Penetration of liquid droplets into hydrophobic fibrous materials under enhanced gravity

Cite as: J. Appl. Phys. **125**, 145304 (2019); doi: 10.1063/1.5092227
Submitted: 8 February 2019 · Accepted: 20 March 2019 ·
Published Online: 10 April 2019

View Online Export Citation CrossMark

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ABSTRACT

In this paper, experimental and numerical simulations were devised to study and formulate the force required for forcing a droplet to penetrate into a thin nonwetting fibrous structure. Due to the complexity of the problem at hand, we considered only thin fibrous structures comprised of parallel or orthogonally layered fibers. The experiments were conducted using ferrofluid droplets placed on electrospun polystyrene fibrous coatings. A permanent magnet was used to apply a body force to the droplets from below, and the assembly was placed on a sensitive scale for measuring the applied force. Numerical simulations were conducted using the Surface Evolver finite element code validated through comparison with dedicated experimental results. We studied how the force needed to initiate droplet spontaneous penetration into a thin fibrous coating varies with varying the volume of the droplet or the geometric properties of the coating. Using a combination of simulation results and experimental observations, easy-to-use but approximate expressions were derived and used to predict the force required to initiate droplet spontaneous penetration into the above-mentioned fibrous material. These analytical expressions allow one to circumvent the need for running a numerical simulation for each and every droplet–coating combination of interest and thereby expand the application of our work to conditions different from those considered here.

I. INTRODUCTION

Droplet penetration into the pores of a porous surface may take place spontaneously or in response to an external force, depending on the geometrical and wetting properties of the surface–droplet system.[1,2] Understanding the interactions between a droplet and a fibrous material is of great significance to water-resistant membranes and barriers,[3–7] wound dressing and functional textiles,[8–11] self-cleaning coatings and surfaces,[12–14] fuel cells,[15–17] and fog harvesting[18–20] among many others. Another example of an industrially important problem involving droplet–fiber interactions is the removal of dispersed droplets from a gas (e.g., engine exhaust) or a liquid (e.g., diesel fuel) stream, often referred to as coalescence filtration, which has remained an empirical problem since its infancy. Examples of such studies are the experiments reported in Refs. 21–26 where droplet penetration through a coalescing filter (averaged over the entire exposed surface of the filter) was measured at different air flow rates or for filters made of different polymers. Understanding and formulating droplet–fiber(s) interactions allows one to quantify the tendency of fibrous media to reject or absorb an incoming liquid droplet, and it can be used to custom design the media for their intended specific applications. For instance, in a study on droplet impact on electrospun fibrous membranes, it was shown that inertial droplet penetration into a membrane can be categorized into different regimes depending on the interplay between droplet inertia (promoting droplet penetration) and capillary forces (resisting penetration in the case of hydrophobic membranes, but helping in the case of hydrophilic membranes).[27–30] Such an enabling knowledge can also be used in designing water-repelling membranes for desalination or a variety of other applications as mentioned earlier.[3–20] In this context, the current paper is the first to report the use of a magnetic field in quantifying the resistance of a nonwetting fibrous material to droplet spontaneous penetration. In our study, however, no inertia is considered for the droplets so that a quasistatic approach could be considered to simplify the analysis. More specifically, we use a permanent magnet to measure the force needed to make a ferrofluid droplet penetrate into a thin nonwetting fibrous