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Role of particles spatial distribution in drag reduction performance of superhydrophobic granular coatings

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ABSTRACT

This work presents a detailed computational study on the role of microstructural properties of a superhydrophobic granular coating on its drag reducing performance. More specifically, the effects of the Young–Laplace contact angle, particle diameter, and solid volume fraction on drag reduction are studied for submerged superhydrophobic granular coatings under negative (suction) and positive hydrostatic pressures. In addition, four different particle arrangements (square, staggered, reticulated, and random) are considered to investigate the effects of particle spatial distribution on coatings' drag reduction performance. This was accomplished by accurately predicting the 3-D shape and surface area of a coating's wetted area fraction, and then by using this information to solve the flow field over the coating in a Couette configuration to obtain its drag reduction efficiency. As expected, it was found that drag reduction performance of submerged superhydrophobic coatings decreases with increasing hydrostatic pressure. However, in contrast to coatings comprised of sharp-edged pores, it was found that drag reduction efficiency of granular coatings monotonically increases with decreasing the pressure when the pressure is negative. It was also found that spatial distribution of the particles has no significant effect on drag reduction. The only exception to this conclusion is the case of coatings with reticulated particle packing. Results of our simulations are compared with available data in the literature and discussed in detail.

1. Introduction

Superhydrophobic (SHP) coatings, coatings that bring about roughness and hydrophobicity, have been reported to reduce the friction drag between a body of water and a surface (Extrand, 2004; Shirtcliffe et al., 2004; Choi and Kim, 2006; Lee et al., 2008; Rothstein, 2010; McHale et al., 2009, 2010; Sbragaglia and Prosperetti, 2007a). This effect is attributed to the ability of a rough hydrophobic surface to entrap air bubbles in its pores and thereby reduce the contact between the solid surface and the water. The contact area and the friction between the water body and the SHP surface can be manipulated by controlling the volume and the pressure of the air bubbles entrapped in the pores of the SHP surface in the submerged condition (Verho et al., 2012) as well as for the case of a droplet deposited on a SHP surface (Vourdas et al., 2015, 2016). SHP surfaces can potentially be applied to the hull of a boat or the inner walls of a pipe to reduce friction (Dong et al., 2013; Jiang et al., 2010; Pan and Wang, 2009).

SHP surfaces are often produced by microfabricating small features on a smooth surface and then applying a hydrophobic coating to the roughened surface (e.g., Shirtcliffe et al., 2004; Choi and Kim, 2006). A more cost-effective alternative is to coat the smooth surface with a porous hydrophobic material, e.g., Polystyrene fibers or aerogel particles among many others (Ma et al., 2008; Emami et al., 2011; Emami et al., 2012; Samaha et al., 2012; Wang et al., 2017). Depending on coating geometry and flow parameters, the Wenzel state (fully-wetted), the Cassie state (fully-dry), or a series of transition states in between the two extreme states may prevail over a submerged SHP surface (Bucher et al., 2015; Bormashenko, 2015; Marmur, 2003; Bormashenko et al., 2007; Verho et al., 2012). Unfortunately, even a slight departure from the Cassie state may result in a rapid increase in the surface wetted area (solid area in contact with water), and a consequential diminishment of the drag reduction effect, as will be discussed later in this paper (Hemeda and Tafreshi, 2015).

Predicting the shape and position of the air–water interface over a SHP surface comprised of round objects (e.g., spherical objects) is not a trivial task. This is because the air–water interface does not become pinned to the round entrance of the pores, and

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so its shape and position can easily vary in response to variations in the instantaneous pressure over the surface (Emami et al., 2011; Extrand and Moon, 2012). This in turn makes the drag-reduction benefit of the surface highly pressure dependent. In a previous study, we developed a modeling method to predict the shape and position of the air–water interface in order to obtain the wetted area of a granular SHP coating as a function of pressure (Amrei and Tafreshi, 2015a, b). While the drag force caused by a SHP surface is related to its wetted area, the nature of this relationship is not very clear, as will be discussed with more details in the next section. Therefore, the current study is devised to calculate the drag reduction advantage of a granular SHP coating in terms of its microstructural parameters. For the sake of simplicity, our study is limited to the case of granular coatings made of spherical particles with identical size but ordered or random spatial distributions.

The remainder of this paper is organized as follows. In Section 2, we present a brief overview on the drag reduction benefits of SHP granular coatings. Section 3 presents our approach to model the shape and position of the air–water interface (AWI) over a SHP granular coating. Our drag reduction calculation method is described in Section 4 along with a validation study in Section 5. Results and discussion are given in Section 6 followed by our conclusions in Section 7.

2. Drag reduction from superhydrophobic granular coatings

As mentioned earlier, a cost-effective approach to produce a SHP surface is to coat a substrate with a hydrophobic material that can add roughness to the surface. Fig. 1a shows an example of such a surface made of pulverized aerogel particles. When the void between the particles is completely filled with air, the surface is generally considered to be at the Cassie state (fully dry). However, when the pressure over the AWI is elevated (either because droplet's Laplace pressure is too high or because the surface is submerged), water may penetrate into the void space between the particles to partially wet the surface (i.e., causing the surface to depart from the Cassie state). Fig. 1b shows a schematic of an idealized granular coating deposited on a flat surface (a layer of spherical particles with identical diameters). As discussed previously (Emami et al., 2011; Bucher et al., 2015; Extrand and Moon, 2012; Amrei and Tafreshi, 2015a, b), the balance between the forces acting on the AWI (shown with red color in Figs. 1c and 1d), will eventually determine the location of the AWI and the wetting state of the surface. Knowing the location of air–water–solid contact-line (referred to here as three-phase contact-line or contact-line for brevity) from the balance of forces, and the surface geometry, one can predict the wetted area of the surface (green area above the AWI in Figs. 1c and 1d). A body of water moving over a SHP granular coating experiences frictional (no-slip) contact with the coating's wetted area, but slippery (shear-free) contact along the AWI (see Fig. 1c and d). Overall, one can expect a reduction in the total surface friction due to the reduction in the total wetted area of the surface in comparison to the uncoated flat surface. The decrease in the friction drag over a SHP surface is often characterized using slip length b which is a geometric interpretation based on the average distance underneath the top of the particle coating at which the velocity extrapolated to zero (see Fig. 1d).

While the drag force caused by a SHP surface is related to its wetted area, the nature of this relationship is not very clear. As shown in (Steinberger et al., 2007; Karatay et al., 2013) for instance, the air bubble entrapped in the sharp-edged pores of a SHP surface may protrude into the flow region (if the pressure outside the pores is less than that inside the pores) to increase the drag force without increasing the wetted area of the surface (wetted area remains the same due to AWI pinning). As will be seen later in this paper for unpinned AWIs (round pores), bubble protrusion into the flow domain does not severely affect the surface drag reduction performance as it comes with a decrease in the surface wetted area. However, the drag reduction benefits of a surface comprised of round-edged pores (or particles, for instance) is generally lower than those of sharp-edged pores (e.g., a surface made of vertical mirco-posts) with identical solid area fractions. This is because of the aforementioned need for the AWI to move into the pore space to a depth that allows it to conform to the Young–Laplace contact angle (YLCA). This will obviously increase the wetted area of the surface even in the absence of a hydrostatic pressure over the surface. In fact, friction on a SHP granular surface depends on three main parameters, area and the 3-D shape of the wetted solid surface, area and the 3-D shape of the AWI (either concave or convex), and the size distribution of the individual wetted areas (or individual shear-free areas). To further study these parameters in this paper, we produce virtual SHP granular coatings with random or ordered particle arrangements and study their drag reduction performance in a Couette flow geometry as shown in Fig. 1c and d. The calculation details are given in Section 3 and 4.

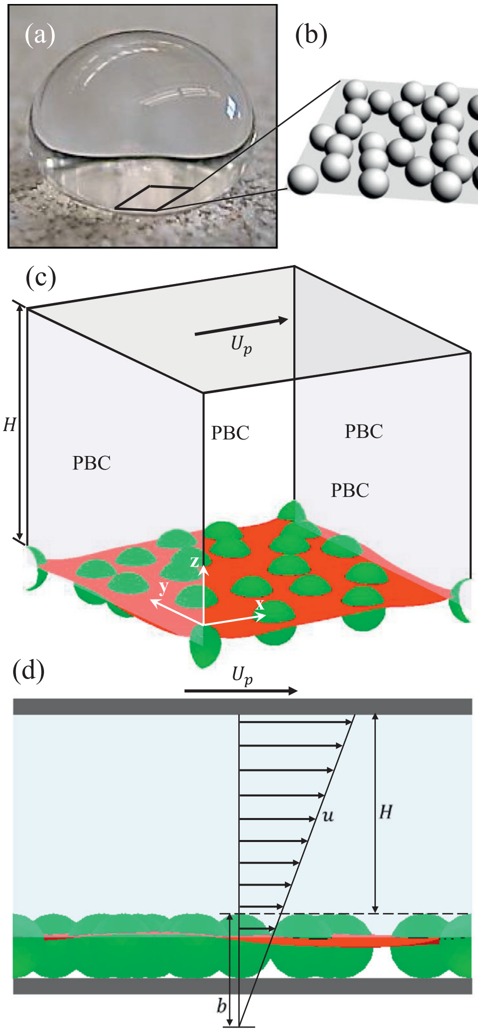

Fig. 1. (a) Droplet deposited on a granular surface made of pulverized aerogel particles (b) schematic representation of an idealized granular coating deposited on a flat surface (c) Schematic representation of the computational domain considered for calculating the flow over a superhydrophobic granular coating in a Couette configuration. (d) Schematic diagram describing the slip length concept for flow over granular SHP coating.