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Effects of roughness on droplet apparent contact angles on a fiber

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ABSTRACT

This paper reports on our investigation of the effects of surface roughness on the equilibrium shape and apparent contact angles of a droplet deposited on a fiber. In particular, the shape of a droplet on a roughened fiber is studied via the energy minimization method implemented in the surface evolver finite element code. Sinusoidal roughness varying in both the longitudinal and radial directions is considered in the simulations to study the effects of surface roughness on the most stable shape of a droplet on a fiber (corresponding a global minimum energy state). It is found that surface roughness delays droplet shape transition from a symmetric barrel to a clamshell or an asymmetric barrel profile. A phase diagram that includes the effects of fiber roughness on droplet configurations—symmetric barrel, clamshell, and asymmetric barrel—is presented for the first time. It is also found that droplet apparent contact angle tends to decrease on rough fibers. Likewise, roughness tends to increase the force required to detach a droplet from a fiber but the effect diminishes as droplet size increases relative to the size of surface roughness. The results presented in our study have been compared with experimental data or those from prior studies whenever possible, and good agreement has been observed.

1. Introduction

Understanding the interactions between a droplet and a fiber is of great importance to many applications. These applications include, but are not limited to, droplet filtration/separation, spray coating, electronic cooling, health and safety, fog harvesting, protective clothing, and medicine [1–6]. A simple manifestation of this effect in nature is the dew formation on spider webs or cactus spines, where life relies on the interactions between a droplet and a fiber in arid climate. Droplet–fiber interactions have been studied in many pioneering studies, and it has been shown that the Apparent Contact Angle (ACA) θ_{app} of a droplet with a fiber can be quite different from the Young–Laplace Contact Angle (YLCA) obtained for a small droplet of the same liquid deposited on a flat surface made from the same material [1–6]. Depending on fiber diameter, fiber surface energy, droplet volume, and droplet surface tension, two different conformations have been observed for a droplet deposited on a fiber. The first conformation, the barrel shape, tends to occur for larger droplets (relative to fiber), or for when the YLCA is relatively small. The second conformation, the clamshell, is mostly observed with small droplets, or when the YLCA is relatively high. In the former conformation, the droplet wets the fiber symmetrically while in the latter, the fiber is wetted on one side only. There are also droplet–fiber combinations where both of these conformations can be observed [4–11].

Roughness has been shown to affect the wettability of a surface. Wenzel proposed a relationship between YLCA θ_{YL} and the ACA of a droplet on a rough flat surface as $\cos\theta_{app} = r\cos\theta_{YL}$ where r is the ratio of the actual to the projected area of the rough surface [12]. However, the measured contact angles may not always match the predictions of this simple equation (see e.g., [13–19]). The knowledge gap is even wider when it comes to droplet contact angle on rough fibers (see e.g., [20–24]), and this has served as the motivation for undertaking the work presented here.

The remainder of this paper is structured as follows. First, we introduce our rough fiber equation and discuss the numerical modeling approach used to simulate the 3-D shape of a droplet on such a fiber (Section 2). We then present a validation study where we compare the predictions of our numerical simulations with the experiment for a few simple configurations in Section 3. Our investigations of the effects of surface roughness, fiber diameter, and droplet volume on the shape and ACAs of a droplet deposited are

Abbreviations: ACA, Apparent Contact Angle; PP, Polypropylene; PG, Propylene Glycol; SE, Surface Evolver; ULSD, Ultra Low Sulfur Diesel; YLCA, Young–Laplace Contact Angle.

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