Convective Mass Transfer from Submerged Superhydrophobic Surfaces: Turbulent Flow

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ABSTRACT
Superhydrophobic surfaces have received considerable attention in recent years. The surface has a strong water-repellent characteristic that could produce slip flow and drag reduction. 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, holds promise for a broad range of applications. Longevity of the entrapped air is an outstanding problem for these coatings. Under pressure and flowing water, the air micropockets eventually dissolve into the ambient water or burst and diminish. Herein, we analyze from first principles an air mass transfer problem. Using integral methods, we extend our prior laminar flow solution to turbulent flows. We introduce an effective slip to the turbulent boundary layer characterized by a modified 1/7-power law velocity profile. 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 decoupled mass-transfer problem is solv-able using an approximate integral method previously optimized by Reynolds, Kays, and Kline (1958). A mass-transfer correlation is derived as a function of the surface geometry (or gas area fraction), Reynolds number, and Schmidt number. Longevity, or time-dependent hydrophobicity, could be estimated from the resulting mass-transfer correlation. As expected, turbulence greatly enhances the rate of convective mass transfer, and thus superhydrophobicity is not maintained as long as it would be under corresponding laminar flow conditions.

1. INTRODUCTION

Superhydrophobic surfaces employ optimally designed surface chemistry and roughness to repel water. They are characterized by water droplets beading on the solid surface at static contact angles (CA) exceeding 150°, and by significantly low contact-angle hysteresis. Amongst several others, examples of such surfaces in nature are the self-cleaning lotus leaves [1]. When submerged, these surfaces can entrap air between their micro-or nanostructures re-sulting in a surface with alternating air-water and solid-water interfaces. The presence of the air-water interface is responsible for the "slip effect", resulting in a reduction in the skin-friction drag exerted on a moving surface [2, 3]. Rothstein [2] reports drag reduction exceeding 40% and 50% in, respectively, laminar and turbulent flows, although Gad-el-Hak [4] argues that the turbulent flow results are less reliable.

Most engineered superhydrophobic surfaces are made up of microposts or microridges manufactured via advanced microfabrication techniques [5, 6]. Large-scale manufacturing of such surfaces is prohibitively expensive. An alternative solution to circumvent the high cost is to produce surfaces made up of random deposition of hydrophobic particles or electrospun fibers [3]. Along with the challenges of microfabrication, the lifetime of the surface is also a factor for the applicability of the coating. As long as air pockets are entrapped in the coating's pores, the surface remains