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Underwater Superhydrophobiciy: Fundamentals and Applications

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Abstract

Bioinspired superhydrophobic surfaces have attracted great interests from fundamental researches to engineering applications. The functionality of superhydrophobicity, especially for an underwater situation, depends on a large area fraction of entrapped liquid-gas interfaces, which, however, are subject to instabilities induced by various physical phenomena, such as pressurization, air diffusion, fluid flow, and condensation. The wetting states strongly affssect the functionality of superhydrophobic surface, like liquid slippage and cavitation. The current work is dedicated to elucidating the underlying mechanisms of stability and wetting transition of underwater superhydrophobicity, providing novel strategies for durable and robust design, and introducing the applications in drag reduction and cavitation control.

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Keywords: Wetting Stability, Drag Reduction, Superhydrophobic Surfaces, Wetting Transition

1. Introduction

Bioinspired superhydrophobic surfaces are enabled by an optimized combination of surface roughness and material chemistry [1], and have great potential applications in self-cleaning, drag reduction, and energy conversion [2-4]. The key mechanism to realize superhydrophobicity is to maintain a large area fraction of liquid-gas interfaces in a pinning Cassie state. However, the stability of Cassie state can be affected by various physical phenomena. By inducing pressurization, a fully wetted Wenzel state can be induced by wetting transition, leading to the collapse of the menisci and the failure of the superhydrophobicity. When these surfaces are fully submerged underwater, air diffusion from entrapped air cavities into bulk water may also gradually result in wetting transition, and can be further deteriorated under fluid flow conditions. Moreover, microdroplet condensation within air cavities could also lead to wetting transition. Understanding the wetting transition mechanisms is essential for the design and regulation of Cassie-based superhydrophobicity and its functionality. In this work, we investigate the stability and wetting transition of submerged superhydrophobic surfaces influenced by pressure, air diffusion, fluid flow, condensation, and propose strategies for robust design.

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2. Stability of underwater superhydrophobicity

In a submerged environment, the entrapped air cavities on structured hydrophobic surfaces are isolated from the ambient. The equilibrium of closed air cavities can be established only if both mechanical and chemical ones are achieved. The mechanical equilibrium is governed by the balance of the capillary pressures and the pressure difference between water and entrapped air. Meanwhile, chemical equilibrium is controlled by the air exchange between entrapped air cavities and dissolved air in the bulk water, in which the process can be accelerated by fluid flow in a convection-diffusion regime. Moreover, microdroplet condensation within microcavities is another physical mechanism affecting the stability of underwater superhydrophobicity. In what follows, we will examine in details to see how physical factors lead to the wetting transition of submerged superhydrophobic surfaces.

2.1. Pressurization

Pressurization is one of the most important factors leading to the wetting transition of submerged superhydrophobic surfaces, which greatly limits their applications. The volume of trapped air in the air cavities decreases once the water pressure is enhanced, which can lead to the sliding of the three-phase contact line and consequently the wetting transition. Taking submerged cylindrical micropores structured superhydrophobic surface for example, we can obtain the equilibrium states of the system and the wetting transition process by analyzing the system free energy under different hydrostatic pressures.

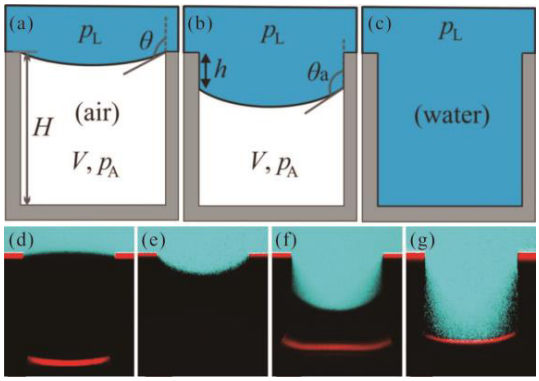

Fig. 1. Schematics of different wetting states (a-c) and confocal microscopy images of different wetting states (d-g). (a) Cassie state; (b) metastable state; (c) Wenzel state; (d) Cassie state; (e) critical pinning state; (f) metastable state; (g) Wenzel state.

Combining the bulk energy of air G_b, the potential energy of liquid G_g, and the total surface energy G_s, the free energy G is expressed as $G = G_b + G_g + G_s$. Considering the gas as ideal gas, the free energy G is written as [5],

$$\tilde{G} = \frac{1-f}{\gamma_{lg}\pi r^2}[(p_1 - p_l)V_{in} + (p_0 - p_l)V_0 + p_0 V_0 \ln\frac{p_l}{p_0}] + (1-f)(2\frac{1-\cos\theta}{\sin^2\theta} - \frac{2h}{R}\cos\theta_e - 1), \tag{1}$$

where $\tilde{G}$ is the nondimensionalized total free energy, f is the solid fraction, γ_{lg} is the liquid gas surface tension, r is the radius of the micropore, p_1 and p_0 are the reference and final states pressure of the air, p_l is the liquid pressure, V_0 and V_{in} are the volume of the micropore and the liquid protruding into the pore, respectively, θ is the