LANGMUIR

Article

pubs.acs.org/Langmuir

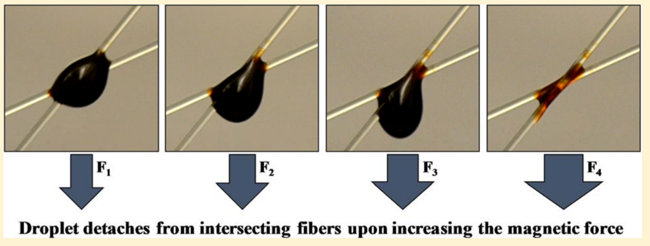
Novel Approach to Measuring the Droplet Detachment Force from Fibers

M. M. Amrei, D. G. Venkateshan, N. D'Souza, J. Atulasimha, and H. Vahedi Tafreshi*

Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, Richmond, Virginia 23284-3015, United States

Supporting Information

ABSTRACT: Determining the force required to detach a droplet from a fiber or from an assembly of fibers is of great importance to many applications. A novel technique is developed in this work to measure this force experimentally by using ferrofluid droplets in a magnetic field. Unlike previous methods reported in the literature, our technique does not require air flow or a mechanical object to detach the droplet from the fiber(s); therefore, it simplifies the experiment and also allows one to study the capillarity of the droplet−fiber system in a more isolated environment. In this article, we investigated the effects of the relative angle between intersecting fibers on the force required to detach a droplet from the fibers in the in-plane or out-of-plane direction. The in-plane and through-plane detachment forces were also predicted via numerical simulation and compared with the experimental results. Good agreement was observed between the numerical and experimental results. It was found that the relative angle between intersecting fibers has no significant effect on the detachment force in the out-of-plane direction. However, the detachment force in the in-plane direction depends strongly on the relative angle between the fibers, and it increases as this angle increases.



1. INTRODUCTION

Understanding the underlying physics of droplet movement inside fibrous media is a challenging problem of crucial importance to many engineering applications such as liquid−liquid separation, liquid−gas filtration, textiles, microfluidics, water transport in fuel cells, and even water harvesting, to name a few.[1−7] A simple manifestation of the role of droplet−fiber interactions in nature is the dew formation on spider webs or cactus spines where life in arid climates relies on the capillarity of fibrous structures.[8,9] Early studies on the interactions between a droplet and a single fiber have mostly been focused on predicting the equilibrium shape of a droplet.[10−16] A few studies have also been dedicated to measuring the force needed to move a droplet along a fiber (e.g., refs 17−23), detach it from the fiber in the perpendicular direction (e.g., refs 24−27, see also refs 28 and 29), or detach it from two intersecting fibers (e.g., refs 30−33). In most of these studies, droplet motion along or away from the fiber(s) has been caused by air flow, surface wetting heterogeneity, or an external mechanical device such as a modified cantilever tip of an atomic force microscope (AFM). The experimental method developed in the work presented here, on the other hand, circumvents many complications that arise from the use of air or an external device to detach or move a droplet. For instance, when air is used as the driving mechanism to detach a droplet from a fiber, the resulting force can become somewhat dependent on the aerodynamic field around the droplet−fiber assembly (e.g., laminar vs turbulent, dependent on the flow orientation with respect to fibers) as well as the geometry of the test chamber used for the experiment.[18,26,27,33] Likewise, bringing an AFM cantilever tip (even treated with a phobic coating) into contact with the droplet, while being an ingenious approach, may change the original problem of a droplet interacting with a fiber to a new problem of a droplet interacting with a fiber and a cantilever tip (and its associated droplet shape changes).[21,24,31] The use of an AFM microscope for such measurements also comes with additional limitations with regard to imaging the droplet during the experiment, the cost of modifying the cantilever tip, and the inconvenience of working with a sophisticated instrument designed for measuring atomic force rather than moving a droplet on a fiber. The method developed in this article is based on using ferrofluid droplets in a magnetic field. It is quite easy to implement and is very flexible with regard to varying the direction in which the force measurement is being conducted. Nevertheless, like most other experimental methods, the method proposed here has some limitations, as will be discussed later in this article.

The remainder of this article is structured as follows. First, our experimental setup and the method used to measure the force required to detach a droplet from intersecting fibers are discussed in Section 2. Our numerical simulations conducted using the finite element Surface Evolver code are described in Section 3. Our experimental and computational results obtained for the detachment of a droplet from a single fiber

Received: August 29, 2016
Revised: October 31, 2016
Published: November 22, 2016

DOI: 10.1021/acs.langmuir.6b03198
Langmuir 2016, 32, 13333−13339