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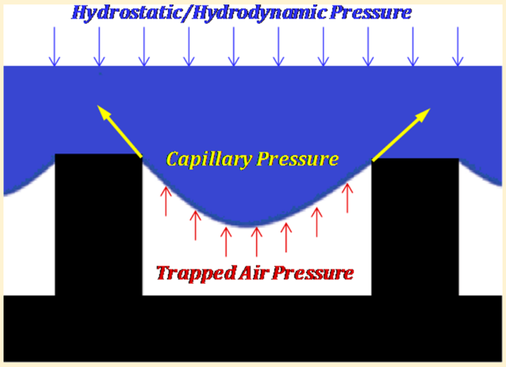
General Formulations for Predicting Longevity of Submerged Superhydrophobic Surfaces Composed of Pores or Posts

A. A. Hemeda and H. Vahedi Tafreshi*

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

ABSTRACT: Superhydrophobicity can arise from the ability of a submerged rough hydrophobic surface to trap air in its surface pores, and thereby reduce the contact area between the water and the frictional solid walls. A submerged surface can only remain superhydrophobic (SHP) as long as it retains the air in its pores. SHP surfaces have a short underwater life, and their longevity depends strongly on the hydrostatic pressure at which they operate. In this work, a comprehensive mathematical framework is developed to predict the mechanical stability and the longevity of submerged SHP surfaces with arbitrary pore or post geometries. We start by deriving an integro-partial differential equation for the 3-D shape of the air—water interface, and use this information to predict the rate of dissolution of the entrapped air into the ambient water under different hydrostatic pressures. For the special case of circular pores, the above integro-partial differential equation is reduced to easy-to-solve ordinary differential equations. In addition, approximate nonlinear algebraic solutions are also obtained for surfaces with circular pores or posts. The effects of geometrical parameters and hydrostatic conditions on surface stability and longevity are discussed in detail. Moreover, a simple equivalent pore diameter method is developed for SHP surfaces composed of posts with ordered or random configuration—an otherwise complicated task requiring the solution of an integro-partial differential equation.



1. INTRODUCTION

Superhydrophobic (SHP) surfaces are characterized by water droplets beading on them with contact angles exceeding 150°. This is thanks to the peculiar ability of such surfaces in trapping air in their pores, thereby reducing the contact between water and the solid surface (the Cassie state).[1] The reduced solid—water contact area can result in a reduction in the skin-friction drag, if the surface is exposed to a moving body of water.[2] For such applications, the stability of the air—water interface (AWI) under pressure is critically important. An elevated pressure can force the water into the air-filled pores of the surface and lead to a partial or complete wetting of the surface (the Wenzel state). A similar phenomenon also takes place during the evaporation of a droplet on an SHP surface: pressure inside the droplet increases due to evaporation and forces the AWI into the air-filled pores beneath the droplet.[3−6] The method of balance of forces has been used to predict the pressure at which the surface starts transitioning from the Cassie state to the Wenzel state, the critical pressure, for surfaces made up of grooves, posts, and particles.[7−14] Critical pressure has also been measured experimentally in many pioneering studies.[15−19] While critical pressure can be used to judge if the Cassie state is mechanically stable under elevated pressures, it is the surface longevity that matters the most for a submerged SHP surface. Longevity is the time that it takes for an SHP surface to transition to the Wenzel state. Optical techniques have been used to experimentally estimate the longevity of SHP surfaces with different microstructures under elevated pressures.[15,20−24] These studies have shown that longevity decreases with increasing hydrostatic pressure. No theory, however, has yet been developed to establish a quantitative relationship between the longevity of an SHP surface and its microstructural parameters (e.g., diameter and height of posts or pores). Our group was the first to propose a mathematical framework to quantify the longevity of an SHP surface.[25] Our previous study, however, was only applicable to surfaces made of parallel grooves as the equations were derived in a 2-D space (see also ref 26). In the current work, new formulations are derived in a generalized 3-D form such that predicting the critical pressure and longevity of surfaces composed of dissimilar pores and posts with arbitrary round cross sections (not necessarily circular) with ordered or random arrangements is made possible. The formulation presented in this work can directly be used to design and optimize the microstructure of an SHP surface for different applications ranging from self-cleaning to underwater drag reduction.

Our generalized formulations for critical pressure and longevity predictions are presented in section 2 for surfaces made of arbitrary pores and posts. Specific solution methods and closed-form analytical expressions are derived for surfaces with circular pores and circular posts in sections 3 and 4, respectively. Proposing new equivalent pore diameter defi-

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