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Measuring Force of Droplet Detachment from Hydrophobic Surfaces via Partial Cloaking with Ferrofluids

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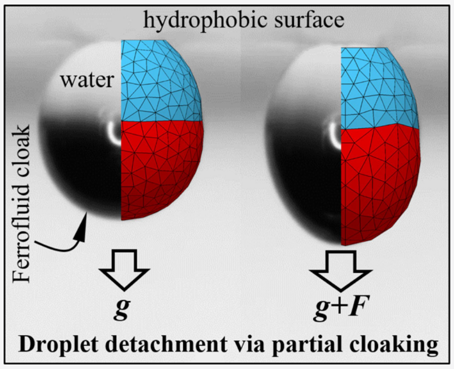
ABSTRACT: This paper presents a new approach to measure the force required to detach a water (a polar liquid) droplet from a hydrophobic surface. This is done by partially cloaking the droplet with a high-surface-tension oil-based ferrofluid and using a magnet to apply a controllable body force to the resulting compound droplet. Placing the assembly on a sensitive scale, the magnet can then be brought closer to the droplet to detach it from the surface while recording the forces applied to the droplet. The work presented here is novel as it uses the concept of partial cloaking in which the solid−droplet contact area is not contaminated by the ferrofluid (and the measured forces do not need postprocessing). Our study is accompanied by numerical simulations aimed at improving our understanding of the interplay between the interfacial forces in a two-phase droplet under the influence of a strong (detaching) body force and at providing additional data for in-depth analyses of these forces. In particular, the minimum ferrofluid volume required for successful water droplet detachment from hydrophobic surfaces is computed for ferrofluids of different surface tensions, and they are compared to experimental data obtained from detaching water droplets from electrospun polystyrene coatings. It is also shown that the detachment force measured via partial cloaking is independent of the volume of the ferrofluid used for the experiment.



■ INTRODUCTION

The nature is filled with spectacular examples where a droplet beads up on a hydrophobic surface but does not roll down on it when the surface is titled or shaken.[1−3] In fact, a droplet's tendency to adhere to a surface can be quite strong despite exhibiting a large apparent contact angle (ACA) on the surface (the so-called rose-peta effect).[3] This behavior has been observed with surfaces composed of polymeric fibers, such as those produced via electrospinning,[4−6] among many others. Fibrous surfaces are of particular importance for many practical applications such as anti-icing (e.g., ref 7), drag reduction (e.g., ref 8), heat transfer (e.g., ref 9), or self-cleaning (e.g., ref 10).

To characterize the degree of hydrophobicity of a surface, one needs to measure the force needed to detach (or move) a droplet from (or on) the surface (i.e., normal and lateral adhesions). The traditional approach to measure the force of lateral adhesion between a water droplet and a surface has been to measure the role-off angle (the inclination angle at which the droplet rolls off the surface). Obviously, this method becomes inefficient if the force needed to move the droplet is greater than the weight of the droplet. Alternative methods, therefore, have been proposed over the years to overcome this problem. These methods include, but are not limited to, centrifugal force (e.g., refs 11 and 12 for lateral adhesion and refs 13 and 14 for normal adhesion), the use of an external device such as the tip of an atomic force microscope,[15−17] or an air flow (e.g., refs 18−20) for both lateral and normal adhesions. The first study to report measuring droplet detachment force using a magnet was the work of Amrei et al.,[21] who studied normal adhesion force between a hydrophilic fishing line and a water-based ferrofluid droplet in 2016 (see also the work of Timonen et al.[22] for the use of magnetic field in studying droplet lateral adhesion). The method of ref 21 was then extended by Jamali et al.[23,24] to measure the force needed to detach (or move) a ferrofluid droplet from (or on) a "sticky" hydrophobic fibrous surface [e.g., electrospun polystyrene (PS)]. These authors also measured the force needed to make a ferrofluid droplet penetrate into the pores of their hydrophobic surface[25] (see also ref 26 for splitting ferrofluid droplets using a magnetic field). Although the method of ref 21 was easy to implement and accurate for its simplicity, it could only be used for detaching ferrofluid droplets. To expand the application of this method to the case of nonmagnetic fluids (e.g., water), Farhan and Tafreshi[27] have recently developed a new droplet detachment approach in which the nonmagnetic droplet was cloaked with an immiscible ferrofluid (in the form

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