



Full Length Article

Droplet adhesion to hydrophobic fibrous surfaces

M. Jamali^a, A. Moghadam^a, H. Vahedi Tafreshi^{a,*}, B. Pourdeyhimi^b^a Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, Richmond, VA 23284-3015, United States^b The Nonwovens Institute, NC State University, Raleigh, NC, United States

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ABSTRACT

A water droplet can exhibit a high apparent contact angle on a hydrophobic fibrous surface. However, a high contact angle does not guarantee droplet mobility on the surface. The reasons behind droplet adhesion to a hydrophobic fibrous surface has not yet been analyzed or formulated. In this work, the force required to detach a droplet from a hydrophobic fibrous surface is investigated experimentally and computationally. Electrospun Polystyrene mats are considered for this study as they exhibit high contact angles coupled with poor droplet mobility. To better isolate the effects of microstructural properties of the mats and study their effects on droplet detachment, randomness of the fiber orientation is minimized by producing highly oriented fibers in orthogonal layers. As the earth gravity is not strong enough to detach small droplets from such surfaces, aqueous ferrofluid droplets are used in a controllable magnetic field to enhance the effect of gravity. The detachment process is recorded via a high-speed camera and the images are used to detect the moment of detachment and to analyze droplet shape before and during detachment. Numerical simulations are also conducted to provide additional insight into the physics of droplet detachment, and more importantly, to develop an equation for estimating droplet detachment force from a fibrous surface. In this paper, we discuss the effects of fiber properties, e.g., Young-Laplace contact angle or fiber spacing, on the force needed to detach a droplet from a fibrous surface.

1. Introduction

Coating a surface with hydrophobic fibers can serve as a cost-effective alternative to micro-fabricating a hydrophobic roughened surface, a surface characterized by high apparent droplet contact angles (ACAs) [1–8]. Fibrous coatings are usually made by depositing layers of randomly orientated fibers on top of one another, and while a droplet can exhibit high ACAs on such surfaces, its adhesion to the surface may still be quite strong and/or unpredictable [1–8]. Nevertheless, one can assume droplet adhesion to a surface to be somehow related to its contact angle(s) on that surface [9–14].

Previous studies have shown that a droplet deposited on a coating with unidirectional fibers may exhibit different ACAs in different directions [15–18]. Therefore, one can potentially improve or control the adhesion force between a droplet and a fibrous coating by controlling the orientation of the fibers. The easiest way to produce a fibrous mat with directional fibers is to deposit parallel fibers in orthogonal layers. This helps to produce coatings with reasonably controlled thickness and porosities [19–24]. As will be seen later in this paper, the strength of droplet adhesion to such a surface depends strongly on the extent of interactions between the orthogonal fibers and the droplet. In this

work, we characterize these interactions both computationally, via finite element simulations, and experimentally, using coatings comprised of orthogonal electrospun Polystyrene fibers. We obtain the force needed to detach a droplet from such orthogonal fibrous coatings in a direction normal to the surface (referred to here as droplet detachment force).

The remainder of this paper is organized as follows. Section 2 describes our experimental (Section 2.1) and computational (Section 2.2) methods in detail. Section 2 also includes a one-on-one simulation–experiment comparison for model validation. The results of our study are presented in Section 3, in separate subsections for the experiment and computational results. A force balance analysis is presented in Section 4 to better understand forces resisting droplet detachment from a fibrous surface. Section 4.1 describes forces provided by individual fibers in contact with a droplet whereas Section 4.2 presents equations for the overall capillary forces acting on a droplet. Section 4.2 also presents an approximate equation that can be used to estimate the force required to detach a fiber from a fibrous surface.

* Corresponding author.

E-mail address: htafreshi@vcu.edu (H.V. Tafreshi).URL: <http://www.people.vcu.edu/~htafreshi/> (H.V. Tafreshi).

2. Methods

2.1. Droplet detachment experiment

In this section, we first discuss the steps considered in producing electrospun Polystyrene (PS) coatings, and then present our method of measuring the force of adhesion between droplets of different volumes and these orthogonal fibrous structures.

Electrospinning is a means of producing nanofibers from a solution driven by a strong electrostatic field. To produce electrospun PS mats, we dissolved PS pellets in a 70–30 wt% Toluene–Tetrahydrofuran (THF) mixture to obtain a solution with 25 wt% PS concentration (a PS concentration of 25% was chosen based on previous experience with electrospinning PS with the same setup [4,5]). The solution was allowed to rest for a day to ensure homogeneity. A positive voltage of 5.5 kV with respect to a grounded target was applied to a hypodermic syringe tip mounted on a syringe pump with an infusion rate of 2.5 $\mu\text{L}/\text{min}$. The distance between the syringe tip and the target was set to 85 mm. The substrate was a microscope cover glass from McMaster Carr. To produce coatings with aligned fibers the substrate was placed on an axially moving rotating drum with rotational and translational speeds of 1200 rpm and 1.5 cm/s, respectively. The orthogonally-layered structures were made by rotating the substrate by a 90-degree angle after depositing each layer (see [4,5] for more information), and the average fiber-to-fiber spacing was varied by varying the total spinning time for each layer. Fig. 1a shows a SEM image of such an orthogonally-layered fibrous material. Note that, due to the inherent instability of the electrospinning process, it is not easy to obtain perfect fiber alignment or fiber–fiber spacing, and this obviously contributes to the errors associated with our experimental data, as will be discussed later in the paper.

To measure the force required to detach a droplet from a surface, we use ferrofluid droplets in a magnetic field [25]. This method is quite easy to implement, and it is also flexible with regards to changing the direction at which droplet detachment force is measured (see Fig. 1b). This is in contrast to the more established methods through centrifugal forces [26], an atomic force microscope [27], or air flow [28,29]. The force of detachment was measured using a sensitive scale (Mettler Toledo XSE105DU with an accuracy of 0.01 mg). The ferrofluid used in the experiment (purchased from EMG508, Ferrotech, USA) was an aqueous suspension of Fe_3O_4 nanoparticles (contained 1% volumetric) with a mixture density of $\rho = 1.05 \text{ g}/\text{cm}^3$ at 25 °C. Note that, the detachment force obtained from our experiments using a ferrofluid droplet can be generalized to droplets of other fluids after scaling with their surface tension ratios.

Droplets of various volumes (2–7 μL) were produced using a New Era NE-300 syringe pump, and gently deposited on the electrospun mats. The mats were mounted on a 3-D printed holder and the holder was placed on the scale. Next, the scale was zeroed and a magnetic force was vertically applied to the droplet by a nickel-plated axially magnetized cylindrical permanent magnet with a diameter of 22 mm and a length of 22 mm (K&J Magnetics). The magnetic force was increased incrementally by lowering the magnet (attached to a Mitutoyo electronic height gauge) toward the droplet, and the corresponding readings on the scale digital display was videoed (to ensure that the scale reading at the moment of droplet detachment is recorded). Note that the detachment process consists of a series of quasi-static equilibrium states, where droplet shape changes in response to the external force, and a fast and spontaneous process, where it actually detaches from the surface. Our detachment force measurements correspond to the final state of droplet equilibrium before the spontaneous detachment process starts (see [25]). The entire droplet detachment experiment was recorded with a digital high-speed camera (Phantom Miro Lab 340 with) with a Tokina 100 mm F 2.8 D lens. An additional camera (Nikon D3100 camera with an AF-S micro Nikkor 105 mm lens) was used to take pictures from the residue left on the mat or from the

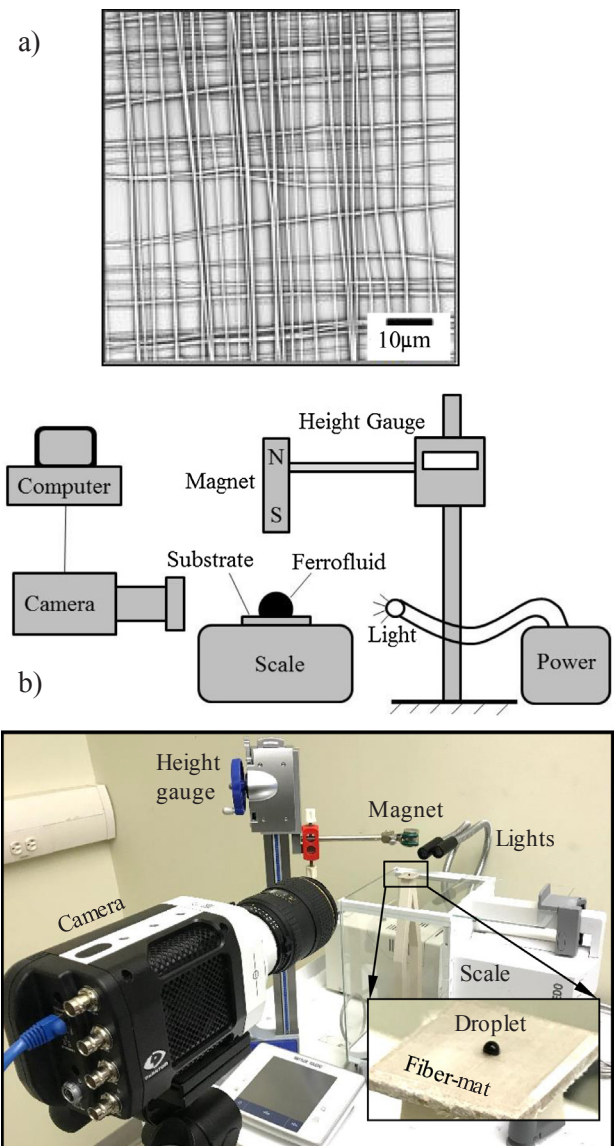


Fig. 1. An example of our electrospun mats comprised of two orthogonal layers (3 min spinning per layer) of aligned PS fibers with a diameter is about 0.5 μm in shown in (a). Schematic and actual image of our experimental setup is given in (b).

droplet at an angle perpendicular to the high-speed camera.

2.2. Droplet detachment simulation

We use the Surface Evolver (SE) finite element code in this work for our simulations. SE uses an iterative method to obtain the equilibrium shape of a droplet by minimizing the total energy of the air–water–solid system (Eq. (1) [30]).

$$E = \sigma A_{aw} - \sigma \cos \theta^{YL} \iint_{A_{sw}} dA + \iiint \rho g z dV_a \quad (1)$$

In this equation, A_{aw} , A_{sw} and V_a denote the air–water and solid–water interfacial area, and droplet volume respectively. Also σ , ρ and θ^{YL} are surface tension, density, and Young–Laplace contact angle, respectively. For our calculations, the solid–water interfacial area A_{sw} and volume of wetted fibers V_s are defined and programed in SE so that the code can correctly calculate the droplet volume V_a in presence of interacting fibers.

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