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Universal expression for droplet–fiber detachment force

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The study reported here is devised to formulate the force required to detach a droplet from a fiber in terms of fiber and droplet physical dimensions and wetting properties. More specifically, a series of experiments were conducted to detach ferrofluid droplets from fibers with different diameters and Young–Laplace contact angles (YLCAs) in a controlled magnetic field and to measure their detachment force. Numerical simulation was conducted to complement the experiment and also to provide validation and insights into the balance of forces acting on a detaching droplet. Our analysis starts with proposing a series of expressions that relate droplet detachment force to its geometrical dimensions at the moment of detachment (at the final equilibrium state before spontaneous detachment). To circumvent the need for conducting experiments or computer simulations to obtain these geometric dimensions, we developed a mathematical relationship that uses an existing set of detachment force data, obtained for an arbitrary droplet–fiber system, to predict the force of detachment for the droplet–fiber system at hand. To further facilitate the use of the above relationship, we used our own data to create an easy-to-use correlation for detachment force. This semi-empirical correlation can be used universally for droplet detachment force prediction without the need for running an experiment or a computer simulation for YLCAs greater than about 20°. *Published by AIP Publishing.* https://doi.org/10.1063/1.5032106

I. INTRODUCTION

Formulating the physics of droplet adhesion to a fiber is interesting intellectually and important industrially. A typical example of droplet–fiber interactions in nature is the dew formation on spider webs or cactus spines, where droplets first adhere to such fibrous structures when they are small but then move along the fibers or detach from the fibers when they grow larger.[1–3] Obviously, quantifying the force of adhesion between a droplet and a fiber is crucial in designing fog-harvesting media,[4–8] filtration media for liquid–gas or liquid– liquid separation,[9–13] functional textiles, [14,15] and open microfluidic system among many other applications.[16–19]

Starting with the pioneering work of Carroll four decades ago,[20,21] the droplet equilibrium shape on a single fiber (i.e., symmetric barrel, asymmetric barrel, or clamshell) has been vastly studied by various groups.[22–28] However, only a few studies have been focused on quantifying droplet detachment force from a fiber,[29–35] and each study has been conducted for a specific set of parameters [e.g., droplet volume, fluid surface tension, fiber diameter, and fiber contact angle (CA)] different from those of other studies. The study reported here is a combined experimental–computational investigation focused primarily on measuring the force required to detach a droplet from a fiber in a direction normal to the fiber axis (referred to here as droplet detachment force) for fiber–droplet systems with different dimensions or Young–Laplace contact angles (YLCAs), for the first time. In addition, this paper presents easy-to-use mathematical expressions that can be used to predict the force needed to detach a given droplet from an arbitrary fiber using existing data obtained for a fiber–droplet system with different dimensions or physical properties.

The remainder of this paper is organized as follows: Our experimental procedure and computational method are discussed in Sec. II. Our experimental data are presented and compared with their computational counterparts in Sec. III. A detailed force balance analysis is given in Sec. IV for forces acting on a droplet–fiber system. Section V presents different equations for force estimation and proposes a final universally applicable expression for predicting droplet detachment force from a fiber. This section is followed by our conclusions in Sec. VI.

II. APPROACHES

In this section, we outline the basics of the experimental and computational approaches considered here to quantify the force required to detach a droplet from a fiber.

A. Measuring droplet detachment force

Previous experiments on droplet detachment from a fiber were chiefly driven by either an air-flow (e.g., Refs. 30 and 31) or an external mechanical device like an atomic force microscope (AFM) cantilever (e.g., Refs. 32 and 33). Our group has recently developed a simple ferrofluid-based method to measure droplet detachment force from a fiber. This method allows for a direct measurement of detachment force, and it circumvents many complications that arise from using air-flow or an AFM cantilever. Like every other measurement methods, however, the technique discussed here has some limitations as was discussed previously.[34]

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