Droplet Transport Using Surface Ratchets

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Abstract:

In this work, we report the design, fabrication, and preliminary experiments to study textured surface ratchets for droplet transport. The surface ratchet utilizes hysteretic interaction between a surface and droplet to yield a net force. By fabricating micro-scale surface roughness in phase with one side of a droplet and out of phase with the other, the total hysteretic force will have direction. Experiments have been done to determine the energy limits where this net hysteretic force can result in droplet movement. Edge-tracking software was developed to track droplet edge movement and to choose the correct range of operating parameters. Vibrating droplets of varying sizes were tracked on a first generation of straight ratchets. Based on these preliminary experiments, we have designed and fabricated curved ratchets. Movement was observed for certain ratchet designs.

Introduction:

Ratchets have long been an area of great interest for physicists and engineers. Rectifying motion has proved to be a very useful method of providing energy. While lures of the perpetual Brownian-ratchet still fascinate many people, more practical advancements turn up regularly. Ratchets continue to become more important especially as the scale of operation continues to decrease. This occurs as surface energies begin to dominate physical relationships, and requirements for system energy supplies decline.

One field of increasing importance is droplet microfluidics. This new area has far reaching impact, ranging from lab-on-chip systems to opto-fluidic components. Within this area, methods of droplet movement have become an essential field of research. Ratcheting droplets is a very promising solution to the problem of continuous, predictable droplet motion.

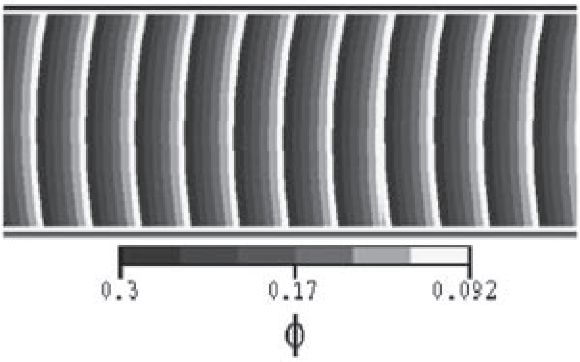

Figure 1: A contour plot of the surface energy is shown for multiple ratchets.

Surface Ratchet Theory:

The surface energy of the substrate was varied in an asymmetrical, periodic pattern as shown in Figure 1. This was achieved by microfabricating pillars on which a sessile droplet would rest. Commonly referred to as a Fakir state, it is possible for a droplet to sit on top of the pillars, or any roughened surface, in an equilibrium state. Because the bottom of a droplet only comes into contact with the pillar tops, the surface energy of the substrate is dependant on this surface area of the pillar tops. Furthermore, the pillar top surface area can be varied by changing pillar diameter or pillar density.

It is useful to represent the surface energy of a rough surface as a ratio of pillar top surface area to total surface area, which we refer to as the roughness factor. Figure 2

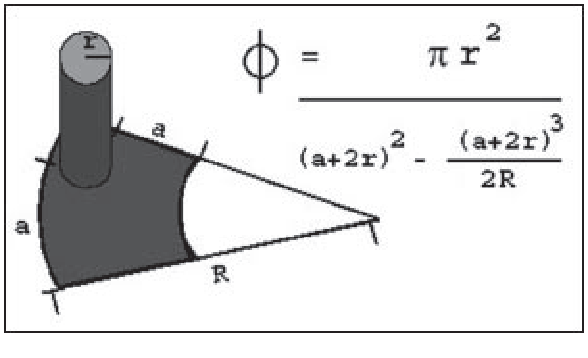

Figure 2: Computation of the roughness factor is shown for a curved surface ratchet.

shows how surface roughness is quantified for a curved surface ratchet. This representation of roughness is very useful because it is directly proportional to the substrate's surface energy. It is also used to provide estimations of a droplet's contact angles.

Surface Ratchet Operation:

The first requirement for operation is that energy must be transferred to the droplet to cause the droplet footprint to expand and contract, or breathe. We used vibration at droplet resonance to transfer energy to the droplet, although any method to invoke droplet footprint oscillation would suffice. As the droplet edges oscillated, the three phase contact lines interacted with the rough surface. Hysteresis occurs and resists edge movement; however, because one droplet edge is in phase with the surface ratchet and the other side is out of phase, each contact line experiences different hysteresis. A much stronger hysteretic force is possible on the front contact line than the back contact line.

Based on estimations relating surface roughness with advancing and receding contact angles, it was apparent that a much stronger hysteretic force opposes receding contact lines than advancing contact lines. Thus, it is theoretically possible to provide enough energy to advance a contact line, but not enough to allow it to recede after advancement. This is precisely what occurs on the front edge of the droplet with each oscillation. During each breath, the droplet pulls itself along the ratchet.

One very important requirement for droplet transport to occur is that a very precise amount of energy must be provided to the droplet. If not enough energy is provided, the droplet oscillates without its edges moving. This is known as the "stick" energy region. If too much energy is provided, the droplet edges oscillates with too much energy for hysteresis to play an important role. This is known as the "slip" energy region. Therefore, there is a small window referred to as the "slip-stick" energy region, in which hysteresis dominates droplet edge movement.

Results:

Motion was observed for certain ratchet designs, providing the proof of concept. However, we are only at the early stages of understanding and controlling surface energy ratchet operation. Further work is being carried out to quantify motion and to develop the efficiency of the ratchets. Investigation is under way into varying ratchet characteristics to ensure more dependable droplet transport.

Acknowledgements:

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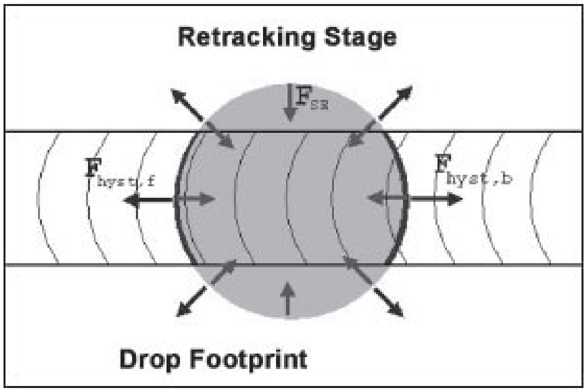

Figure 3: The forces acting on the droplet contact line are shown. The inward radial force is a result of minimizing droplet surface area. This is opposed by the outward radial force of hysteresis.