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Controlled manipulation of floating objects on deformed fluid interfaces and conditions for stable equilibria

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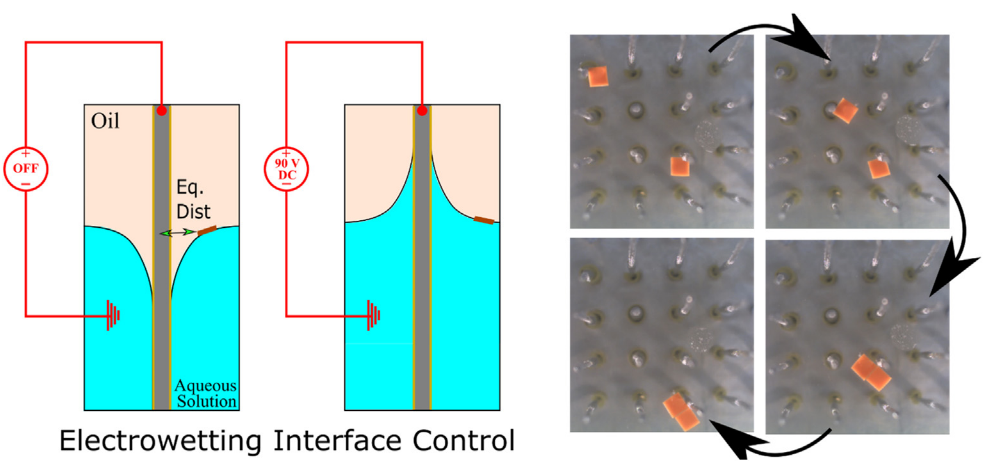
GRAPHICAL ABSTRACT



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ABSTRACT

At the millimeter scale, interactions between floating and semi-immersed objects are significant. The local curvature of the interface is modified by the weight/buoyancy forces of floating objects, and by the surface properties of semi-immersed objects. The curvature changes generate attractive (or repulsive) interactions between floating parts, and semi-immersed objects. This work demonstrates how electrowetting can manipulate these interactions in order to position, align, assemble and transport parts attached to the fluid interface. This demonstrates one way in which fluid interfaces can provide an alternative to standard pick and place technology for part positioning/assembly. Typically, the part/rod forces are purely attractive or repulsive, but under some conditions, floating objects reach a stable equilibrium with a finite gap between the floating and semi- immersed bodies. Stable equilibrium positions were measured for rectangular prisms suspended on a water/oil interface and a fixed cylindrical rod. Measurements showed that the equilibrium position depends on the ratio of $\frac{\triangle\rho t}{w}$ where t is the part thickness; w is its width, and $\triangle\rho$ the part/fluid density difference. The stable equilibrium position provides for repeatable positioning without risk of parts sticking to the semi-immersed bodies.

1. Introduction

Particles at interfaces play a key role in many applications including cleaning, separations [17,19], colloid stabilization [17],

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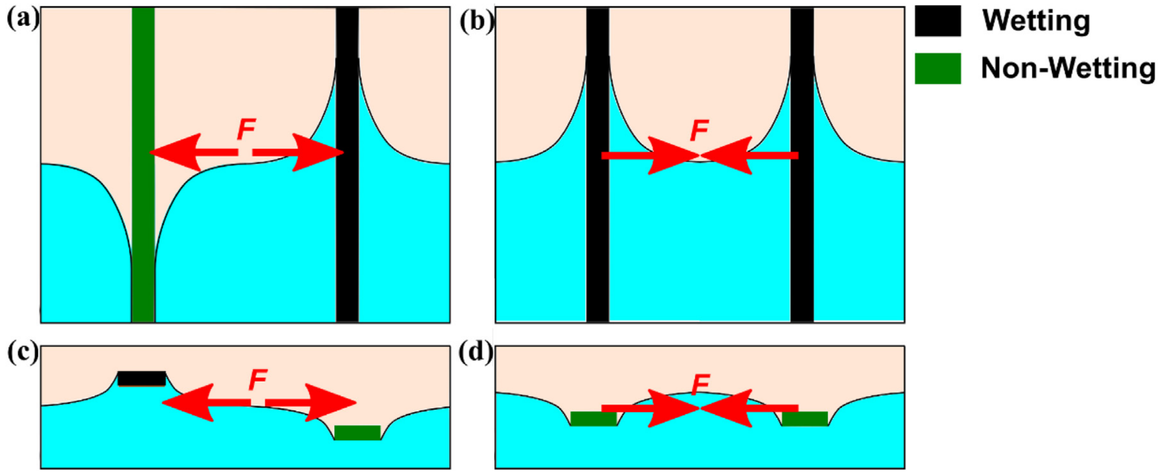

Fig. 1. Capillary interaction force between semi-immersed rods that create different (a) and same curvatures (b). Capillary floatation force between floating components that create different (c) and similar curvatures (d).

and inter-particle assembly [1,14]. Over a broad range of wetting conditions, particles remain stable on interfaces [18]. These particles can deform the interface and interact with other semi-immersed and floating objects that also deform the interface.

Microscale interactions at fluid-fluid interfaces have proven useful for facilitating particle manipulation through different methods. For instance, photo-induced effects have been used for manipulating floating particles. The flow of a photo-responsive surfactant (and consequently, the fluid flow) around a floating particle was controlled by shining light to the interface [25]. In another work, holographic optical tweezers were used to manipulate floating dielectric particles [9].

Microscale manipulation by traditional grasp and release processes proves challenging due to surface forces [20]. Surface forces that are negligible at larger scales including capillary and Van der Waals forces are larger than gravity at these sizes. In traditional manufacturing environments they are often poorly controlled—making it difficult to release objects consistently. However, developing systems that harness surface forces could improve microscale manipulation to simplify the challenges of sorting, positioning and aligning microscale components. In the Knuesel & Jacobs work [11], a water-oil interface served to pre-align microscale components for subsequently self-assembling onto a semi- immersed substrate without a tool or any serial manipulation. The authors demonstrated a high-yield, high-rate microscale assembly process. Sowerby et al. used the axisymmetric meniscus of a fluid-air interface around a cylindrical rod for concentrating buoyant particles at the three-phase contact line [24] to efficiently collect biological particles as samples for detection/screening [27].

Fluid interfaces are of particular interest for manipulating floating particles with both attractive and repulsive forces possible. The weight/buoyancy force on a floating particle (i.e. a "floatation force" as illustrated in Fig. 1c,d) or the wetting properties of a solid surface in contact with the interface (i.e. an "immersion force" as illustrated in Fig. 1a,b) deform the fluid interface. Kralchevsky and Nagayama concluded that energy minimization drives an attractive force between two components if both components generate a similar interface curvature (Fig. 1b, d) while opposite interface curvatures generates a repulsive force (Fig. 1a,c) [6,13]. The concept of "capillary charges" allowed the authors to calculate the inter-particle force, F, with a formula that is analog to Coulomb's law [12]:

$$F = -2\pi \cdot \gamma \cdot \frac{Q_1 \cdot Q_2}{L} \tag{1}$$

where Q_1 and Q_2 are the capillary charges of each interacting particle [13]), γ is the surface tension and L is the inter- particle distance. The capillary charge of a floating spherical particle on a flat interface is given by

$$Q = r \sin\varphi \tag{2}$$

where r is the particle diameter and φ is the angle of the meniscus relative to the horizontal. See [5] for a more comprehensive review.

The afore-mentioned works have added valuable insight for understanding interactions of spherical particles at fluid interfaces. This work focuses on floating microscale components with a prismatic geometry. In order to use the interfacial forces to manipulate components at the fluid interface, a method is required for changing the fluid interface with a practical control input.

Electrowetting is a promising approach. In electrowetting, the apparent contact angle of a fluid changes under an applied electric field. It is reversible and applicable to a wide range of fluids and configurations. [21,22]. Using EW, the apparent contact angle of a sessile drop can be modulated by over 100°.

Recent work has shown that electrowetting of flat surfaces can be used to manipulate objects [28]. This work complements this work by showing how electrowetting can provide a reversible control method around partially-wetted rods. Rods allow for additional flexibility in the path of floating objects compared to flat plates.

Typically, the interface curvature around the rods is determined by the wetting properties of the rod alone and cannot be readily modulated. Sowerby demonstrated an alternative interface control method in which mechanical motion of a rod with a hemispherical tip deformed the interface without penetrating it [24]. Similar results might be obtained using a semi-immersed rod with high contact angle hysteresis. These mechanical methods may be able to maintain a surface deformation for longer periods and do not require advanced manufacturing techniques to create thin dielectric layers required in electrowetting. However, mechanical methods of controlling the interface are limited in their speed and are difficult to implement with high spatial density. Direct electrical actuation via electrowetting facilitates tighter packing of the actuated rods. Recent publications have shown promising advances in actuation reliability [7,23] and development of low cost electrowetting material systems [10]. Additionally, the Sowerby method is not capable of fully reversing the interface curvature from positive to negative curvatures. However, curvature reversal is not needed to concentrate floating parts near the deformed interface to facilitate imaging of dilute particle solutions.