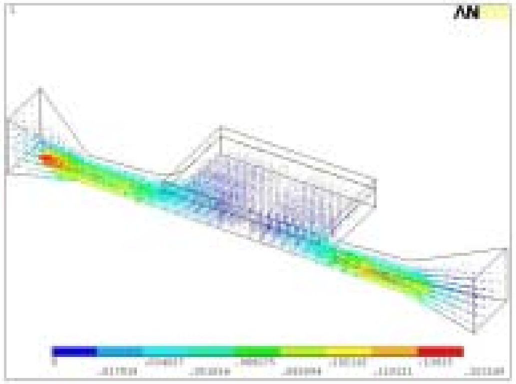


Top of Suction
Stroke

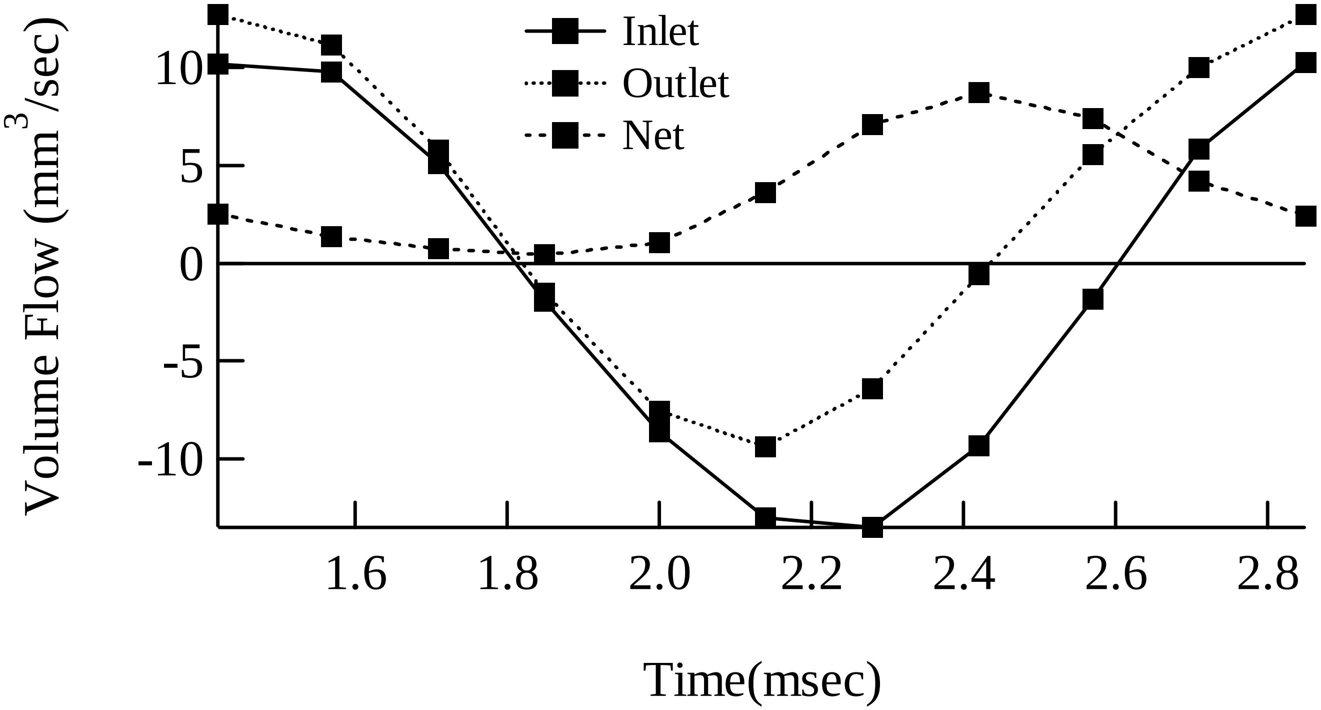


Mid of Suction
Stroke

Bottom of Pressure
Stroke



Flow Rates
700 Hz



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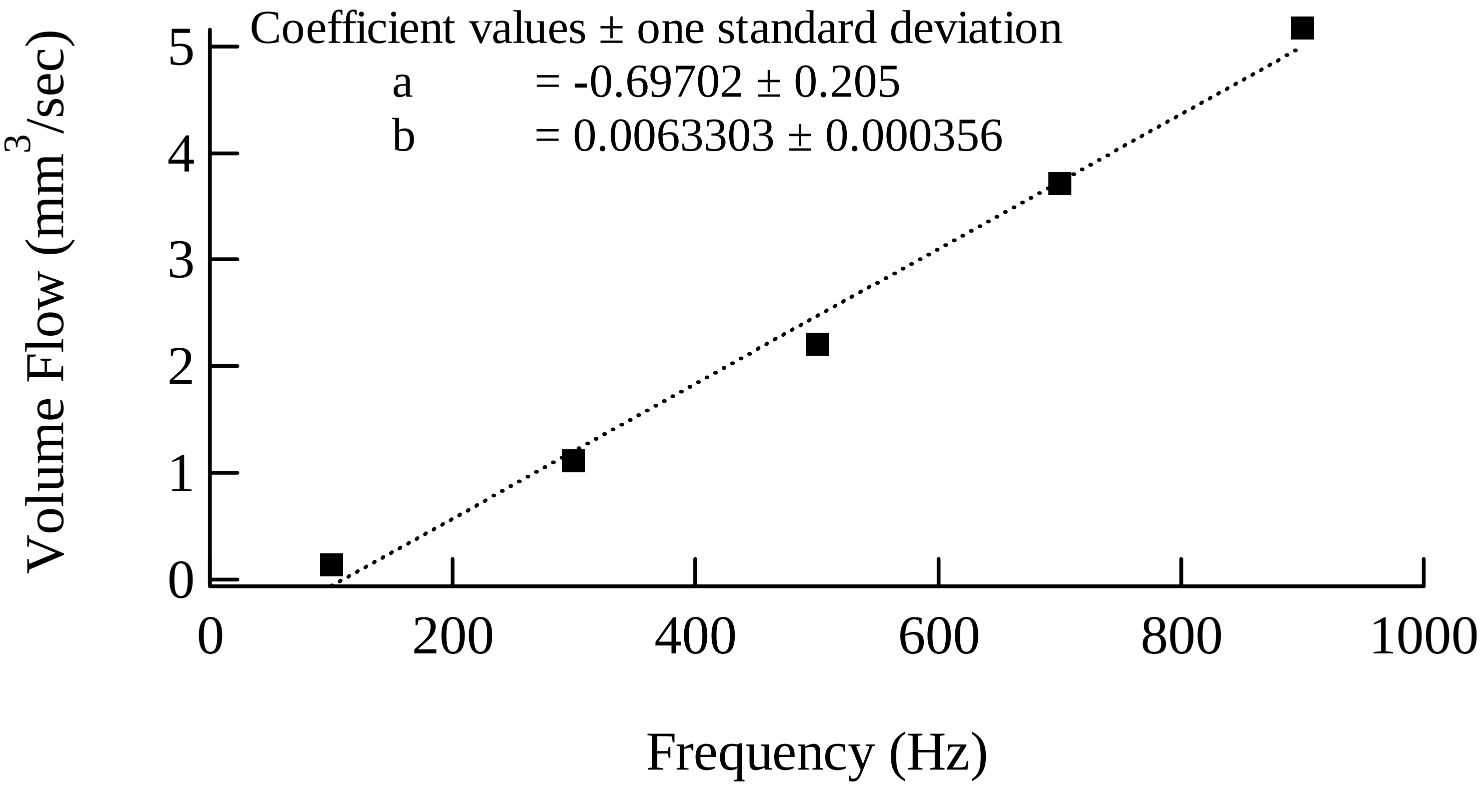
Net Flow Rate



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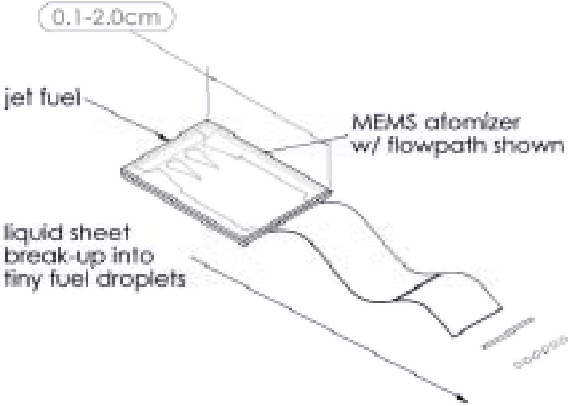
Further Design and Physics Issues

- Physics
  - Nonlinear diaphragm behavior.
  - Accuracy of simple electrostatic models.
- Design
  - Maximize flow rate.
    - Slot designs
    - Larger size



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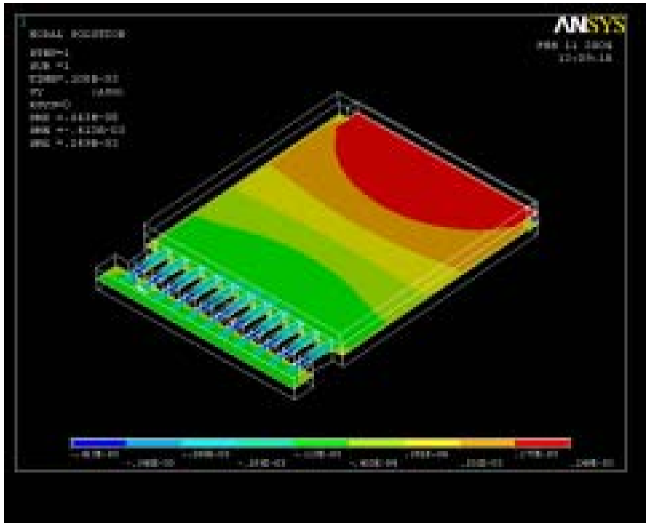
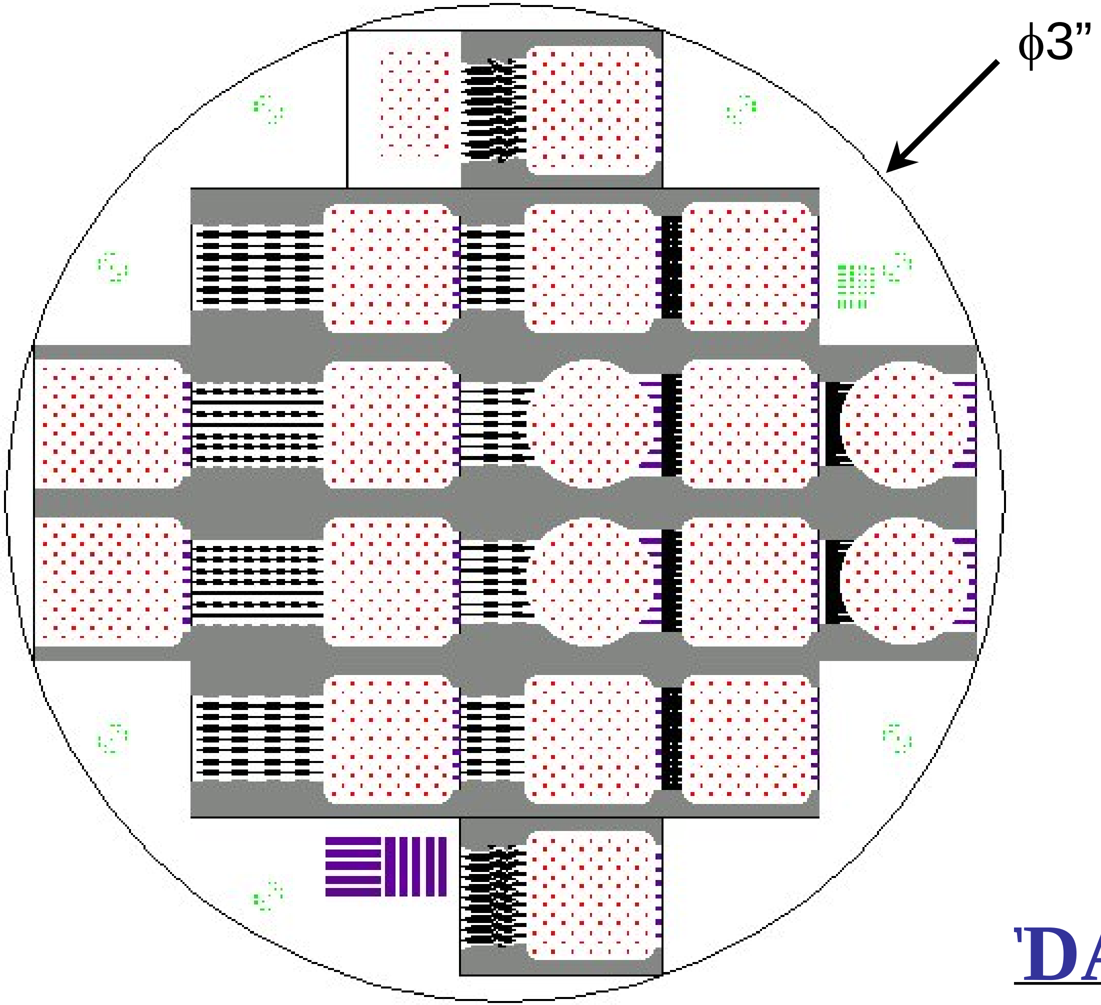
Full Simulations of 1 cm Devices

- Full manifolding
- Different valve configurations
- Non-linear where required
- Electrostatics



Fabrication

Layered design with diaphragm sandwiched between two similar substrates



Packaging

Summary

- MEMS devices show great promise.
- Task is to translate promise into practice.
- Must consider larger range of problems than in conventional technology.

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