Experimental drag reduction study of super-hydrophobic surface with dual-scale structures

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ABSTRACT

Hydrophobic surfaces with micro- or nanoscale pillars have been attracting considerable interest from scientists. In nature, such surfaces can be found on lotus leaves or under the feet of pond skaters. One significant property of these surfaces is friction drag reduction (FDR). Many studies have been conducted to demonstrate this reduction in terms of laminar and turbulent flows. The slip-length hypothesis is often used to explain this phenomenon. In this study, processes with the advantages of simplicity and cost effectiveness were used to fabricate dual-scale structures. Durable super-hydrophilic and super-hydrophobic surfaces were easily obtained from these structures. FDR was measured on a super-hydrophobic surface and was compared to that on smooth and super-hydrophilic surfaces. The experimental results in a circulating water channel revealed the Reynolds number range within which substantial FDR can occur on a super-hydrophobic surface. The mechanism of FDR and the role of slip are discussed by comparing experimental results.

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1. Introduction

The friction drag reduction (FDR) property of hydrophobic surfaces allows for their use in a wide range of applications such as car windows, ocean vessels, and building surfaces. There are two basic types of artificial hydrophobicity according to the surface structure: pillar-type and channel-type. The common feature of these two types is the presence of micro- or nanoscale structures on their surfaces. These structures trap air and thus generate an air layer between the water and the body surface. Such a scenario allows for water slip, thus causing FDR. The air layer is thus considered a lubricant for the flow of water over the surface.

Various experimental approaches have been used to create hydrophobic surfaces. Some of them include template methods [1], ion bombardment [2], lithography [3–5], chemical deposition [6], self-assembly of a monolayer [7] and photocatalysis [8]. The common characteristics of these methods are high cost, long fabrication times, and difficulties in covering a large surface area. To overcome these demerits, a super-hydrophobic surface using the so-called nanowire entanglement structures (NWES) was created by a dipping method based on an anodization process in oxalic acid [9]. This technique offers the advantages of low fabrication cost, simplicity, and easy coverage of a large surface area.

Along with studies on the fabrication of artificial super-hydrophobic surfaces, much research has been carried out on the demonstration of FDR. FDR has been verified by theoretical, numerical, and experimental studies based on the slip hypothesis in terms of laminar and turbulent flows. Direct numerical simulation (DNS) [10] and theoretical prediction [11] of turbulent channel flow was performed to validate the effect of slip. Experimental results that demonstrated significant drag reduction for laminar [12–15] and turbulent [16–18] flows in microchannels and normal-sized channels [19,20] were presented. Recent measurements of slip length on hydrophobic surfaces were not confined to channel flow. Flow slip between two rotating parallel disks [21] and a cone-plate [22] was observed. The factors that affect slip on a hydrophobic surface were determined experimentally. The role of nanoscale roughness [23] and the scaling effect [24] of surface geometry were investigated, and air layer restoration and retention [25] were shown.

A typical example of super-hydrophobicity in nature is the lotus leaf. A water droplet on a lotus leaf shrinks to a sphere that has minimum contact area with the surface. In addition, a water droplet easily runs off a lotus leaf even at a very small sliding angle (less than 1°). Scanning electron microscope (SEM) images of structures on a lotus leaf are shown in Fig. 1. The figure shows numerous microscale pillars. On each of these pillars, an extremely large number of nanoscale pillars are present. A structure that has a combination of micro- and nano-elements is called a dual-scale structure.
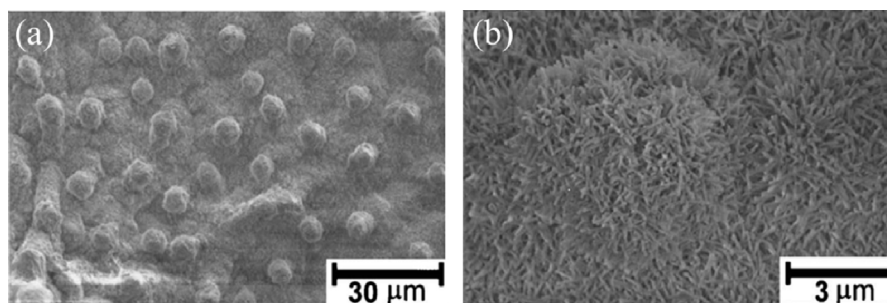
Fig. 1. SEM images of a lotus leaf surface. Micropillars with a diameter of approximately 7 μm are shown in (a), and an extremely large number of bristly nanopillars are shown in (b).

Two factors are known to determine the contact angle with the surface: the surface energy and the structure of the surface. According to the classical Young's equation

$$\cos\theta = \frac{\gamma_{sv} - \gamma_{ls}}{\gamma_{lv}} \qquad (1)$$

The surface energy of the solid material determines the contact angle of the material. Contact angle is calculated by the surface energy between solid/liquid (γ_{ls}) and solid/vapor (γ_{lv}). That means the material property itself determines hydrophilicity or hydrophobicity of the surface. However, one more factor affects this property of the surface. From the equation of Cassie and Baxter, the roughness of the surface changes the surface's wettability:

$$\cos\theta_{CB} = \alpha\cos\theta - (1 - \alpha) \qquad (2)$$

where α is the fraction of the contact area.

If the roughness of the surface increases, the contact area increases. Thus, a hydrophilic surface changes to a super-hydrophilic surface and a hydrophobic surface changes to a super-hydrophobic surface. Therefore, if we change the surface structure, we can easily obtain super-hydrophilic and super-hydrophobic surfaces. In the Cassie state, the hydrophobic property prevents water from penetrating rough structures. Hydrophobic surfaces trap air and thus generate an air layer between the water and the body surface. Such a scenario allows for water slip, thus causing FDR. The air layer is thus considered a lubricant for the flow of water over the surface.

The slip length hypothesis is considered a basis for explaining FDR owing to the slip of the flow over super-hydrophobic surfaces. Many techniques to measure slip length were developed to study flow on the surfaces [26].

Navier's hypothesis states that the velocity at a surface is proportional to the shear rate. This can be expressed as

$$u(y = 0) = \beta\left.\frac{du}{dy}\right|_{y=0} \qquad (3)$$

where β (shown in Fig. 2) is the slip length and du/dy is the shear rate or velocity gradient in the direction normal to the surface. The velocity at the wall, $u(y = 0)$, is called the slip velocity.

In the present work, considerable FDR was measured for smooth, super-hydrophilic, and super-hydrophobic flat surfaces. Simple and cost-effective processes were used to fabricate these three surfaces. Each experimental result was compared with the theoretical prediction, and FDR and the role of slip was explained by the comparison. A considerable FDR was observed for the super-hydrophobic flat plate in the Reynolds number (Re) region. The result indicated that a super-hydrophobic surface causes a turbulent flow to behave like a laminar flow in a small Re range, which is highly desirable for flat-plate friction reduction
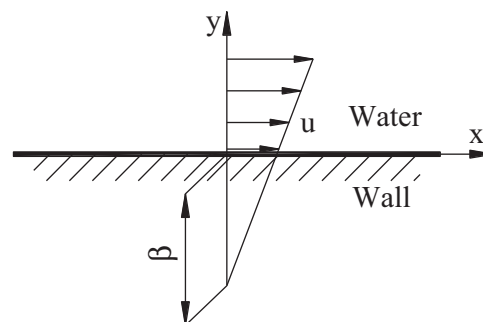

Fig. 2. Slip length over a surface.

2. Experimental

2.1. Fabrication of dual-scale super-hydrophobic and super-hydrophilic surfaces

A pure (99.5%) industrial aluminum sheet ($300 \times 140 \times 5$ mm) was used as the basic material. Maskant solution was painted on one side of the sheet to protect it during the anodization process. The aluminum was anodized in a 0.3 M oxalic acid solution at a constant voltage of 40 V for 12 h. During anodization, the oxalic acid solution was maintained at 26 °C by a double-walled water jacket. Usually, a platinum plate is used as the cathode in the anodization process. However, it was not necessary to use platinum to achieve a regular pore arrangement, and thus, the same aluminum plate was used as a cathode.

Aluminum reacts with the ionized acid solution because of the voltage applied during anodization. Aluminum surface becomes anodic oxide film and this film grows as the reaction begins. Typically, holes appear on the aluminum surface in a certain condition from the result of oxide growth. Fig. 4(a) shows the surface of industrial aluminum anodized at 40 V and 15 °C for 12 h.

The anodization conditions (temperature, voltage, and time) affect the oxide growth and arrangement of these holes. High temperature accelerates the oxide film growth and irregular coral-like
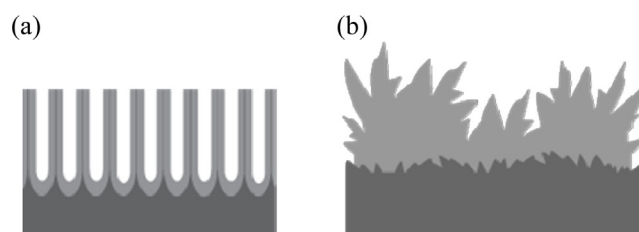

Fig. 3. Schematic diagram of anodized surface structures: (a) low temperature (15 °C); (b) high temperature (26 °C).