ABSTRACT

This paper reports a novel physical phenomenon useful for droplet manipulation and sorting. When a droplet is placed between two laminar streams of differing viscosity, it migrates toward the low viscosity stream due to the shear rate between the streams. By controlling the relative widths of the two streams, we utilize viscophoresis to sort droplets by size. We validate the mechanism through simulations and experiments.

KEYWORDS: Droplets, droplet sorting, migration, viscosity, gradient

INTRODUCTION

The ability to sort droplets by physical or chemical characteristics is a key module in droplet-based screening platforms. Droplet sorters can be divided into two categories. One relies on the interaction of droplets with active fields, such as dielectrophoresis (DEP) [1], surface acoustic waves (SAW) [2], and flow perturbations generated from integrated membrane valves [3]. The second category consists of passive sorting mechanisms which rely on the interaction of droplets with channel structures, including deterministic lateral displacement (DLD) [4] and asymmetric bifurcations [5]. We previously reported tensiophoresis, a droplet sorting technique which relies on the migration of droplets in a surfactant concentration gradient created by laminar flow [6]. This technique was successfully used to passively sort droplets by size and chemical composition; however, one limitation is that tensiophoresis is not compatible with droplet chemistries where the droplet is already coated with surfactant. In this paper, we demonstrate that a viscosity gradient can achieve the same size-sorting capability as tensiophoresis, but without the need of surfactants. This novel mechanism provides a passive, tunable method to sort droplets by size, and it is compatible with droplet systems using fluorocarbon oils.

THEORY

In 1979, Chan and Leal demonstrated that droplets placed in a shear gradient will migrate to the higher velocity stream [7]. In presence of a shear gradient, the streamlines on the droplet’s higher shear side is greater than the one on the other half, resulting in a net force causing the droplet to migrate in the direction of decreasing shear (Fig. 1A). The droplet subjected to shear will deform, causing a discontinuity
in normal stress. This in turn generates a force which counters the deformation and causes droplet migration.

In a microfluidic chip, we create a sharp velocity gradient by introducing two miscible streams of different viscosity (Fig. 1B). Two parallel streams are introduced into the sorting channel such that the upper stream has smaller viscosity than the lower stream. The stream with lower viscosity moves at a faster velocity, thus forming a shear gradient at the interface. Droplets subjected to this sharp shear gradient migrate to the upper stream.

**EXPERIMENTAL**

To demonstrate the concept of viscophoresis, a tertiary microfluidic junction with a 1000 µm wide sorting channel was fabricated in polydimethylsiloxane (PDMS) using soft lithography. Droplets were introduced through the lower inlet while the middle and upper inlets were used to inject FC-70 and FC-3283 (3M), respectively. Both are fluorocarbon oils of similar chemical composition; however, the absolute viscosity of FC-70 is 17 times that of FC-3283. Droplet migration was visualized using a bright field inverted microscope and recorded with a high-speed camera. Quantitative analysis of droplet trajectory, migration velocity, deformation, etc. was performed using droplet morphology and velocimetry (DMV), a droplet tracking software developed by our group [8].

**RESULTS AND DISCUSSION**

Using simulation and experiments, the concept of viscophoresis is studied in a microfluidic channel. CFD Simulations (Fig. 2A&B) confirm that droplets migrate to the high velocity stream in accordance to Leal’s analytical model. However, simulations required a viscosity ratio of 100:1 to achieve droplet migration, whereas experiments only required a 17:1 ratio. One of the potential differences is that the simulation is 2D model, where the shear forces are projected only on the side boundaries of the droplet. In experiments, we use two parallel streams of fluorocarbon oil (FC-70 and FC-3283) to generate the gradient in shear flow (Fig. 3A). As predicted, droplets migrate to the lower viscosity stream (FC-3283), and they deform during migration according to Leal’s model. The migration velocity of the droplet depends on the shear rate (Fig. 3B) and it is independent of surfactant coverage.

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**Figure 2:** CFD model of Viscophoresis (A) Droplet migration in a sharp velocity gradient. (B) The velocity profile of upper and lower stream.

**Figure 3:** Quantitative analysis of Viscophoresis (A) 1. Tri-junction microfluidic channel where FC 70 (µ = 24mPa.s), FC 3283 (µ = 1.4mPa.s) and droplet phases meet. 2. Droplet touches the interface 3. Deformation of the droplet while migration 4. Droplet after migration (B) Migration velocity increases with shear rate
Since the location of the interface can be precisely controlled by laminar flow, this technique can be exploited to perform size based sorting of droplets (Fig. 4). Larger droplets, which have a greater likelihood of contacting the interface, migrate into the upper stream and collect at the upper outlet, whereas small droplets do not migrate and are collected at lower outlet.

CONCLUSION
In this paper, we have demonstrated the concept and implementation of viscophoresis, migration of droplets across a viscosity gradient. This simple and passive droplet actuation technique does not require on-chip structures or complex instrumentation. We used viscophoresis to perform droplet sorting based on size. Future work will explore the utility of viscophoresis in biological assays.

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CONTACT
* Amar Basu; phone: +1-313-578-1567; abasu@eng.wayne.edu