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Simulations of Micropumps Based on Tilted Flexible Structures

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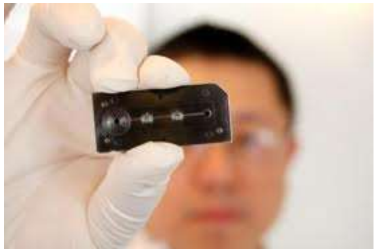
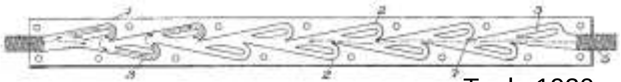
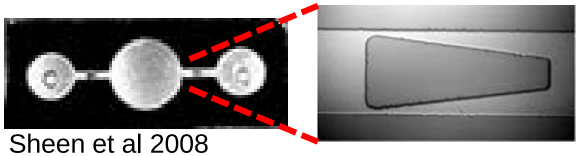
Introduction

- Micropumps are key components for
  - Biological fluid handling (PCR, mTAS)
  - Microelectronic cooling
- Small size:
  - Reduce sample & reagent volumes
  - Parallel and integrated operations
  - Desire size ~ volume dispensed
- Valveless micropumps
  - Avoid clogging for particle flows
  - Gentle on biological material
  - Many designs fail in viscous regime

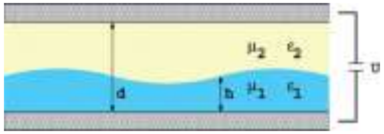




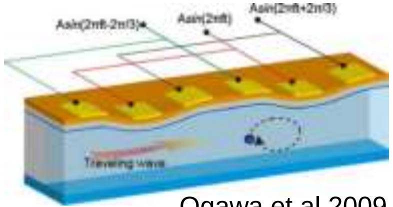
Tesla 1920



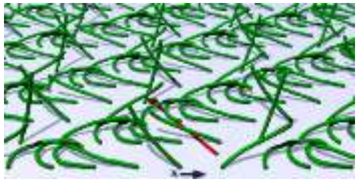
Sheen et al 2008



John et al 2008



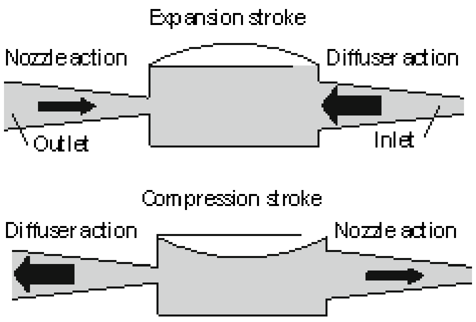
Ogawa et al 2009



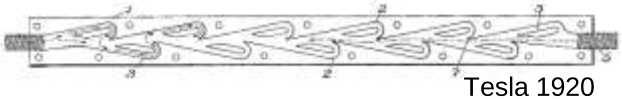
Osterman et al 2011

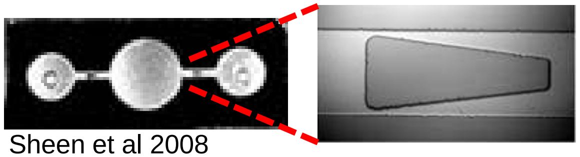
Valveless Pumps: Rectifiers

- Pumps based on flow rectification
  - Flow actuation provided by oscillating piston or membrane
  - Resistance to flow is direction dependent
- Early example includes the work of Tesla
- Recent examples exist at the microscale (e.g. Sheen *et al.*)
- Flow rectification for most designs vanishes as the flow becomes viscous, slow, and as the scale is reduced, due to the principle of reversibility



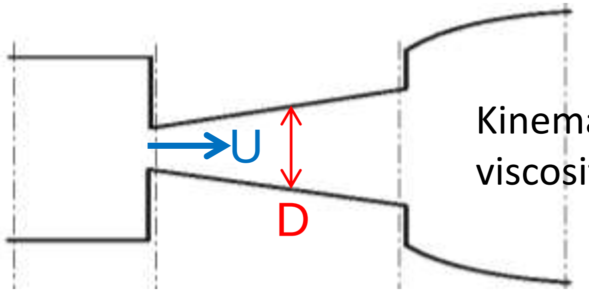
Iverson et al 2008


Tesla 1920


Sheen et al 2008

Pumping at Low Reynolds Number

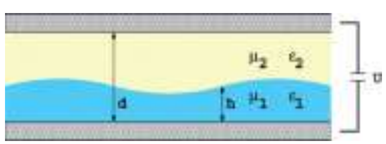
Nozzle-Diffuser



Kinematic viscosity ν

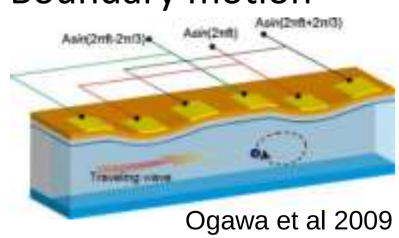
- For low flow rates, viscous fluids, or small length scale, Reynolds number UD/ν is small
- Most rectifiers (e.g. nozzle-diffuser), though simple, operate at Re > 200
- As Re decreases (<1), flow in nozzle and diffuser direction become identical by the principle of reversibility, so **no net pumping**
- **Example solutions**: acoustic (high-frequency), asymmetric motion (2-fluid, boundary, active cilia), electrokinetic, etc.

2-fluid



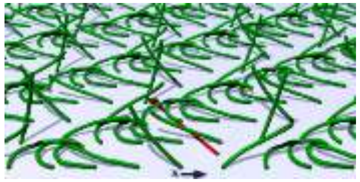
John et al 2008

Boundary motion



Ogawa et al 2009

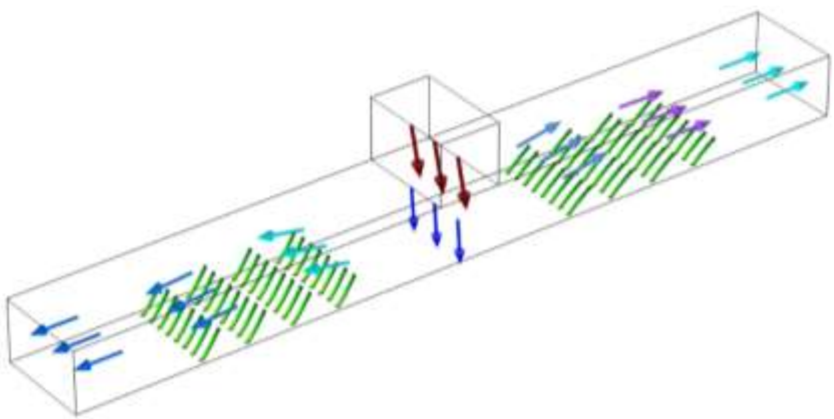
Active cilia



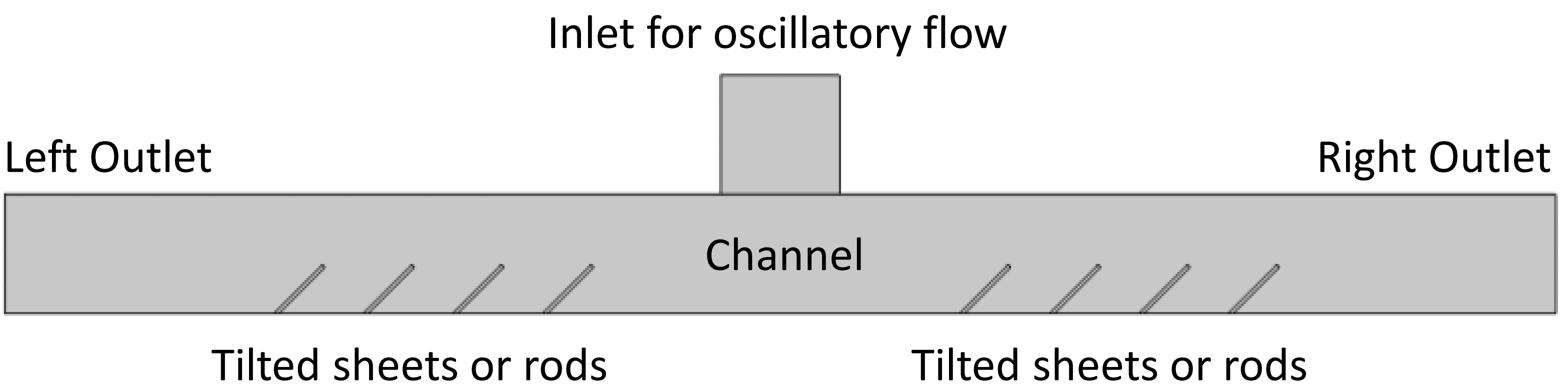
Osterman et al 2011

Outline

- We propose a new pump design based on rectifiers (e.g. Tesla) and tilted fibers (passive cilia)
- We have used COMSOL Multiphysics to validate the design over a range of flow rates, viscosities, and design parameters
- The technical challenge was to maintain mesh quality using custom prescribed mesh displacements on internal guide surfaces



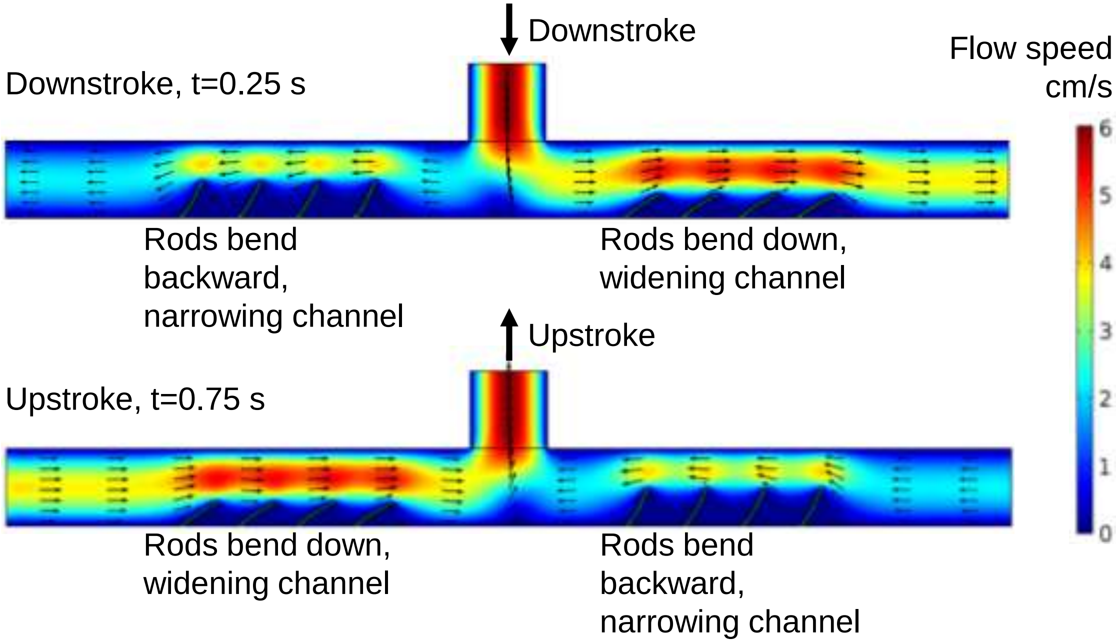
Micropump Design



Micropump design consists of:

- a source for oscillatory fluidic motion, e.g. a piston
- a channel lined with tilted flexible rods or sheets to provide rectification

Physical Picture

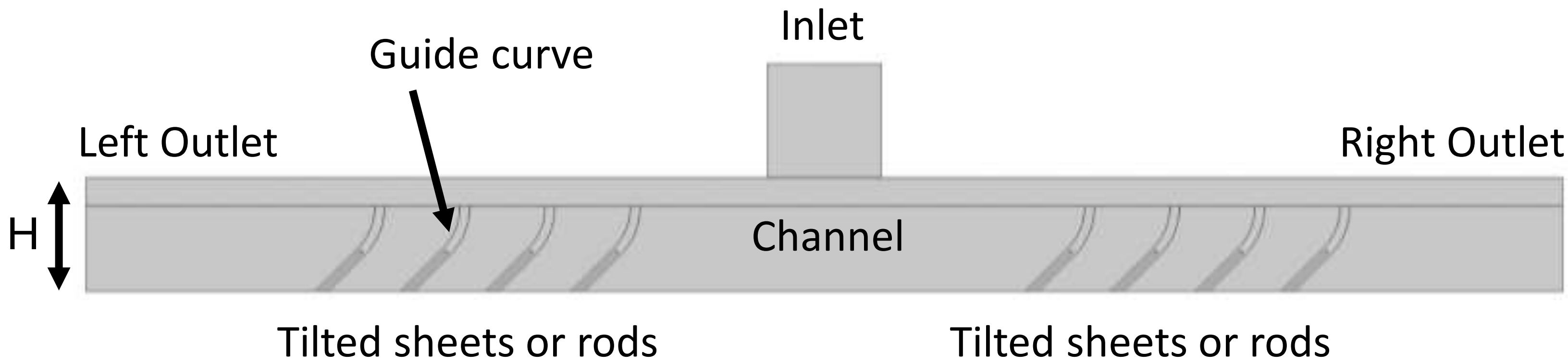


When flow is against the rods, they bend backward, narrowing the channel and increasing flow resistance.

When flow is in the direction of rod tilt, the rods bend forward, widening the channel and decreasing flow resistance.

By placing titled rods on either side of the inlet, the bending happens on opposite sides out of phase, thereby pumping net fluid to the right.

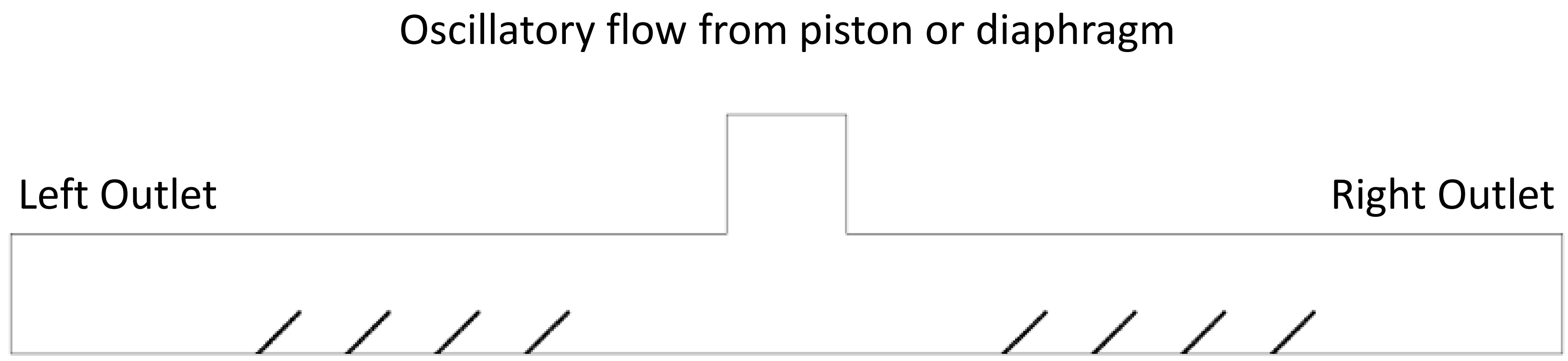
2D Model Setup



COMSOL Fluid-Structure Interaction (FSI) interface employed

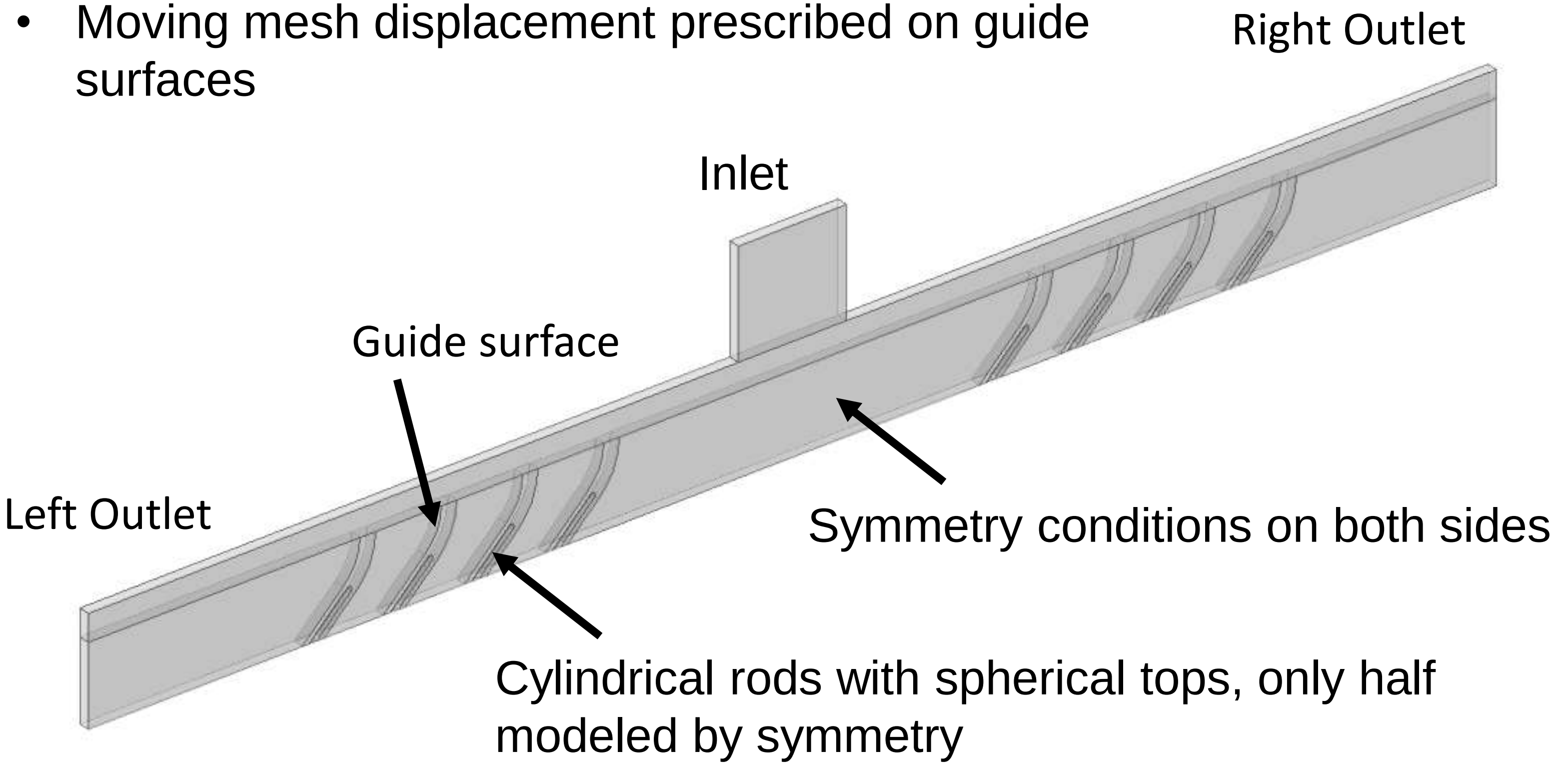
- Navier-Stokes equations model the laminar flow in the channel
- Sheet/rods modeled as linear elastic material
- Moving mesh displacement prescribed on guide curves adjacent to each tilted element, maintains mesh quality even with large displacements
- Inlet velocity parabolic in space, sinusoidal in time

2D Model Pumping Simulation

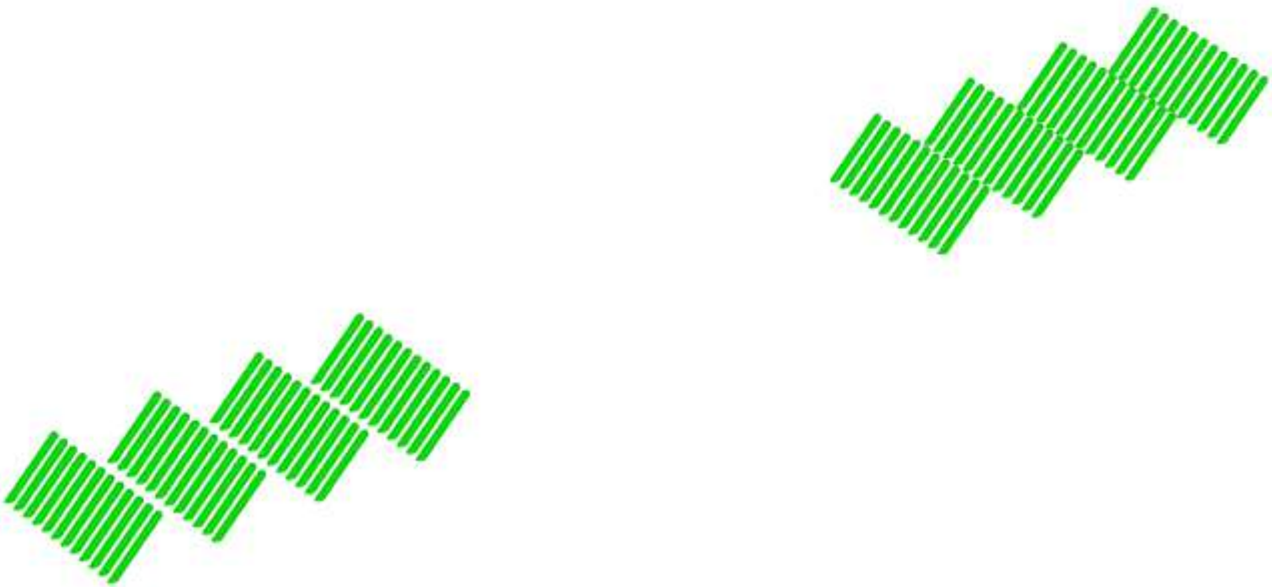


3D Model Setup

- Model setup similar to 2D case.
- Computational domain is thin slice of a 3D channel, by symmetry.
- Moving mesh displacement prescribed on guide surfaces



3D Model Pumping Simulation



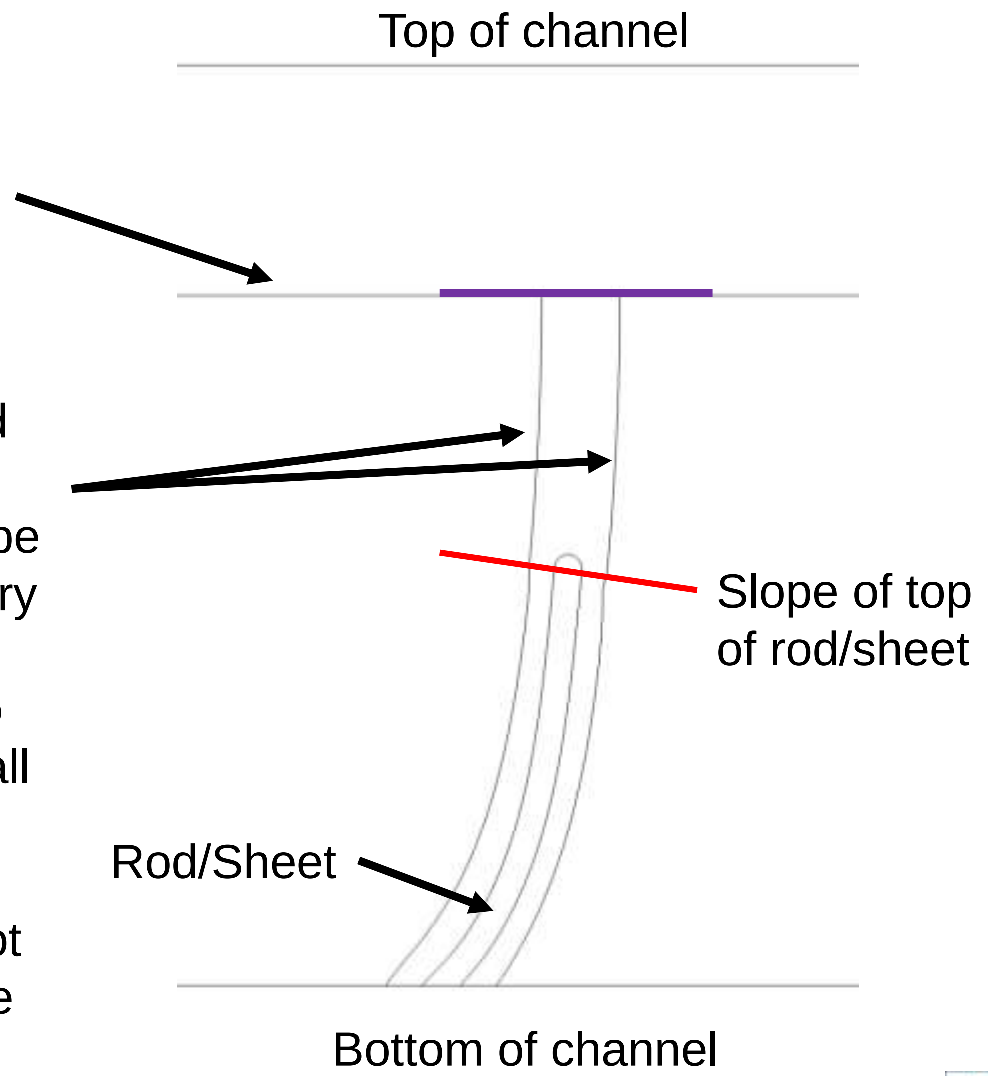
Channel walls not shown

Prescribed Mesh Displacement on Guides

Mesh displacement prescribed as horizontal

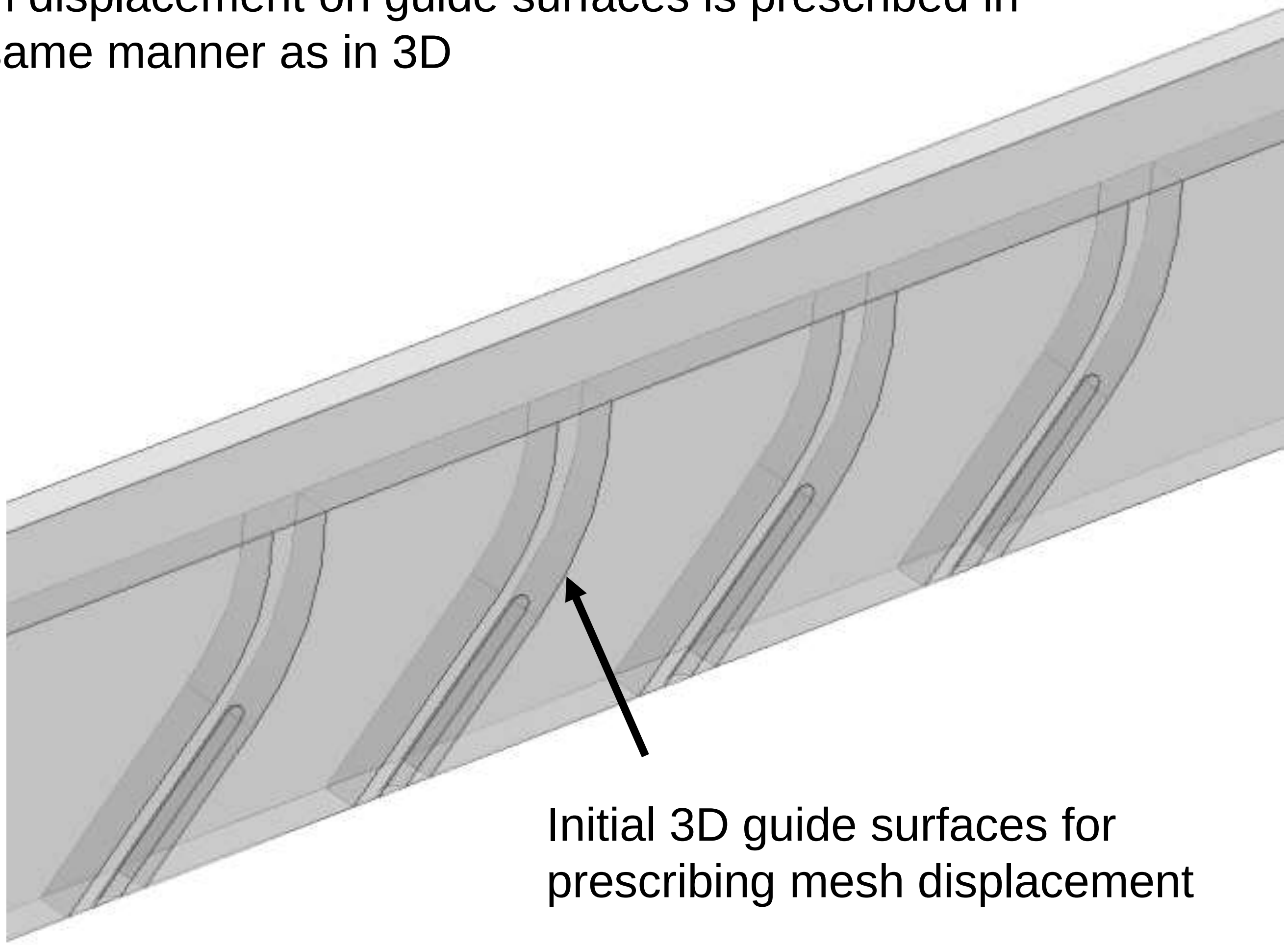
Displacement prescribed by analytic formula that ensures guide curve slope varies linearly in boundary parameter “s” and guide curve is perpendicular to red and purple lines, at all times.

Mesh displacement is not prescribed below red line



Prescribed Mesh Displacement on Guides

Mesh displacement on guide surfaces is prescribed in the same manner as in 3D

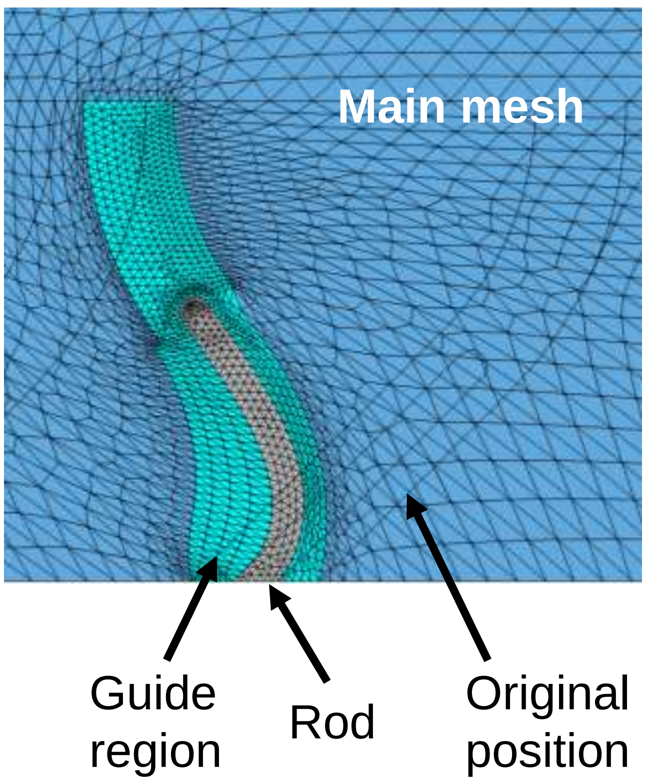


Initial 3D guide surfaces for prescribing mesh displacement

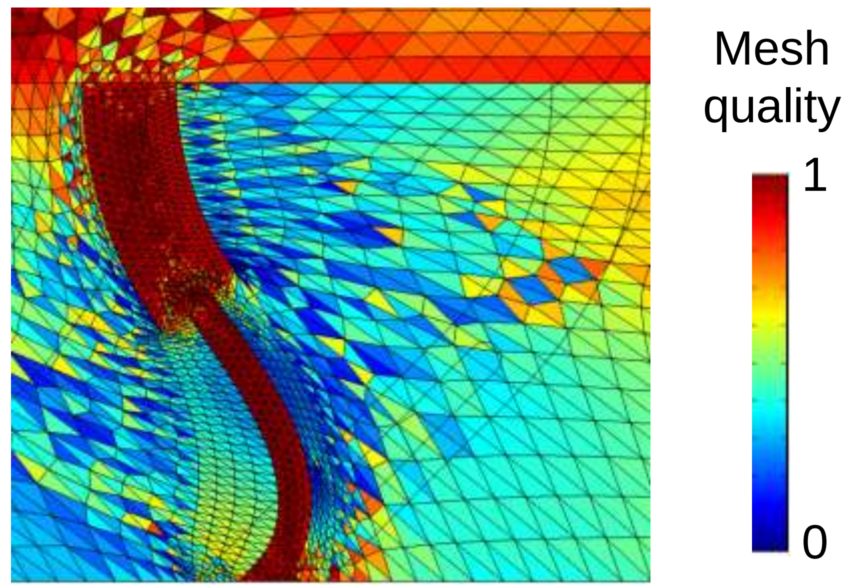
Mesh Quality

Prescribed displacement of internal surfaces maintains good mesh quality even with large rod deformation

Mesh regions

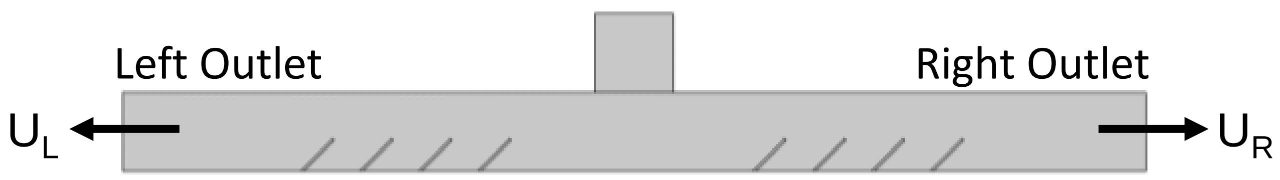


Mesh quality



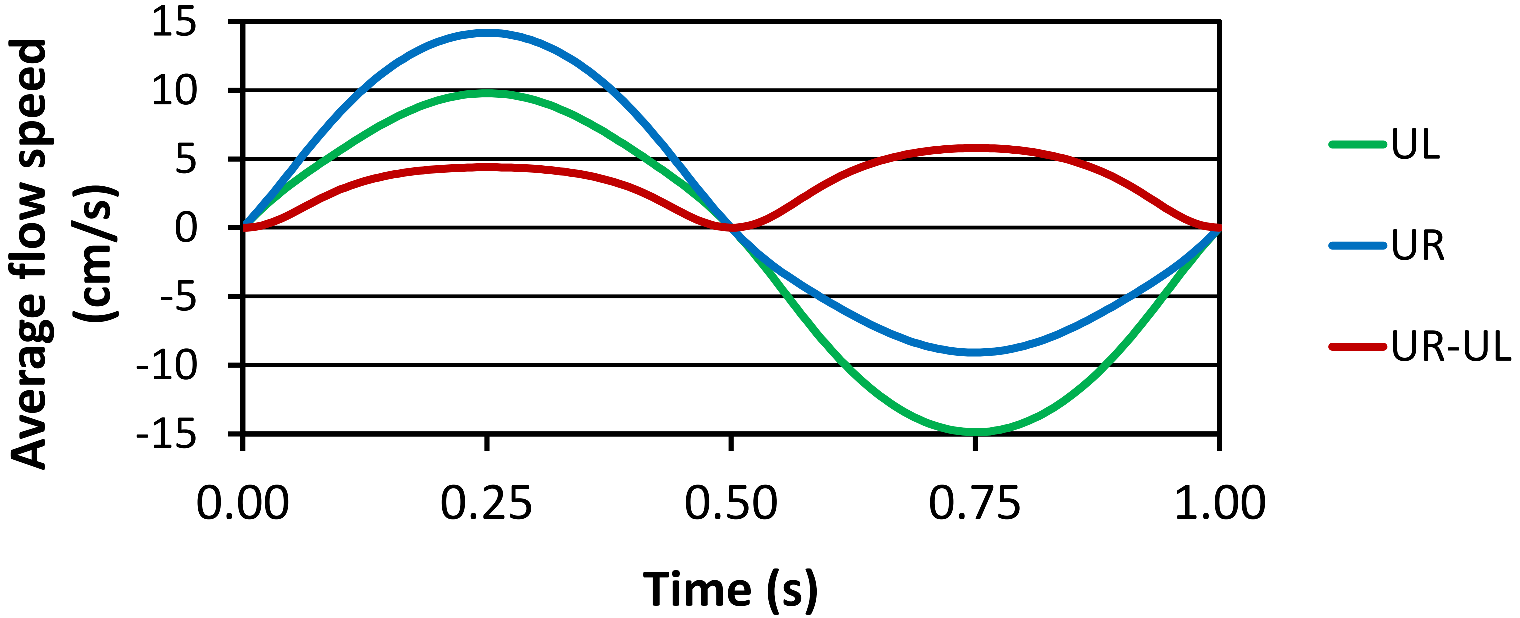
Minimum mesh quality: 0.018

Predicted Net Pumping at Re = 24

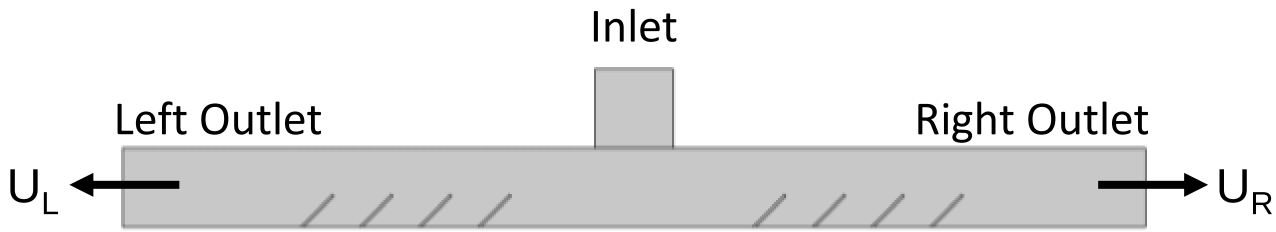


Net fluid pumped to right is U_R-U_L

Fluid viscosity is 0.01 cm^2/s, Reynolds # is 24

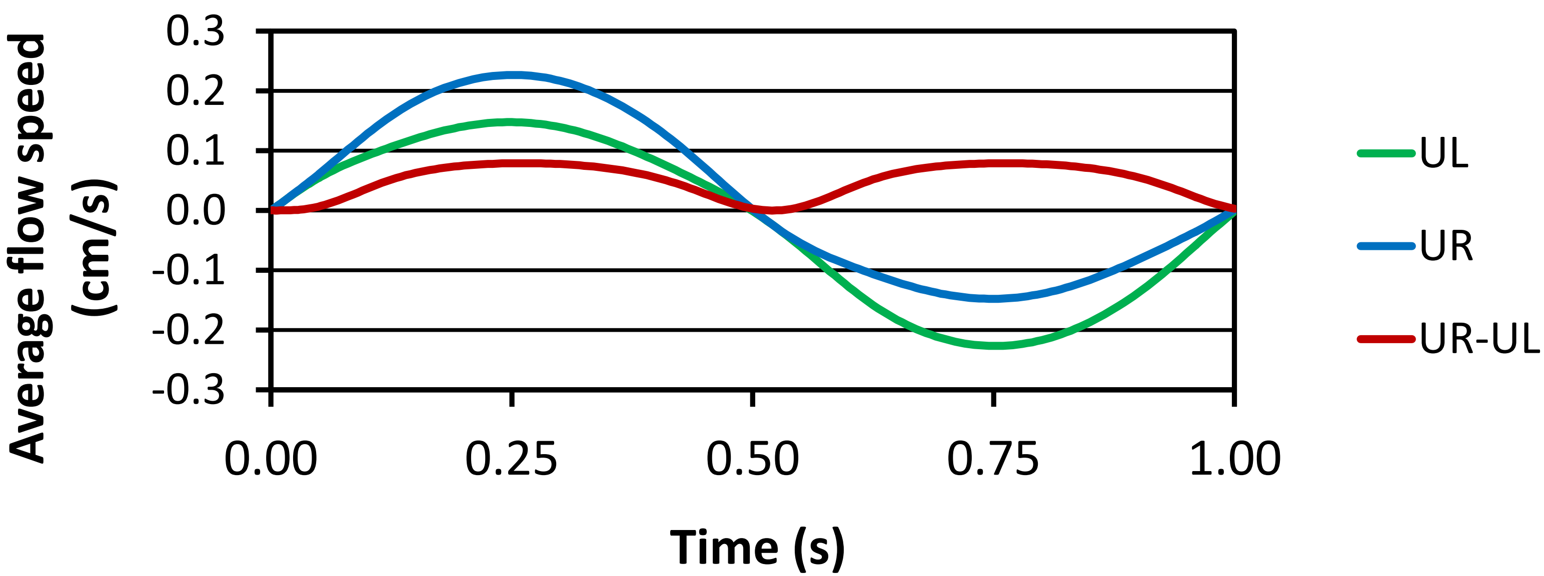


Predicted Net Pumping at Re = 0.006



Net fluid pumped to right is U_R-U_L

Fluid viscosity is 0.64 cm^2/s, Reynolds # is 0.006



Conclusions and Future Work

- We have presented a micropump design based on rectification and passive cilia that can pump at low Reynolds numbers
- COMSOL simulations have shown proof of concept of the design, over a range of parameters
- In order to run all 3D simulations, and in some cases 2D simulations, it was necessary to prescribe the moving mesh displacement on internal guide surfaces bounding each tilted flexible element
- Future work includes testing the design over a larger parameter space, including tilt angle and rod cross-section