Convective Mass Transfer From Submerged Superhydrophobic Surfaces

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Received date //////; Accepted date //////

Abstract
Longevity of entrapped air is an outstanding problem for using superhydrophobic coatings in submersible applications. Under pressure and flowing water, the air micropockets eventually dissolve into the ambient water or burst and diminish. Herein, we analyze from first principles a simple mass transfer problem. We introduce an effective slip to a Blasius boundary layer, and solve the hydrodynamic equations. A slowly evolving, non-similar solution is found. We then introduce the hydrodynamic solution to the two-dimensional problem of alternating solid–water and air–water interfaces to determine the convective mass transfer of air's dissolution into water. This situation simulates spanwise microridges, which is one of the geometries used for producing superhydrophobic surfaces. The mass-transfer problem has no similarity solution but is solvable using approximate integral methods. A mass-transfer solution is achieved as a function of the surface geometry (or gas area fraction), Reynolds number, and Schmidt number. The analytical results are compared to numerical simulations of the laminar Navier–Stokes equations. Longevity, or time-dependent hydrophobicity, can be estimated from the resulting mass-transfer correlation.

1. NTRODUCTION

Superhydrophobic coatings possess a strong water-repellent characteristic, which enhances the mobility of water droplets over such surfaces [1]. The coating traps air within its micropores, such that a submerged, moving body experiences shear-free and no-slip regions over, respectively, the air pockets and the solid surface. This, in turn, may lead to significant skinfriction reduction [2, 3]. Additional applications of hydrophobic surfaces include enhancing evaporation [4, 5, 6], hindering frost [7, 8, 9, 10], and resisting corrosion [11, 12].

A popular method of manufacturing a superhydrophobic surface is microfabrication in which microridges or posts are placed on a surface in a regular configuration [13, 14, 15]. The orientation with respect to the flow, spacing, and aspect ratio of the microposts or microridges can be adjusted to optimize the drag reduction [16] and the stability of the air–water interface [17] against transition from dewetted Cassie [18] to wetted Wenzel [19] state.

The coating maintains its superhydrophobicity as long as the air remains entrapped. Even when the air–water interface on a submerged superhydrophobic surface is mechanically stable, the surface is likely to lose its entrapped air over time. This effect is believed to be due to the dissolution of air into water, and is expected to accelerate when the hydrostatic pressure is increased, as the solubility of air into water increases with pressure [20, 21], and when the flow speed increases, which enhances convective mass transfer [22]. Several approaches have recently been developed to measure the longevity of superhydrophobic surfaces [20, 23, 24, 25]. Analytical approaches are lacking, however, due to the complexity of the problem.

In this work, we present a first-principles model to predict the rate of mass transfer of air from superhydrophobic surfaces with spanwise ridges. We assume a two-dimensional, laminar boundary flow over such a surface and solve the decoupled hydrodynamic and mass transfer problems. A single-phase flow is assumed, and the air pockets supply only a linearized boundary condition. While more