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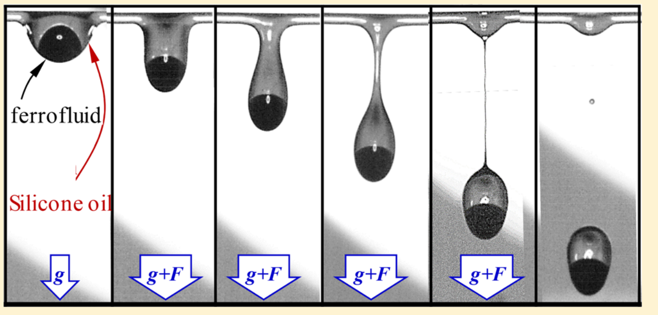
Using Magnetic Field to Measure Detachment Force between a Nonmagnetic Droplet and Fibers

N. M. Farhan and H. Vahedi Tafreshi*

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

Supporting Information



ABSTRACT: The ability to predict and/or measure the force needed to detach a droplet from a fiber (or an assembly of fibers) is important in designing efficient droplet−air or droplet−fluid separation media for a variety of applications. This paper reports on the use of magnetic force to measure the force of detachment for nonmagnetic droplets for the first time. This is accomplished by adding a small amount of ferrofluid (the secondary fluid) to the original nonmagnetic droplet (the primary fluid) to create a compound droplet with the ferrofluid nesting inside or cloaking the nonmagnetic droplet. Either way, the secondary ferrofluid can be used to induce a body force to the resulting compound droplet and thereby detach it from the fiber(s). The recorded detachment force can be used directly (the case of nesting ferrofluid) or after scaling (the case of cloaking ferrofluid) to obtain the force of detachment for the original nonmagnetic droplet. The novelty of the proposed method lies in the fact that it circumvents the need for using an external object, an airflow, or a centrifugal device for force measurement. The accuracy of our measurements was examined through comparison with validated numerical simulations as well as experimental data in the literature and good agreement was observed.

INTRODUCTION

Quantifying the force required to detach a droplet from a fiber is important as it serves as a starting point in design and development of fibrous materials for applications like droplet−air or droplet−liquid separation,[1−6] water management in fuel cells,[7−10] fog harvesting,[11−15] sensing,[16,17] microfluidics,[18,19] or textiles[20,21] to name a few. Understanding droplet−fiber interfacial forces also helps improve our understanding of the nature and how it inspires biomimetic designs.[22,23]

In the context of droplet−fiber(s) interactions, there are currently three experimental techniques reported in the literature for measuring the force required to detach a droplet from a fiber: detachment driven by a high-speed airflow,[24−26] detachment via an external mechanical object like the cantilever tip of an atomic force microscope (AFM),[27−29] and detachment via a magnetic force.[30−32] The problem with using air as the driving mechanism for droplet detachment is that the resulting forces will depend on the specific design of the chamber used for the experiment, that is, the local laminar or turbulent airflow pattern around the deformed droplet. For the second method, the concern is that using an external object to detach a droplet from a fiber changes the original problem of detaching a pendent droplet to a capillary bridge problem, which may further complicate the experiment (requiring additional equipment) and the interpretation of the resulting data. The use of a magnetic field for droplet detachment and force measurement (a noncontact approach) can alleviate some of the above-mentioned problems, but it can only be considered for magnetic fluids (e.g., a ferrofluid), which obviously is a major limitation for the method from an application viewpoint.

Although never used for droplet detachment from a fiber, it is important here to also mention about the use of a centrifugal force in measuring the force of adhesion between a droplet and a surface in a centrifugal adhesion balance device reported in the literature.[34,35]

In the current study, we have developed a novel experimental approach that allows one to use a magnetic force for droplet detachment even when the droplet is nonmagnetic (e.g., a water or an oil droplet). This is done by adding a small amount of ferrofluid (referred to here as the secondary fluid) to the original nonmagnetic droplet (referred to here as the primary fluid) to create a compound droplet. The secondary ferrofluid can then be used to apply a body force to the resulting compound droplet and thereby detach it from the fiber(s). As will be discussed later in this paper, the secondary fluid may reside inside the primary droplet in the form of a nested droplet[36,37] or wrap around it in the form of a cloak.[40−43] The detachment force measured for the compound

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