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# Effect of fiber orientation on shape and stability of air–water interface on submerged superhydrophobic electrospun thin coatings

B. Emami, H. Vahedi Tafreshi,[a)] M. Gad-el-Hak, and G. C. Tepper
*Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, Richmond, Virginia 23284–3015, USA*

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To better understand the role of fiber orientation on the stability of superhydrophobic electrospun coatings under hydrostatic pressures, an integro-differential equation is developed from the balance of forces across the air–water interface between the fibers. This equation is solved numerically for a series of superhydrophobic electrospun coatings comprised of random and orthogonal fiber orientations to obtain the exact 3D shape of the air–water interface as a function of hydrostatic pressure. More important, this information is used to predict the pressure at which the coatings start to transition from the Cassie state to the Wenzel state, i.e., the so-called critical transition pressure. Our results indicate that coatings composed of orthogonal fibers can withstand higher elevated hydrostatic pressures than those made up of randomly orientated fibers. Our results also prove that thin superhydrophobic coatings can better resist the elevated pressures. The modeling methodology presented here can be used to design nanofibrous superhydrophobic coatings for underwater applications. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3697895]

## I INTRODUCTION

It is known that a hydrophobic surface with micro- or nano-scale roughness can produce superhydrophobicity.[1] When a superhydrophobic surface is brought in contact with water (the non-wetting fluid here), the surface pores can stay dry, entrapping air within their structure, which leads to a reduction in the solid surface area in contact with the water. A reduced contact area can result in a reduction in the skin-friction drag exerted on submerged objects such as ships or torpedoes in relative motion to the water. When the pore space on a superhydrophobic surface is filled with air, the system is at the Cassie state.[2] When water penetrates into the pores and completely replaces the air, the system transitions to the Wenzel state,[3] and the superhydrophobicity together with any drag-reducing advantage vanish. The hydrostatic pressure at which a superhydrophobic surface starts departing from the Cassie state, and therefore the superhydrophobic property starts to vanish, is herein referred to as the critical pressure.[4–6] Note that the focus of this study is the critical pressure of static or quasi-static penetration. Under dynamic penetration regimes, e.g., droplet impact on a superhydrophobic surface, the transition from Cassie state may occur at a much lower pressure.[7–9]

Balance of forces has been used to investigate the shape and stability of the air–water interface on superhydrophobic surfaces with ordered microstructures.[4,6,10–16] Our group has recently used balance of forces to calculate the shape and stability of the air–water interface on superhydrophobic surfaces with randomly distributed posts of dissimilar sizes, heights, and materials[17] as well as elliptical and polygonal shallow pores.[18]

In the current paper, we present a general method that can be used to obtain the exact 3D shape of the air–water interface on any arbitrary surface under elevated pressures. This information, specifically, can be used to obtain the critical pressure for surfaces and coating used in underwater applications.[19–25] We apply the balance of forces (and the first law of thermodynamics) on the air–water interface while accounting for the changes in the pressure of the entrapped air caused by the deflection of the interface. Our force balance analysis results in an integro-differential equation for the interface shape, which can then be solved numerically and used to obtain the pressure at which the surface departs from the Cassie state, i.e., the critical pressure. Unlike many previous works, the air–water meniscus is not forced to maintain a constant curvature inside pores of non-circular cross-sections.

Manmade superhydrophobic surfaces are often manufactured via microfabrication of hydrophobic grooves or posts. Microfabrication, however, is a costly process and cannot easily be applied to large surfaces with arbitrary shapes. An alternative approach to produce a superhydrophobic surface is by depositing hydrophobic fibers on a substrate using electrospinning.[26–29] With the traditional dc-electrospinning, however, one has less control over the coating microstructure (see Fig. 1(a)). Tepper and his co-workers have proposed the so-called dc-biased ac-electrospinning to better control the orientation of the fibers in a fibrous mat (see Refs. 7–9, 30, and 31 for detailed information about dc- and ac-electrospinning). The image shown in Fig. 1(b) is an example of a coating produced via dc-biased ac-electrospinning. It is expected that either dc- or ac-electrospinning can be used in the future to "engineer" superhydrophobic surfaces for different technologies including underwater/submerged applications.

The first attempt to predict the stability of air–water interface on an electrospun coating was the work of Tuteja *et al.*[16] These authors considered a simplified geometry of

[a)]Author to whom correspondence should be addressed. Electronic mail: htafreshi@vcu.edu.

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