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Simulation of meniscus stability in superhydrophobic granular surfaces under hydrostatic pressures

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ABSTRACT

In this work, a series of numerical simulations has been devised to study the performance of granular superhydrophobic surfaces under elevated hydrostatic pressures. Using balance of forces, an analytical expression has also been developed to predict the critical pressure at which a submersed idealized granular superhydrophobic surface comprised of spherical particles, orderly packed next to one another, departs from the Cassie state. Predictions of our analytical expression have been compared with those of a series of 3-D full-morphology numerical simulations, and reasonable agreement has been observed between the two methods. Full-morphology simulations were then used, for the first time, to compute the critical pressure of superhydrophobic surfaces comprised of randomly distributed spherical particles (e.g., superhydrophobic coatings developed by depositing of hydrophobic aerogel particles), where no analytical method is applicable due to the complexity of the coatings' morphology. Results of our numerical simulations indicate that for coatings made up of mono-disperse hydrophobic particles, critical pressure increases with increasing the solid volume fraction. However, increasing particle diameter results in lower critical pressures when the coating's solid volume fraction is held constant.

1. Introduction

It is known that a combination of hydrophobicity and micro- or nanoscale surface roughness can result in a phenomenon known as superhydrophobicity. Research has shown that liquid flow slips on a superhydrophobic surface. This is because a rough hydrophobic surface can entrap the air in its pores, resulting in a reduced contact between water and the frictional solid walls. From a macroscale viewpoint, this causes a reduction in the overall drag force exerted on the surface. From an engineering standpoint, superhydrophobic surfaces can be exploited to reduce the drag force exerted on submerged moving objects such as ships, submarines, or torpedoes.

When the pores in a superhydrophobic surface are filled with air, the system is considered to be at the Cassie state [1]. If the pressure is high, water may penetrate into the pores of the surface and displace the air. This results in the elimination of the superhydrophobicity, and transition to the so-called Wenzel state [2]. The pressure at which a superhydrophobic surface departs from the Cassie state is hereon referred to as the critical pressure [3].

Superhydrophobic surfaces are usually manufactured by the microfabrication of grooves or posts on a hydrophobic surface. Hence, most of the theoretical [4–9] and experimental [10–14] studies in the literature correspond to microfabricated surfaces. Microfabrication, however, is a costly process and cannot be easily applied to large surfaces with arbitrary shapes. An alternative approach to produce a superhydrophobic surface is by depositing hydrophobic fibers or particles on a substrate. Our group, among many others [15–21], is currently active in producing and characterizing fibrous and granular superhydrophobic coatings. As will be discussed in the next section, such coatings can be produced at a much lower cost and can better conform to the surface of objects with arbitrary shapes. Coatings produced by randomly deposited fibers or particles do not, however, provide a precise control over the surface microstructure, and are more susceptible to elevated pressures [22].

As mentioned earlier, the major problem in utilizing superhydrophobic surfaces for submersible applications is that the slip effect diminishes under elevated hydrostatic pressures (i.e., depths). The objective of the study presented here, therefore, is to better our understanding of the importance of microstructural parameters such as particle size or porosity on the superhydrophobic performance of such coatings under elevated hydrostatic pressures. In the current study, we only consider surfaces made up of granular materials. Surfaces obtained by fiber deposition will be studied in a future work.

In the next section, we present a superhydrophobic surface made up of ground aerogel particles as an example of granular superhydrophobic surfaces. In Section 3, we present an analytical

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