Modeling drag reduction and meniscus stability of superhydrophobic surfaces comprised of random roughness

Mohamed A. Samaha,[a] Hooman Vahedi Tafreshi,[b] and Mohamed Gad-el-Hak[c]
Department of Mechanical Engineering, Virginia Commonwealth University, Richmond, Virginia 23284-3015, USA

(Received 30 July 2010; accepted 6 December 2010; published online 11 January 2011)

Previous studies dedicated to modeling drag reduction and stability of the air-water interface on superhydrophobic surfaces were conducted for microfabricated coatings produced by placing hydrophobic microposts/microridges arranged on a flat surface in aligned or staggered configurations. In this paper, we model the performance of superhydrophobic surfaces comprised of randomly distributed roughness (e.g., particles or microposts) that resembles natural superhydrophobic surfaces, or those produced via random deposition of hydrophobic particles. Such fabrication method is far less expensive than microfabrication, making the technology more practical for large submerged bodies such as submarines and ships. The present numerical simulations are aimed at improving our understanding of the drag reduction effect and the stability of the air-water interface in terms of the microstructure parameters. For comparison and validation, we have also simulated the flow over superhydrophobic surfaces made up of aligned or staggered microposts for channel flows as well as streamwise or spanwise ridges configurations for pipe flows. The present results are compared with theoretical and experimental studies reported in the literature. In particular, our simulation results are compared with work of Sbragaglia and Prosperetti, and good agreement has been observed for gas fractions up to about 0.9. The numerical simulations indicate that the random distribution of surface roughness has a favorable effect on drag reduction, as long as the gas fraction is kept the same. This effect peaks at about 30% as the gas fraction increases to 0.98. The stability of the meniscus, however, is strongly influenced by the average spacing between the roughness peaks, which needs to be carefully examined before a surface can be recommended for fabrication. It was found that at a given maximum allowable pressure, surfaces with random post distribution produce less drag reduction than those made up of staggered posts. © *2011 American Institute of Physics*. [doi:10.1063/1.3537833]

I. INTRODUCTION

A combination of hydrophobicity and micro- or nanoscale surface roughness can result in an effect known as superhydrophobicity, characterized by water droplets beading on the solid surface at contact angles exceeding 150°. When fully submersed in water, such surface can cause the so-called "slip effect," resulting in significant reduction in the skin-friction drag exerted on the surface.[1] Superhydrophobic coatings can be utilized as a passive method of flow control and may potentially become a viable alternative to the more complex and energy consuming active or reactive flow control techniques such as wall suction/blowing.[2]

Most engineered superhydrophobic surfaces are made up of microposts or microridges manufactured via advanced microfabrication techniques. The microposts can be fabricated in form of aligned (i.e., flow direction parallel to a side of a square formed by four posts) or staggered (i.e., flow direction parallel to a diagonal of a square formed by four posts) arrangement. On the other hand, microridges can be in the form of streamwise or spanwise configuration. Microfabricated superhydrophobic surfaces have been extensively studied in the last few years both experimentally and numerically.[3–9] The superhydrophobic surface can entrap air cavities between microposts or microridges producing two different interfaces. One of them is between air and water, which significantly reduces the shear stress. The second interface is between water and solid (ridges or posts), at which the customary resistance to the flow is considered. Cheng *et al.*,[10] for example, numerically calculated the influence of the total shear-free area or the air-water interface area (area at which slip effect takes place) as well as its dependency on the slip length. Kunert and Harting[11] numerically simulated hydrophobic rough microchannel flows. Lauga and Stone[12] numerically studied effects of gas fraction and periodicity on the slip length for a transverse configuration. They validated their results with those analytically predicted by Philip[13] for streamwise configuration. Davis and Lauga[14] demonstrated an analytical solution for a thin mesh superhydrophobic surface. In an earlier paper, the same authors[15] provided a mathematical model of laminar flow over a curved bubble "mattress." Sbragaglia and Prosperetti[16] analyzed the velocity boundary condition on a surface composed of slip sites with random distribution, somewhat similar to those studied in the current paper. They also investigated the effect of the

[a]Electronic mail: samahama@vcu.edu.
[b]Electronic mail: htafreshi@vcu.edu. URL: http://www.people.vcu.edu/~htafreshi/.
[c]Author to whom correspondence should be addressed. Electronic mail: gadelhak@vcu.edu. URL: http://www.people.vcu.edu/~gadelhak/.

