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Resonance induced wetting state transition of a ferrofluid droplet on superhydrophobic surfaces

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We investigated manipulating wetting transitions of ferrofluid droplets on planar superhydrophobic surfaces by electromagnetic stimulation. We showed that even if magnetic forces are small at small liquid volumes (1–10 μl), they can be effectively used to induce Cassie to Wenzel transition when the exciting frequency is close to the resonant frequency. We related the wetting transition to the increase of the Laplace pressure as a consequence of the large deformation that occurs close to the resonant frequency; on the contrary, inertia forces were not able to induce such a transition. This study promises a new approach to manipulate ferrofluid droplets for various microfluidic and lab-on-chip technologies.

1. Introduction

Many microfluidic applications utilize continuous-flow silicon, polymer, or glass-based microchannels equipped with valves, mixers, pumps, and sensors to perform rapid reactions, detection, and analyses [1–3]. While these devices have demonstrated significant promise, the integration of various components is often challenging and a bottleneck in lab-on-a-chip technologies. In addition, the adaptability of these devices to new applications or to the addition of new components is limited; typically, the devices have to be redesigned and newly fabricated, which can have significant lead times. More recently, discrete droplet-based approaches where a liquid plug is suspended in an inert carrier fluid have received interest Fair [4] owing to the ability to control individual droplets independently and to perform complex tasks in nano- to pico-liter volumes Niu et al. [5], Rastogi and Velev [6]. However, challenges due to contamination of isolated plugs by diffusion through the carrier fluid can occur and accurate volume conservation is difficult to achieve.

In contrast to closed channel microfluidic architectures, recent interests in controlling discrete liquid droplets on surfaces have emerged to help eliminate the need for microchannels. Mechanisms for droplet manipulation include electrowetting [4,7–9], dielectrophoresis Gascoyne et al. [10], thermocapillarity [11], surface acoustic waves [12,13], magnetic forces in combination with superparamagnetic particles [14,15]. In particular, magnetic actuation has demonstrated several unique advantages [16]. An updated review on micro magnetofluidics can be found in Nguyen [17]. For example, superparamagnetic particles can be remotely manipulated by permanent magnets or electromagnets located off-chip, which provides the possibility to decouple the substrate in contact with the droplets from the actuation stage. In such a case, the surface can be low cost and disposable which eliminates cross-contamination, while the actuation stage (more expensive and complex) can be repeatedly used since it is not in direct contact with the fluid sample. In addition, the magnetic interaction is weakly dependent on pH, ionic strength, and temperature Pamme [16], which promises a more robust platform. Furthermore, magnetic actuation is particularly suitable for biological and biomedical applications since low frequency magnetic fields do not harm biological tissues Pamme [16]. However, in contrast to the other actuation mechanisms mentioned above, the magnetic force is a body force, i.e., the magnetic moment is proportional to the volume. As droplets decrease to microscale sizes, the actuation mechanism is less effective. For example, in the case of a droplet sliding on a surface, the smaller the droplet, the larger the frictional force is compared to the driving body force.

Combining the use of superhydrophobic surfaces with magnetic actuation, however, promise a platform to move, store, and mix microdroplets with low adhesion. In addition, by using periodic microstructured surfaces to create these superhydrophobic surfaces, to create superhydrophobic surfaces, the different wetting states, i.e., Wenzel or Cassie–Baxter state [18,19], can be used to achieve three-dimensional manipulation. For example, the bottom surface can be functionalized, and upon wetting and dewetting of

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the droplet, a reaction can occur with the droplet and surface, which can be subsequently followed by mixing and droplet transport. While the Cassie to Wenzel transition by applying external fields and forces has been of particular fundamental interest to researchers [20,21], the possibility of controlling wetting regimes with magnetic fields has not been demonstrated and offers new possibilities for the rapid development of microfluidic devices [22–24].

In this work, we induce Cassie to Wenzel wetting transitions of ferrofluid droplets on superhydrophobic microstructured surfaces using planar electromagnets. The wetting transition occurs by taking advantage of droplet resonance where an oscillating magnetic field is applied, and subsequently reduces the energy required to achieve the wetting transition. The demonstration of droplet wetting transition is an important component towards realizing a magnetic-based microfluidic platform in the future.

2. Experimental setup

Fig. 1 shows a schematic of the experimental setup used to manipulate and capture images of the ferrofluid droplet. The ferrofluid (EMG705, Ferrotec) used in the experiments, consists of magnetic particles with diameters of approximately 30 nm suspended in water, where the physical properties are reported in Table 1. The ferrofluid droplets ranging in volume from 1 μl to 10 μl were placed on the superhydrophobic microstructured surface (see Section 2.A) by pipette. The apparent contact angle, measured by a custom goniometer, ranged from 130° to 140° on the surfaces, which is slightly lower than water due to the presence of surfactants in the ferrofluid.

The electromagnetic actuation stage was placed directly underneath the superhydrophobic surface, which utilizes copper micro-coils printed on double-sided copper-plated printed circuit boards (PCBs). DC and AC currents were supplied through the copper coils to vary the magnetic field strength to change the wetting states of the droplet, respectively.

Each of the experiments was recorded by a high-speed camera (Phantom v7.1, Vision Research) with backlight illumination to enhance the contrast of the droplet.

2.1. Superhydrophobic surface

The superhydrophobic surfaces consist of periodic pillar arrays with diameters of $d = 2$ μm, height 8 μm and spacings of $\delta = 5$ μm or $\delta = 7$ μm. They were fabricated in silicon using contact lithography and deep reactive ion etching (DRIE). To make the surfaces superhydrophobic, they were subsequently silanized by trichlorosilane using chemical vapor deposition (CVD). A SEM picture is given in Fig. 2.

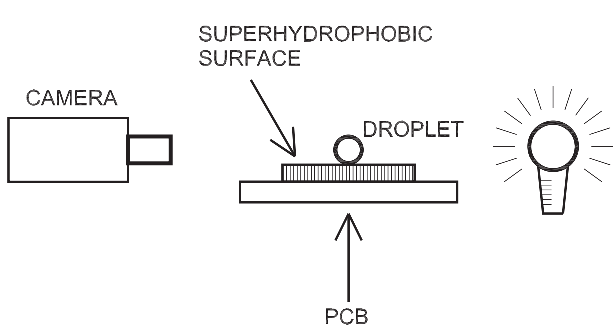

Fig. 1. Schematic of the experimental setup showing the sample placed on top of the electromagnetic actuation stage. Visualizations were obtained from the side using a high speed camera with backlit illumination.

Table 1
Physical properties of the ferrofluids Ferrotec EMG705 [25].

Property	Value
Density, ρ	1194 kg/m^3
Viscosity, η	2.48 mPa s
Surface tension, σ	42.1 mN m
Magnetic susceptibility, χ_m	1.89
Saturation magnetization	206.6 G

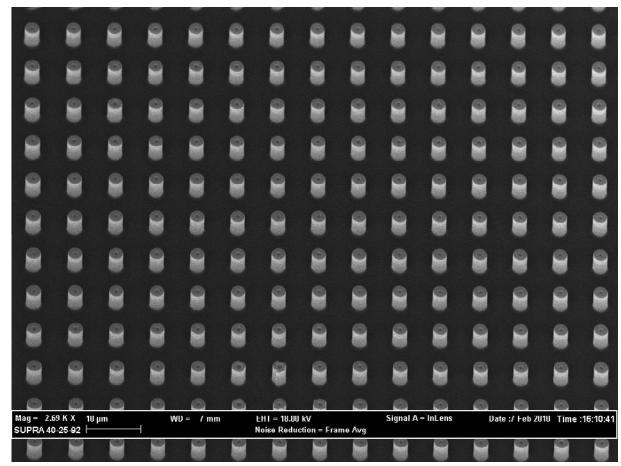

Fig. 2. SEM picture of a superhydrophobic surface used in the experiments; spacings of $\delta = 5$ μm.

2.2. Micro-coil electromagnets

The planar micro-coil electromagnets were designed and fabricated, similar to ones developed by Beyzavi and Nguyen [26]. Planar rectangular coils were chosen for simplicity [27,26]. The copper wires were defined using standard lithography and chemically etched in ferric chloride solution. The copper wires are 35 μm thick and 100 μm wide. Planar coils consist of a series of n current-carrying wires with finite length. To compute the magnetic field generated by a single coil, or by any geometrical arrangement of coils, the magnetic fields created by each wire is determined. The superposition of the magnetic fields of all those segments results in the total magnetic field. Applying the Biot-Savart's law to a segment of wire carrying current I, parallel to the x–z plane, the magnetic field is

$$H_x = 0$$

$$H_y = -\frac{zI}{4\pi}\int_{x_1}^{x_2}\frac{dl}{\left[\sqrt{(x-l)^2+(y-a)^2+z^2}\right]^3} \tag{1}$$

$$H_z = -\frac{(y-a)I}{4\pi}\int_{x_1}^{x_2}\frac{dl}{\left[\sqrt{(x-l)^2+(y-a)^2+z^2}\right]^3}$$

where x_1 and x_2 are the coordinates of the two ends of the segment and a is the distance of the wire from the plane x–z; x, y, z are the coordinates of the point where the magnetic field is computed. Following a coordinate transformation procedure, the magnetic field of a segment oriented at any direction can be obtained following the same equations.

The total magnetic field of a micro-coil consisting of n pieces can be computed by superimposing the magnetic fields from Eq. (1)