ARTICLE IN PRESS
CIS-01829; No of Pages 8
Advances in Colloid and Interface Science xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Advances in Colloid and Interface Science
journal homepage: www.elsevier.com/locate/cis

Historical perspective

Transport velocity of droplets on ratchet conveyors

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A R T I C L E I N F O

Article history:
Received 15 January 2017
Received in revised form 15 August 2017
Accepted 30 August 2017
Available online xxxx

Keywords:
Droplet transport
Microfluidics
Vibrations
Contact line oscillation
Asymmetric surfaces
Anisotropic ratchet conveyor

A B S T R A C T

Anisotropic ratchet conveyors (ARC) are a type of digital microfluidic system. Unlike electrowetting based systems, ARCs transport droplets through a passive, micro-patterned surface and applied orthogonal vibrations. The mechanics of droplet transport on ARC devices has yet to be as well characterized and understood as on electrowetting systems. In this work, we investigate how the design of the ARC substrate affects the droplet response to vibrations and perform the first characterization of transport velocity on ARC devices. We discovered that the design of the ARC device has a significant effect on both the transport efficiency and velocity of actuated droplets, and that the amplitude of the applied vibration can modulate the velocity of transported droplets. Finally, we show that the movement of droplet edges is not continuous but rather the sum of quantized steps between features of the ARC device. These results provide new insights into the behavior of droplets vibrated on asymmetric surface patterns and will serve as the foundation for the design and development of future lab-on-a-chip systems.

Contents

1. Introduction

Digital microfluidic (DMF) systems are a class of microfluidic devices that transport liquids in the form of discrete droplets [1,2]. The first DMF systems, known as electrowetting or electrowetting on dielectric (EWOD), used a localized electrostatic field to create spatial differences in surface tension [3–5]. Other DMF systems that used thermal [6] and chemical [7,8] gradients to induce localized changes in surface tension also emerged around this time. These DMF systems provided unparalleled control (e.g., individually addressable droplets) and compartmentalization of liquid samples [1,2], which sought much attention for the use of these devices in lab-on-a-chip systems for combinatorial chemistry [9], cell isolation and analysis [10], bio-assays [11], and DNA analysis [12,13]. The precise control of small liquid volumes has also gained interest for other engineering applications such as thermal management of on-chip hot spots [14,15], and self-cleaning surfaces [16,17]. However, the need for complex control systems for directing droplet transport has limited these surface tension driven DMF devices from seeing widespread use in myriad application settings. More recently, DMF systems have been developed using passive, microfabricated surface features that create anisotropies between the edges of the droplet footprint (contact line) [18–20]. These contact line driven DMF devices maintain many of the same advantages of surface tension driven DMF devices, but provide a simpler platform for controlling liquid droplets. However, while surface tension driven DMFs have been well characterized and possess an expansive toolbox of droplet functions [21–23], the full capabilities of contact line driven DMFs have yet to be realized.

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http://dx.doi.org/10.1016/j.cis.2017.08.009

The anistropic ratchet conveyor (ARC) system transports droplets through the combination of two key features. The first is a microfabricated surface pattern composed of hydrophilic, asymmetic features (rungs) that are defined by a hydrophobic background [24–27]. The asymmetry of this pattern divides the droplet into leading and trailing edges, where only the leading edge conforms to the curvature of the rungs, creating a difference or ratio of pinning forces between the leading and trailing edges (Fig. 1). The second feature is a vibration orthogonal to the substrate. The vibration induces the droplet footprint (contact line) to oscillate, cycling between wetting and de-wetting phases. The combination of the droplet edge movement and the difference in pinning forces between the leading and trailing edges results in a net force that induces the droplet to take a step throughout each vibration cycle [24–27].

Previously, we demonstrated how the design of ARC devices can be used to enable more sophisticated droplet functionality [27,28], and here, we present a careful examination of droplet transport on ARC devices. In this study, we characterize the behavior of droplets at the vibration threshold required to initiate transport, examine the effect of the ARC design and droplet volume on transport velocity, and investigate the relationship between transport velocity and amplitude of the applied vibrations. We discovered that the translation of vertical vibrations to horizontal droplet transport, while influenced by droplet resonance, is ultimately determined by an intricate balance of forces between the droplet and substrate surface of the ARC device. As a result of this insight, the droplet response, and ultimately transport velocity, can be influenced by the design of the ARC device. Additionally, changes in the properties of the droplet alter this balance of forces and provide predictable changes to the droplet response. Finally, we discovered that vibration amplitude is correlated with transport velocity, but this relationship is not linear and continuous. Rather, we demonstrate that droplets advance through quantized steps between hydrophillic rungs and increases in transport velocity are realized by increasing the probability of the droplet advancing by larger steps.

Overall, this work expands upon previous reports of ARC devices to provide a more complete understanding of the mechanics that convert vertical vibrations to horizontal droplet transport. The results of this work provide a foundation for the design of future lab-on-a-chip systems, and present new opportunities for utilizing designed surface patterns for controlling droplet behavor and response to mechanical vibrations. The insights gained from our studies also raise new questions and avenues of investigation for droplet mechanics.

2. Understanding ARC threshold

In order to better understand the underlying mechanisms of droplet transport, we characterized the behavior of 8 μL water droplets transported on three different ARC tracks with rungs composed of silicon dioxide (SiO_2) pattern and a fluorooctyltrichlorosilane (FOTS) background (Fig. S1). These tracks are defined by the relationship of the width and period of the hydrophilic rungs (Fig. 2). Two different rung periods were used in this work, 120 μm and 60 μm. Additionally, if the hydrophilic rung is thought of as the working region of the track, then a duty cycle can be calculated, where duty cycle is defined as the width of the rung divided by the period or spacing interval between rungs [27]. The two ARC duty cycles used in this work are 8.3% and 16.6%. Additionally, all tracks used in this portion of our work had a rung radius of 1000 μm.

ARC devices are characterized by the minimum vibration amplitude (ARC threshold) that is required to initiate droplet transport. These measurements are reported and discussed in terms of acceleration to account for the energy input to the system, but the corresponding substrate displacement (Fig. S2) is provided for reference. Above the ARC threshold, droplet transport will still occur, but the effect of larger vibration amplitudes on droplet transport has not been previously characterized. The ARC threshold profiles obtained for all three tracks were characteristic of previous ARC threshold measurements [25,26], and all exhibited a minimum ARC threshold around 80 or 90 Hz (Fig. 3). If the frequency of minimum ARC threshold occurred at resonance, a local maximum in the wetting area of the droplet would occur at this frequency (wherein wetting area is defined as the maximum area of the droplet footprint during a complete cycle of contact line oscillation, which occurs at the end of the wetting phase). However, the wetting area was actually smallest at the frequency of minimum ARC threshold on all three devices. These observations indicate that the factors determining the minimum ARC threshold are more complex than indicated by previous models [26], and the specific design of the ARC devices has a larger effect on the droplet response to vibrations than expected.

The 10/120 ARC track was the most efficient, exhibiting the lowest ARC threshold at all frequencies except 90 Hz (Fig. 3). Wetting area measurements confirmed the expansion of the droplet is also the smallest on the 10/120 track (except 90 Hz). The frequency of minimum ARC threshold also shifts from 80 to 90 Hz, and a local peak in wetting area shifts from 60 Hz to 50 Hz when the period of the tracks is reduced from 120 μm to 60 μm. These measurements indicate that the ARC design significantly influences droplet response to vibrations.

At the point of maximum wetting area (Fig. 3C), the shape of the droplets is dependent on the vibration frequency and the ARC track. All droplets are oscillating in a mode with only two nodes (i.e., the vibrated droplets are not forming multiple lobes during wetting) [29–31]. Droplets vibrated on the 5/60 track at 50 Hz may be at the transition to a higher mode, as the contour is not perfectly elliptical, but this irregularity in contour is more likely due to the anisotropy of the ARC substrate. Another important observation is the stark contrast in aspect ratio of droplets on all tracks when vibrated at 70 Hz compared to other frequencies. The length to width aspect ratio (Fig. S3A) of droplets vibrated at this frequency is substantially lower than all other frequencies.

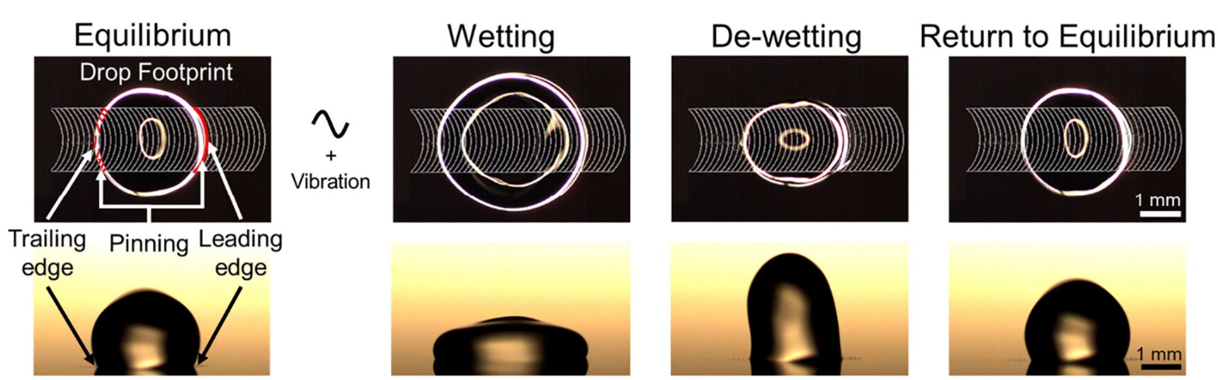

Fig. 1. Transport on ARC devices is enabled by a passive surface pattern and applied vibrations. A periodic pattern of curved rungs creates a difference in pinning forces between leading and trailing edges of the droplet, as only the leading edge of the droplet conforms to the rung curvature. The vibrations, applied orthogonally to the substrate surface, cause the droplet footprint (contact line) to oscillate, driving the droplet through wetting and de-wetting phases. The oscillation of the droplet edges, paired with the difference in pinning forces, creates a net force that results in the droplet taking a step throughout each vibration cycle.

Please cite this article as: Holmes HR, Böhringer KF, Transport velocity of droplets on ratchet conveyors, Adv Colloid Interface Sci (2017), http://dx.doi.org/10.1016/j.cis.2017.08.009