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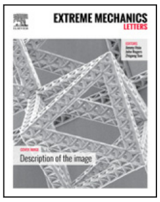

Morphology evolution of liquid–gas interface on submerged solid structured surfaces

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ABSTRACT

liquid–gas interface (LGI) on submerged solid structured surfaces is ubiquitous in nature and has various practical applications. The evolution, equilibrium, and stability of LGI are crucial to the underwater performances and functionalities of the surfaces, such as wetting, drag reduction, heat and mass transfer, etc., and have been studied for decades. In this review, we systematically summarize the underlying mechanisms of the morphology evolution of LGI on submerged solid structured surfaces under both quiescent and flow conditions. First, a thermodynamic framework for the analysis of the equilibrium and stability of submerged LGI in quiescent ambient is introduced. The conditions necessary to achieve equilibrium are surveyed. Then, both effects of hydrostatic pressure and gas diffusion on the morphology evolution of submerged LGI are reviewed. Some specific topics on interface morphologies, critical pressure, metastable state and gas diffusion equilibrium state are discussed. Finally, the morphology evolution of LGI under flow conditions is reviewed, including the effects of laminar and turbulent shear flow, and the flow enhanced gas diffusion.

Contents

1. Introduction

When a solid is submerged underwater, the roughness on the surface may not be fully wetted to form the Wenzel state [1]. In contrast, gas usually can be trapped in the surface structures to

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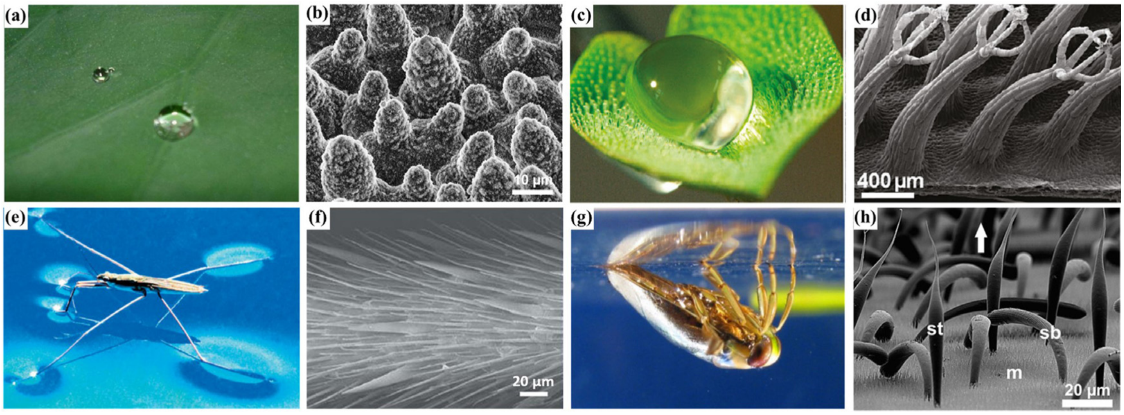

Fig. 1. Underwater liquid–gas interface in nature. (a, b) Lotus leaf: water repellency of lotus leaf due to LGI (a) and the SEM image of the hierarchical micro/nano-structures on the leaf (b). (a) (Reprinted from Guo et al. [2], Copyright 2007, with permission from Elsevier). (b) (Reprinted from Ensikat et al. [3], Copyright 2011, with permission from Beilstein-Institut). (c, d) *Salvinia* leaf: a submerged *Salvinia* leaf with thick entrapped air layer (c) and the SEM image of the eggbeater-shaped structures on *Salvinia* leaf (d) (Reprinted from Koch et al. [4], Copyright 2009, with permission from American Chemical Society). (e, f) Water strider: a water strider walking on the water (e) and the SEM image of the hairy structures on its legs (f). (e) (Reprinted from Feng et al. [5], Copyright 2006, with permission from John Wiley and Sons). (f) (Reprinted from Gao et al. [6], Copyright 2004, with permission from Springer Nature). (g, h) Backswimmer *Notonecta glauca*: a resting backswimmer *Notonecta glauca* submerged in water which is covered by a silvery air plastron entrapped in the hairy structures on its body (g) and the SEM image of the hairy structures (h). (g) (Reprinted from Ditsche-Kuru et al. [7], Copyright 2011, with permission from Beilstein-Institut). (h) (Reprinted from Balmert et al. [8], Copyright 2011, with permission from John Wiley and Sons).

achieve the Cassie–Baxter (CB) state [9,10], consequently resulting in the formation of the liquid–gas interface (LGI) which profiles the boundary of a gas layer or the shape of a bubble [11,12]. Many aquatic species in nature are capable to form LGI around the body to adapt to the underwater conditions. For example, the hierarchical micro-/nano-structures on lotus leaves can support a large area of LGI, leading to the extreme water repellency and self-cleaning property [2–4,13,14] (Fig. 1a, b). The eggbeater trichomes on *Salvinia* leaves are able to stabilize a thick air layer, which can be retained for several weeks [4,15,16] (Fig. 1c, d). Some aquatic insects, such as water strider [5,6,17] (Fig. 1e, f) and backswimmer *Notonecta glauca* [7,8,18,19] (Fig. 1g, h), have hairy structures on their bodies to maintain a continuous LGI, which renders them the abilities to walk on water or breathe underwater. Inspired by nature, researchers have tried to achieve a large area fraction of LGI by designing structured surfaces to implement various underwater functionalities, such as superhydrophobicity [10,20,21], low adhesion [22], and significant liquid slippage [23–26]. Promising applications are also explored in antifouling [27–29], drag reduction [23,30–36], cavitation control [37–41], heat transfer [41–43], etc. All these underwater applications rely on the realization of a large stable LGI, which is the key for excellent performances.

In practical situations, the submerged LGI will be subject to varieties of instabilities and thus the morphology of LGI will evolve as a gas layer or a bubble in many different ways, such as expansion, growth, coalescence, shrinkage, collapse, deformation, and detachment from the surface [44–47]. On the one hand, the LGI will decay due to various reasons like pressurization [48,49], vibration [50], gas diffusion [51,52], and flow condition [53,54], which leads to the wetting transition from CB state to Wenzel state and greatly degrades the performances like water repellency and drag reduction. On the other hand, the reverse process from Wenzel state to CB state indicates the other kind of wetting transition that recovers the LGI as well as the functionalities by depressurization [55,56], gas generation [57–59], electrowetting [60–62], vibration [63,64] etc. The development history of LGI morphology from one state to another, which is called evolution path, depicts the whole changing process of LGI morphology on submerged structured surfaces, revealing the basic regulations of the morphology evolution. Moreover, different topographies of the structured surface will also significantly influence the morphology evolution of LGI [10,44,65]. Reasonable design can enhance the stability, prolong the lifetime, and even achieve the self-recovery of submerged LGI. Therefore, understanding the fundamental mechanisms of morphology evolution and predicting the evolution path are very important and will benefit the design of structured surfaces to achieve the extraordinary properties [66].

Different from the previous reviews, which focused on either the applications of (superhydrophobic) structured surfaces [44,66] or the behaviors of some specific bubbles, like vapor bubbles [67] and nanobubbles [12], this review aims at providing a whole picture of the morphology evolution of LGI on submerged solid structured surfaces and discussing the underlying mechanisms, especially under the influences of hydrostatic pressure, gas diffusion, and fluid flow. First, we will discuss the LGI evolution in quiescent condition in Section 2. A thermodynamic model will be introduced and the effects of hydrostatic pressure and gas diffusion will be addressed individually. Then, we will discuss the effect of fluid flow on LGI evolution in Section 3, especially on the deformation of LGI induced by shear flow and the longevity of LGI regulated by gas diffusion in flow. Finally, we will draw a conclusion and present an outlook in Section 4.

2. Morphology evolution of submerged liquid–gas interfaces under quiescent condition

In quiescent ambient, the morphology evolution of submerged LGI undergoes two consecutive processes, i.e., a mechanical process with a rapid geometrical response of the LGI under hydrostatic pressures, followed by a chemical process with a gradual morphology evolution of the LGI governed by gas diffusion. This section thus focuses on the effects of both hydrostatic pressure and gas diffusion on the morphology evolution of LGI on submerged structured surface under quiescent condition. First, a thermodynamic model will be introduced to analyze the equilibrium and stability of the submerged LGI. Then, the effects of hydrostatic pressure and gas diffusion will be discussed individually.

2.1. Thermodynamic model

A few of theoretical approaches have been proposed to analyze the thermodynamic behaviors of LGI on the submerged structured surface. Force balance analysis is well applied in describing the LGI morphology under hydrostatic pressures [68–70]. Theory of