Simulations of Micropumps Based on Tilted Flexible Structures

M. J. Hancock[1], N. H. Elabbasi[1], M. C. Demirel[2]

[1]Veryst Engineering, LLC., Needham, MA, USA
[2]Pennsylvania State University, University Park, PA, USA

Abstract

Pumping liquids at small scales is challenging because of the principle of reversibility: in a viscous regime, the flow streamlines through a fixed geometry are the same regardless of flow direction. Recently we developed a class of microfluidic pump designs based on tilted flexible structures that combines the concepts of cilia (flexible elastic elements) and rectifiers (e.g., Tesla pump). We report here COMSOL Multiphysics® simulations of micropumps consisting of a source for oscillatory fluidic motion, e.g. a piston, and a channel lined with tilted flexible rods or sheets to provide rectification (Figure 1). 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 (Figure 2). Because the motion of the tilted rods and resulting pumping depend on flow speed, fluid viscosity, and rod rigidity, in principle, the latter may be reduced to enable pumping at arbitrarily low flow speeds or high viscosities.

All computational simulations were performed in the COMSOL software, using the Fluid-Structure Interaction (FSI) interface. Both 2D and 3D simulations have been carried out, for different flow rates and fluid viscosities. The key computational advance of this study is the use of internal boundaries near the rods to guide the moving mesh and maintain good mesh quality up to large rod deformations (Figure 3). The mesh displacement is prescribed on these internal guide boundaries in terms of rod position.

The main physical result of the study is a computational demonstration that micropump designs incorporating tilted flexible structures may be used to pump fluids at moderate to low Reynolds numbers. The simulations shown in Figures 2 and 3 are for open systems consisting of a single oscillating piston or membrane placed between two channels with tilted 2D rods (Figure 2) or 3D rods (Figure 3). In 3D, symmetry conditions are used to reduce the size of the computational domain and allow increased mesh resolution. The net flow through the 2D and 3D devices is compared in Figure 4, demonstrating pumping in both devices at a Reynolds number of 4. In the full paper, simulations showing effective pumping at Reynolds numbers down to 0.001 will be presented. We will also present simulations of a closed system consisting of a single channel with tilted flexible rods and a master-slave pair of oscillating pistons, necessary to conserve the total fluid volume (for incompressible fluids). Instead of using an oscillatory piston, the channel walls themselves may contract and expand to drive flow past the tilted rods.

Micropumps with asymmetric flexible structures could provide versatile fluidic rectification for a wide range of next generation micro- and nanoscale devices for the biomedical, microelectronic, and energy fields, with applications ranging from automated syringes, high-efficiency thermal cooling, and water purification. Moreover, a flexible channel with tilted rods could pump fluid or enable swimming at low Reynolds numbers by virtue of periodic channel constrictions or bending.

Figures used in the abstract

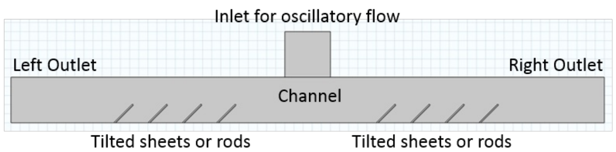

Figure 1: Schematic of a micropump design based on tilted flexible rods or sheets.

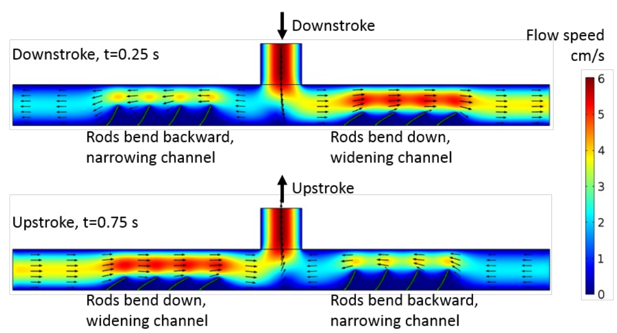

Figure 2: Simulations of a micropump design based on tilted flexible 2D rods. Snapshots of flow velocity and sheet bending are shown at two times. The average flow speed at the inlet is prescribed, 4 sin(2πt) cm/s, where t is in seconds.

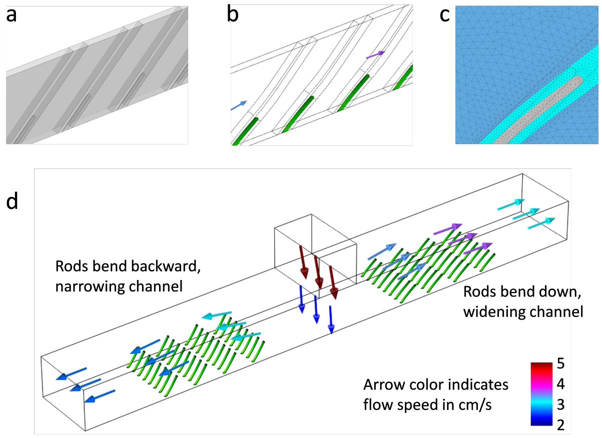

Figure 3: Simulations of a micropump design based on tilted flexible 3D rods. (a) Internal boundaries added as "guide surfaces" near rods. (b) Mesh displacement prescribed on guide surfaces as a function of rod bending. (c) Moving mesh quality maintained as rods bend. (d) Snapshots of flow velocity and rod bending at a quarter period (t = 0.25 s) for the same average inlet flow as in Figure 2.

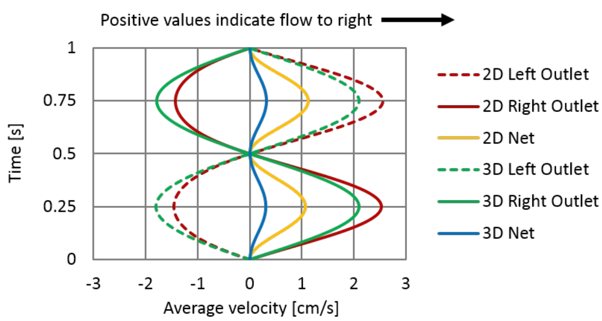

Figure 4: Comparison of average speeds through outlets of micropumps with 2D and 3D tilted rods. Over 1 cycle, net flows are to the right. Net flow speeds pumped with 2D tilted rods (i.e. sheets) are greater than those for 3D rods, since more fluid is displaced by the 2D rods.