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Measurement of inflection angle and correlation of shape factor of barrel-shaped droplets on horizontal fibers

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ABSTRACT

The properties and shapes of drops attached to fibers are important for understanding the movements of drops on fibers in applications such as coalescing filters. One of the features of the shape of a drop attached to a cylindrical fiber is an inflection in the curvature of the drop profile near the contact line between the drop and the fiber surface. Depending on the drop volume, the point of inflection may occur very close to the drop-fiber contact line, and the angle at the inflection point could mistakenly be interpreted as the intrinsic contact angle. Measurement of the angle at the inflection point improves the characterization of the drop profile for a drop-on-fiber system. Many studies provide methods that apply droplet geometric symmetry to extract the profile of drops on flat surfaces. However, none of these methods can be easily applied to drops on fibers due to the curvature of the fiber surface and its effect on the shape of the drop. In the case of drops on fibers, drop properties such as drop length, thickness, inflection angle and volume are useful to obtain the wetting properties of the fiber surfaces without knowing the liquid properties. To determine inflection angles and volumes of axisymmetric barrel-shaped droplets on fibers from 2D images of droplets profiles a polynomial fitting method for fibers (PFMF) was applied. The strategy employed detects the location of the droplet boundary, fits a polynomial to the boundary, and calculates the inflection angle and the volume of the droplet. Volume measurements using the PFMF were consistent with calculations from Surface Evolver™ program. Using the PFMF, a new correlation was generated for a shape factor characterizing the asymmetry of barrel-shaped droplets as a function of liquid properties, fiber radius, and droplet volume.

1. Introduction

The study of wetting properties of surfaces is of significant interest in a wide range of industrial applications. While many previous studies have focused on the analysis of the shape of sessile drops on flat surfaces, more detailed studies need to be carried out to better understand the behavior and shapes of liquid droplets on cylindrical surfaces [1,2] and fiber surfaces, [3–6].

The understanding of drop interactions with single fibers is fundamental to understanding behavior of drops in contact with multiple fibers, as in coalescing filters. A recent review of coalescing filters is given by [7]. In future work the methodologies described here for droplet interactions with a single fiber may be extended to the more complex nature of multi-fiber interactions.

The chemistry and global geometry of the surface and liquid properties are key factors that influence the shape of liquid drops on surfaces [8]. The global geometry of cylindrical fibers can cause the drop to have a different shape compared to when it is placed on a flat surface. It has been shown that, even a contact angle of 0° results in droplet formation on cylindrical fibers [9,10]. The presence of gravity also has an important effect on the shapes of droplets as shown in Fig. 1. Fig. 2 shows the effect of wetting properties on the shapes of drops on fibers. Depending on the contact angle between the droplet and the fiber, the shape of a droplet on a non-wetting surface can range from a spherical cap to a near sphere [11].

As shown in Fig. 3 in general there is a difference between the intrinsic contact angle of a drop on a fiber and the inflection angle of its profile. The inflection angle is useful to characterize the shape of the drop along with a shape factor, $\varepsilon = \frac{X_1}{X_2}$. Accurate description of the drop shape is necessary when images of the drop are used to determine properties including drop volume and intrinsic contact angle.

Provided the Young contact angle is small, the axisymmetric barrel shape conformation occurs in systems where capillary rather than gravity forces define the shape of the drop. As reported in the literature [12,13], an axisymmetric barrel shape is the preferred conformation when Goucher number (or equivalently Bond number [14] defined as

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Nomenclature

Symbols

Bo	bond number
Bo_G	Gilet bond number
g	gravitational acceleration (m/s^2)
Go	Goucher number
m	mass of the droplet
r_f	radius of fiber (m)
V	volume of droplet
X_1	thickness of the upper part of the droplet (m)
X_2	thickness of the lower part of the droplet (m)
γ	surface tension of the liquid droplet (N/m)
ε	shape factor
θ_i	inflection angle
θ_Y	young contact angle
κ^{-1}	capillary length (m)
ρ	density of the liquid droplet (kg/m^3)

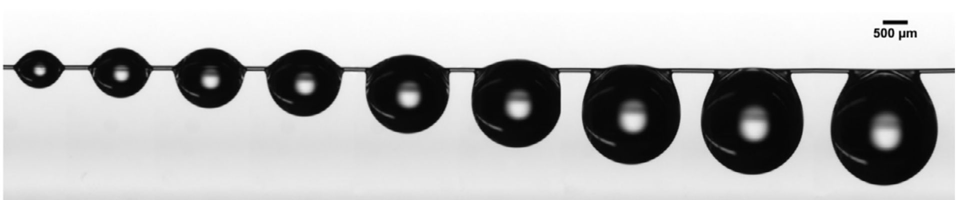

Fig. 1. Change in the shapes of barrel-type Diesel droplets on a Polypropylene fiber by increasing the volume of the droplets (in the presence of gravity).

$Bo = Go^2$) is small. The Goucher number is defined as $Go = \frac{r_f}{\kappa^{-1}}$ where r_f is the radius of fiber and $\kappa^{-1} = (\frac{\gamma}{\rho g})^{0.5}$ is the capillary length. In a study by McHale et al. [15], it was shown that the gravity-induced asymmetry between the upper and lower profiles reduced as the radius of fiber decreased, and symmetric droplets were obtained when the Goucher number was less than 0.05. However, even when the fiber radius is very small ($r_f \ll \kappa^{-1}$), the observed drop shape was asymmetric if the drop thickness ($x_1 + x_2$) is of the order of κ^{-1} [16]. In conclusion, not only the radius of fiber, but also the volume of the droplet must be considered. To do that, Gilet et al. [17] suggested a new Bond number ($Bo_G = \frac{mg}{4\pi r_f \gamma} = \frac{V}{4\pi r_f \kappa^{-2}}$) as the ratio of the droplet weight to the capillary forces. The shape factor of a droplet, however, is not clearly defined by Gilet Bond number. Therefore, to better describe the transition of an axisymmetric barrel-shaped droplet to an asymmetric barrel shaped droplet, here, we provide a new correlation for the shape factor (ε) of the droplet.

It is well understood that a droplet, depending on its dimensional and chemical properties, can form different shapes on fibers with different sizes and surface properties [18,19]; the real problem is, however, encountered when attempting to make precise measurements of the drop dimensions, which is particularly difficult for smaller fibers. Such drop shape analyses are abundantly provided for drops on flat surfaces [20–26], due to a broad availability of image analysis software programs that handle the profiling of the sessile drop shape. However, this task is not as straightforward for drops on fibers since the cylindrical geometry of fibers affects the drops shapes. Although, there are some studies focusing on the extraction of contact angle of a drop on fiber from the drop profile properties such as drop length [27,28], thickness [29], and inflection angle [15,30,31], none aimed to provide reliable, accurate methods to measure such properties for a drop-on-fiber system. Therefore, in this study, we present a method to measure inflection angle (θ_i) and volume of the axisymmetric droplets on fibers, which are among the most challenging measurements for the case of nanoliter drops on fibers, from 2D images of the droplets profiles. To extract the shape of a drop on fiber, a polynomial fitting method for fibers (PFMF) was used.

Software programs are available that can model the surfaces of liquid-gas interfaces. In particular the software Surface Evolver™ [32] was developed based on minimizing surfaced energy by a gradient descent method. Surface Evolver™ has been used to study the shapes of drops on fibers [8] and to validate theoretical models [33]. Unfortunately, Surface Evolver™ requires input of drop volume, hence requires trial and error to fit to an image of a drop to determine the drop volume. The PFMF approach provides a direct method to determine the drop volume without the trial and error, but PFMF must be validated.

The PFMF is validated here by comparing the volumes of drops calculated by PFMF from images of drops generated by Surface Evolver™ of known volumes. It is assumed that because the volumes were accurately reproduced that the shape of the surface was also accurately calculated. The PFMF approach is subsequently applied to determine the change of inflection angle with drop volume and to fit a shape factor correlation.

2. Materials and methods

2.1. Polynomial fitting method for fibers (PFMF)

A polynomial fitting method, among automated drop shape analysis techniques for sessile drops [34], is an accurate way of extracting the

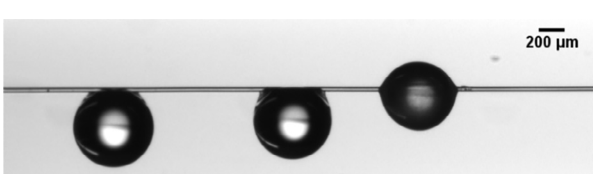

Fig. 2. Change in the droplet shape due to different wetting properties. Liquid drops are approximately the same volume (90 nL) on a polypropylene fiber. Drops from left to right are water, 40% Ethanol and water, and Acetone. The acetone droplet is an asymmetric barrel-shaped drop and the other two are clamshell-shaped drops whose shapes are strongly influenced by large Young contact angles rather than gravity.

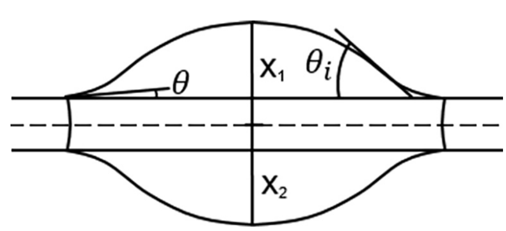

Fig. 3. Schematic side view of an idealized axisymmetric barrel-shaped drop on fiber with shape factor $\varepsilon = \frac{X_1}{X_2}$=1 showing the geometrical parameters for the description of a drop on a single fiber. θ is the intrinsic contact angle, θ_i is the inflection angle. In this study, droplets with a shape factor $\varepsilon \geq 0.85$ are considered axisymmetric barrel-shaped drops.