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Review

A review of the recent advances in superhydrophobic surfaces and the emerging energy-related applications

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A B S T R A C T

A new kind of functional surfaces with particular characteristics, i.e., superhydrophobic surfaces, has recently been developed and applied in many fields, such as airplane, wind turbine, electric power line, photovoltaic cell, heat exchanges, ice slurry generator, and so on. The freezing delay and ice-accumulation avoiding on the surfaces are important to keep stable working condition for these devices. The frictional pressure loss of flow through the tubes or channels with superhydrophobic surfaces is much smaller than that through those without superhydrophobic surfaces. Both the boiling and condensation heat transfer performances on superhydrophobic surfaces can be enhanced. The superhydrophobic surfaces have potential applications and are worthy further investigations. We provide here a review of the fabrications, characterization and the emerging energy-related applications of superhydrophobic surfaces on the basis of the recent progresses of the research and development in this field. The fabrication of superhydrophobic surface, in particular a recently developed SLIPS (slippery liquid-infused porous surface), is summarized. The focuses are placed on the particular characteristics of superhydrophobic surfaces and their applications in energy-related fields. The further research topics are also clarified to promote the future applications.

1. Introduction

It is well known that the leaves of many plants such as lotus leaves show particular characteristics like water-repelling, easily rolling off the surface and antifouling even though the leaves are covered by the dirty water or dusts, as shown in Fig. 1(a). The rainwater can smoothly roll off the lotus leaves without any pinning [1–6]. If the features of lotus leaves can be functionalized on various metal surfaces or substrates, it can be useful and helpful in many applications for energy saving. For examples, it can reduce the friction of liquid flow, avoid fouling and enhance the heat transfer performance.

The wettability of a surface can be characterized by the CA (contact angle). The hydrophilic surface has the contact angle below 90°. The surface with the contact angle of above 90° is known as hydrophobic surface, and the surface with the contact angle above 150° and the rolling angle below 5° is defined as superhydrophobic surface [7], as shown in Fig. 2. It has been understood that the superhydrophobicity of a surface depends on both the surface characteristics and surface energy, i.e., the micro/nanostructures on the surface and modification of surface energy level by chemical substance.

The contact angle is generally measured when a water droplet resides on a surface. The states of water droplets on solid surface are classified into two categories, namely Wenzel state and Cassie–Baxter state [7], as shown in Fig. 3. The water penetrates into the structured (or texture) surface in Wenzel state, which makes the water droplets pin on the surface and cannot easily roll off the surface. The water droplets suspending on the texture surface in the Cassie–Baxter state can easily roll off the surface. The corresponding contact angles for Cassie–Baxter state are also larger than that for Wenzel state, which is ascribed to the structured surface and surface energy. Both the micro/nanostructures or hierarchical structures and coatings with low surface energy are the two key factors influencing superhydrophobicity of the surface because the binary structure modified with hydrophobic substance can extremely reduce the surface energy and further enhance the repellent property.

With the advances in fabricating superhydrophobic surfaces on various metal substrates, these functionalized metal surfaces with extremely low surface energy are gradually applied in industries

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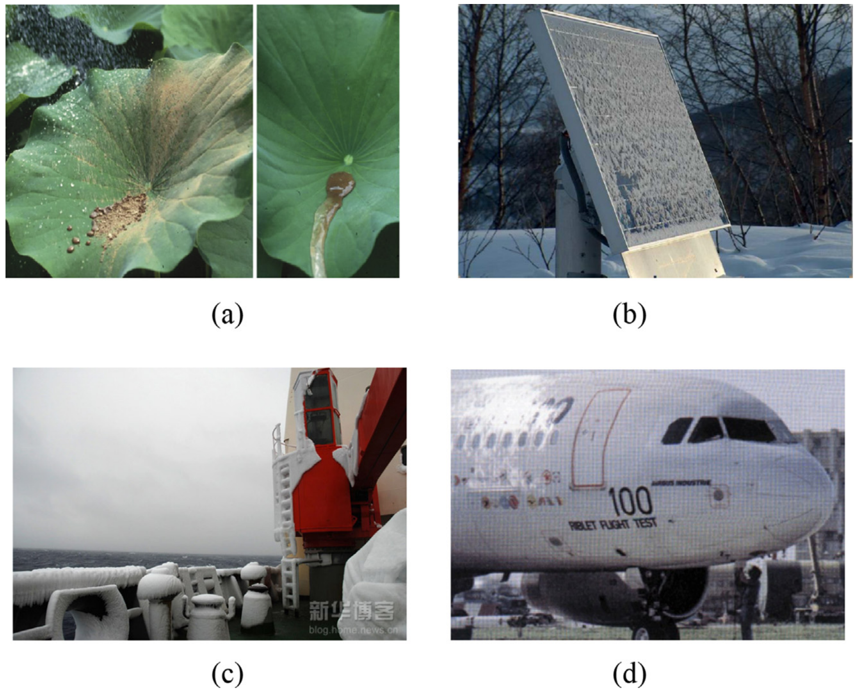

Fig. 1. Superhydrophobic surface and its applications. (a) Lotus leaf [1]; (b) solar cell panel [12]; (c) ship with superhydrophobic surface; (d) airplane with superhydrophobic [20].

and daily life. For example, the high ratio of surface to volume of microfluidic device strongly affects the flow behavior, which increases the pressure loss significantly. Therefore, superhydrophobic surfaces are applied to microfluidic device or microchannels to reduce the pressure loss effectively [8]. Another example is that the plate heat exchangers with such functional surfaces can effectively avoid milk fouling and prevent the reduction of the heat transfer performance during the pasteurization process [9].

It is well known that the efficiencies of solar cells and wind turbines working under the severe conditions are drastically decreased due to the ice and snow accumulation [10,11], and the issues of removing ice from surfaces aroused great attention. The methods of removing ice from surfaces can be divided into two categories: the first one is active method which includes thermal treatments, mechanical scraping and using de-icing chemical agents. The active method is employed after the ice formation, which needs a lot of efforts to separate the ice from the surfaces; the second one is the passive method which prevents the ice formation or ice adhering to surfaces even though the icing occurs. The passive method can effectively remove the ice from the surfaces, in which there is less energy consumption because of the lower ice adhesion strength, resulting in energy-saving. The passive method has potential applications in many aspects such as airplane, wind turbines, photovoltaic devices [12], electric power lines [13], ship, and so on, as shown in Fig. 1(b) and (c). The passive method based on superhydrophobic surface can prevent ice accumulation and reduce the ice adhesion to the surface. It is well known that the icing occurs and ice adheres to the airplane surface when it passes through the freezing temperature zones, which will cause catastrophic risks [14–17]. Although the temperatures of the icing experiments are not lower enough compared to that of aircraft surfaces when it passes through the freezing temperature zones, the experimental results can still be instructive and useful for the aircraft to improve the flight performance [18,19]. Fig. 1(d) shows the image of the airplane with superhydrophobic coating [20]. The influence of wettability on ice adhesion strength on a standard NACA0021 airfoil with superhydrophobicity was studied by Antonini et al. [21] in the icing wind tunnel. The experimental results revealed that the superhydrophobic coatings could prevent ice accumulation on airfoil, resulting in a reduction of as high as 80% of energy used to avoid ice accretion on a normal airfoil. The ice adhesion strength to superhydrophobic surface is much lower than that to the normal surface. Therefore, the superhydrophobic surface shows the characteristics of ice-repelling, which is essential in the anti-icing applications.

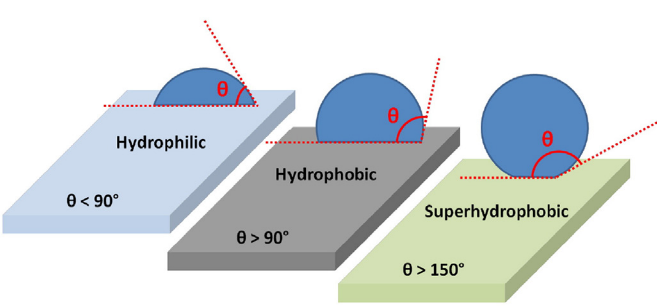

Fig. 2. The states of surfaces with different contact angles [7].

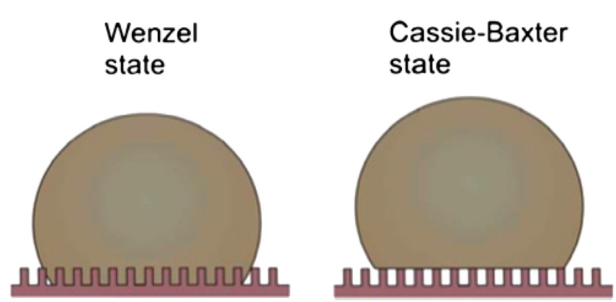

Fig. 3. The states of droplets on texture surface [7].

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