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Study on biomimetic superhydrophobic mechanisms and existing issues

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Abstract. The realm of biomimetic superhydrophobic surfaces encompasses a diverse range of applications, yet the specific biomimetic mechanisms, theories, models, and preparation methods remain shrouded in ambiguity. To address this gap, a meticulous examination of the current theories and preparation methods is imperative for guiding further biomimetic superhydrophobic research. This study, adopting a dual perspective from superhydrophobic theory and the intricate interplay between droplets and surfaces, intricately synthesizes the relevant theories and models pertaining to biomimetic superhydrophobic microstructures. Delving into the existing challenges in theoretical research and preparation methods within the field of biomimetic superhydrophobics, the research not only identifies current limitations but also lays the groundwork for future explorations. This systematic inquiry contributes not only to a nuanced understanding of existing biomimetic superhydrophobic surfaces but also provides a robust foundation for future studies and technological innovations. As the research unfolds, it propels the scientific community towards a more comprehensive grasp of biomimetic superhydrophobic phenomena, promising advancements, and applications across various scientific and technological domains.

Keywords: biomimetic superhydrophobic, theories and models, interfacial forces, superhydrophobic surface preparation, future research directions.

1. Introduction

Many organisms in nature have evolved remarkable structures for their survival. Examples include the shark's skin with its tooth-like nanostructures, the optical microstructures of butterfly wings, the nano-pillar antibacterial structures on cicada and dragonfly wings, the micro-nano composite superhydrophobic structures on lotus leaves, the microstructures on the surface of certain desert beetle elytra that collect moisture and dew, and the directed hydrophilic pathway structures on sedge and rice leaves. These unique nano-scale microstructures can impart exceptional properties to materials, including drag reduction [1], superhydrophobic [2], superhydrophilicity [3], self-cleaning [4], antibacterial properties [5], selective filtration, structural coloration, and regulation of platelet behavior in blood [6]. These functional microstructures found in nature provide important guidance for the human development of new materials. Researchers study the mechanisms and applications of biomimetic microstructures to optimize material design, improve manufacturing techniques, and develop exceptional products. Biomimetics is a significant discipline that has emerged from this, which draws inspiration from natural organisms to solve engineering and design problems by imitating their structures, functions, and processes. One important area within biomimetics is the field of biomimetic superhydrophobia. Jiangyou Long et al. [7] studied the unique superhydrophobic structures on rice leaves and replicated them on metal plates using laser technology. They discovered and confirmed the superhydrophobic and anisotropic droplet sliding properties of these structures. Yang et al. [8] reproduced the microstructures resembling egg beaters on rose petals using 3D printing technology, replicating the macroscopic superhydrophobic and controlled droplet adhesion properties. The work of Autumn et al. [9] used adhesion force experiments to verify that the adhesive properties of a gecko's superhydrophobic foot surface are dominated by van der Waals forces, explaining the mechanism behind the special adhesive functionality of the gecko's biological superhydrophobic surface.

The application scope of biomimetic superhydrophobic is extensive, including surface anti-fouling and self-cleaning in infrastructure and equipment materials, anti-icing and anti-water freezing in low-temperature environments for aircraft, ships, and power lines, materials for oil-water separation in water treatment technology, research on blood-repellent biomaterials in the medical field, and materials for water condensation and liquid transportation in the energy sector. Compared to purely laboratory-based development, exploring nature for inspiration to develop more environmentally friendly passive anti-icing, superhydrophobic, and superamphiphobic solutions may be more feasible. Modern scientific equipment has the capability to help us investigate biological superhydrophobic structures with specific functions that may seem incredible in response to actual environments. Although the structures of biomimetic superhydrophobic have been extensively studied, there are still some issues regarding the specific biomimetic mechanisms, preparation methods, and application expansion. Therefore, it is necessary to study the existing problems in current theories and preparation methods to guide more systematic research on biomimetic superhydrophobic. This paper aims to introduce the relevant theories, preparation methods, and existing issues of biomimetic superhydrophobic microstructures and, based on this, discuss potential research directions for the future.

2. Theory and Models

The study of superhydrophobic originated from the superhydrophobic and self-cleaning properties of lotus leaf surfaces. It was not until the development and widespread application of scanning electron microscopy that scientists gained the ability to explore the secrets behind these unique leaf functions. In 1992, Barthlott et al. [10] revealed the principles behind this phenomenon and named it the "lotus effect". The researchers discovered that lotus leaf surfaces possess dense micrometer-sized protrusions, with a height of approximately 5 micrometers. Upon further magnification, it was observed that these micrometer-sized protrusions were covered with a layer of nanometer-sized papillae, with a height of around 200 nanometers. Additionally, the lotus leaf secretes a layer of waxy substance on its surface to resist external damage. It is the combination of this surface micro-nano composite structure and the presence of the waxy substance that gives the lotus leaf its unique superhydrophobic properties.

Subsequent research has revealed that superhydrophobic surfaces must meet a series of conditions, including being difficult to wet (low surface energy), possessing micro-nano scale roughness, and minimal resistance to the rolling of liquid droplets. These principles form the basis for the design of superhydrophobic materials. As almost all human activities are closely related to water, researchers' interest in superhydrophobic has been growing. However, there is still a lack of systematic summarization and research on the related theories. This section will summarize the fundamental theories of biomimetic superhydrophobic, including wetting models and mechanical principles.

2.1. Superhydrophobic Theory

2.1.1. Young's Equation. When a liquid droplet stably exists on a solid surface, it exhibits different wetting states, which are represented by the contact angle (CA). As shown in Figure 1, the contact angle is defined as the angle between the tangent line of the gas-liquid interface at the point where the gas, liquid, and solid phases meet and the solid-liquid interface. The contact angle, denoted as θ, ranges from

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0° to 180°, and its value can be calculated using Young's equation. In 1805, Thomas Young constructed a model for liquid droplets on a flat solid surface, known as Young's equation model. This model assumes an ideal, perfectly smooth, and homogeneous solid surface, and explains the relationship between the contact angle of the liquid droplet on the solid surface and the gas-liquid-solid interfaces:

$$\gamma sl + \gamma \, lg \cos \theta = \gamma gs \quad (1)$$

Here, γ_{sl}, γ_{lg}, and γ_{gs} represent the interfacial tensions between the solid-liquid, liquid-gas, and gas-solid phases, respectively. θ is referred to as the Young's contact angle or intrinsic contact angle. When θ is less than 90°, the liquid is generally considered to wet or spread on the solid surface, while it is the opposite when θ is greater than 90°. The critical contact angle value for hydrophilic or hydrophobic behavior is 90°, with angles greater than 90° defined as hydrophobic. The greater the contact angle, the better the hydrophobic performance of the surface. Superhydrophobic refers to a wetting state where the contact angle is greater than 150°. In other words, on superhydrophobic surfaces, static liquid droplets tend to maintain a spherical shape on the surface.

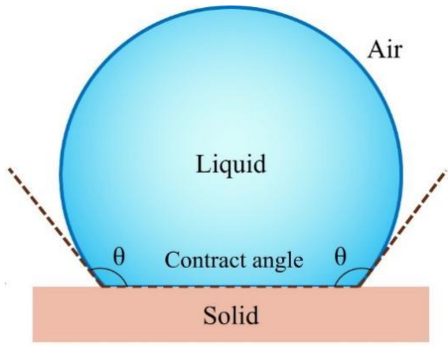

Figure 1. Young's equation model.

Since Young's equation initially did not consider the influence of gravity on liquid droplets and ignored the vertical component of interfacial tension between the liquid and gas phases, it is only applicable under the assumption of a chemically homogeneous and smooth ideal surface, limiting its practical application in real situations.

2.1.2. Rolling Angle. In practical applications, if the surface is inclined at a small angle, as shown in Figure 2b, it can be observed that the droplet on the far right slides down while the droplets on the left do not slide. This demonstrates the inherent difference between static and dynamic contact angles. To study the practical applications of hydrophobic or self-cleaning surfaces, the motion of droplets under small forces must be considered. Therefore, research on dynamic wetting and the phenomenon of contact angle hysteresis is crucial.

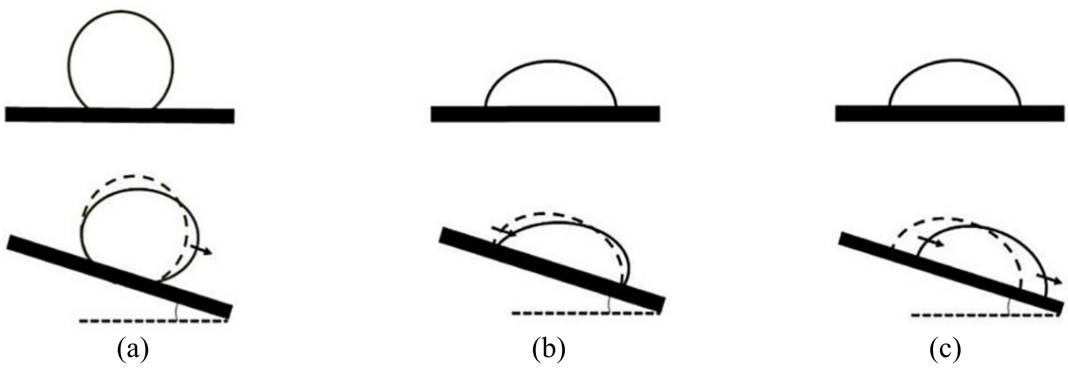

Figure 2. Static and dynamic contact angles.

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With further research, researchers have used the rolling angle to describe the contact and wetting behavior of water droplets on surfaces with a certain inclination angle. The minimum rolling angle is the minimum inclination angle required for a droplet to roll on an inclined surface at a certain angle. To better represent the rolling performance of droplets on inclined surfaces, the difference between the advancing contact angle (θ_A) and the receding contact angle (θ_R), as shown in Figure 3, is used to represent the contact angle hysteresis on solid surfaces.

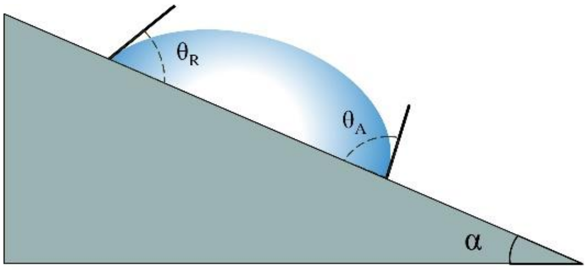

Figure 3. Advancing and receding contact angles.

2.1.3. Wetting Models

1) Wenzel Model

In reality, solid surfaces have a certain roughness, and surface composition is not completely homogeneous. The contact angles calculated using Young's equation differ significantly from the measured contact angles. Therefore, Young's equation does not apply to actual solid materials. As shown in Figure 4, Wenzel imagined a surface with a certain roughness based on Young's equation, where the contact interface between the droplet and the surface is in complete contact. In this case, the actual contact area between the droplet and the solid surface is larger than the projected area of the contact area, which changes the contribution of the surface roughness factor to the system energy. Therefore, the surface roughness factor enhances the hydrophilicity/hydrophobicity of the solid surface.

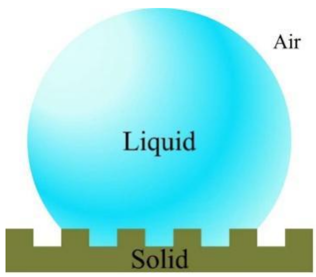

Figure 4. Wenzel model.

Wenzel introduced the roughness factor based on the Young's equation and published the Wenzel equation in 1936:

$$\gamma \lg \cos\theta *= r(\gamma gs - \gamma sl) \tag{2}$$

Substituting the Young's equation into the equation, we have:

$$\cos\theta *= r\cos\theta \tag{3}$$

where r (roughness factor) is the ratio of the actual surface area to the projected area in the solid-liquid interface, so r ≥1. From the above equation, it can be seen that when $\theta < 90°$, $\theta^* < \theta < 90°$, and when $\theta > 90°$, $\theta^* > \theta > 90°$. Therefore, according to the Wenzel model, it can be inferred that the roughening of the surface can make the inherently hydrophilic surface more hydrophilic, while the inherently hydrophobic surface becomes more hydrophobic. The Wenzel theory assumes that the droplet completely wets the rough structure of the solid surface, resulting in a "pinning effect" [11] at the edge of the droplet's three-phase line due to the presence of surface protrusions and grooves. The movement of the droplet requires overcoming a large barrier, so droplets that satisfy the Wenzel model are more difficult to move, resulting in a significant contact angle hysteresis.

Although the Wenzel model inspired research on changing the hydrophobicity of material surfaces by altering surface roughness, this model cannot explain some superhydrophobic phenomena on rough surfaces. For example, the surfaces of lotus leaves and petals both exhibit similar hydrophobicity, but droplets on petals do not roll as easily as on lotus leaves.

2) Cassie-Baxter Model

To explain the different droplet behaviors on superhydrophobic surfaces such as lotus leaves and petals, as shown in Figure 5, Cassie and Baxter further expanded on the Wenzel model and proposed that the droplet does not fully contact the rough surface, but instead, there are gas bubbles at the contact interface, forming a composite contact interface where solid-liquid and gas-liquid coexist.

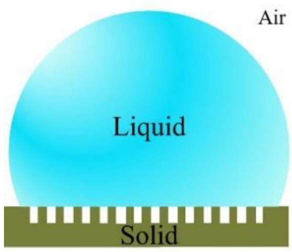

Figure 5. Cassie-Baxter model.

In 1944, Cassie and Baxter published the Cassie-Baxter theory model. In general, the wetting behavior of droplets under this model can be explained using the Cassie-Baxter equation:

$$\cos\theta* = fs \cos\theta s + fg \cos\theta g \quad (4)$$

where fs and fg are the apparent contact areas of the solid-liquid and gas-liquid interfaces, respectively, with fs + fg = 1. θs and θg are the intrinsic contact angles of the droplet on the smooth solid surface and the gas surface, respectively, and θg is 180°. This equation can be rearranged as:

$$\cos\theta* = fs(\cos\theta s + 1) - 1 \quad (5)$$

According to this equation, it can be deduced that as the apparent contact angle $\theta*$ and the solid-liquid contact area increase, the contact angle θs between the droplet and the solid surface also increases. Under this model, droplets on superhydrophobic surfaces are imagined to only come into contact with the rough surface through the rough protrusions, while the other areas are separated from the droplet by a layer of gas, creating a suspended state. In this situation, the surface exhibits hydrophobicity, and the tendency for droplets to roll increases, providing theoretical support for the explanation of the lotus effect.

3) Other Transition Wetting Models

In practical research, especially in the study of biomimetic superhydrophobic surfaces, it has been found that many prepared rough hydrophobic surfaces do not belong to a single model explanation. In fact, they exhibit different wetting states at different scales. For example, the Partial Wenzel wetting state, where at the nanoscale the surface exhibits a Cassie wetting state, while at the microscale it exhibits a Wenzel wetting state. Despite still having hydrophobic characteristics at a macroscopic level, the droplets adhere to the surface, with contact angles reaching 90 or even 180 degrees without slipping. This phenomenon, similar to the surface of rose petals in nature, is known as the "rose effect" [12]. For the Gecko state, it has been proven that this phenomenon is dominated by van der Waals forces. Kellar Autumn et al.'s work [9] conducted adhesive experiments on gecko footpads using hydrophilic and hydrophobic surfaces. They concluded that gecko footpads are covered with ultra-fine superhydrophobic hairs, and geckos adhere to the surface through the van der Waals forces generated by the capillary effect

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of water on the hairs. At the same time, droplets on superhydrophobic surfaces exhibit a significant contact angle hysteresis state, which is dominated by van der Waals forces. This behavior has potential applications in the lossless transport of liquids.

In addition, changes in environmental pressure, temperature, or liquid type can also affect the wetting state when droplets come into contact with a surface. From an energy perspective, the Cassie state is considered a metastable state, while the Wenzel state is considered a stable state. Therefore, by changing pressure and temperature, the transition from Wenzel to Cassie can be achieved. Changing the liquid type can alter the wetting state by modifying the wetting properties between the liquid and the surface. Boreyko et al.'s experiments [13] demonstrated that adding ethanol to water droplets can promote droplet spreading, leading to a transition to the Full Wenzel state. By vibrating the droplet, ethanol can evaporate, restoring the Partial Wenzel state to the Full Cassie state.

2.2. Forces Acting on Droplets and Superhydrophobic Surfaces

The previous section introduced the definition of contact angle, calculation equations, rolling angle, and wetting models. However, the essence of hydrophobicity is based on the forces acting on the droplet at the interface. Therefore, analyzing these forces can provide a better understanding and prediction of the behavior of droplets on surfaces with specific properties.

2.2.1. Static Contact

1) TPCL (Triple Phase Contact Line)

At the interface between the droplet and the surface, three phases - liquid, gas, and solid - come into contact with each other. At the triple-phase contact line, each phase experiences a tension that acts on the interface with the other two phases. These tensions represent the strength of interactions between the phases and are commonly used to describe interactions between different phases. In an equilibrium triple-phase contact line, the three tensions balance each other, ensuring the stability of the entire interface. The triple-phase contact line is crucial for understanding wetting, capillary action, and adhesion between different phases.

The properties of TPCL, including its shape and position, can significantly affect the interaction between the fluid and the solid surface. Extrand et al. [14] proposed that a superhydrophobic surface can only be achieved when the contact line density exceeds a critical value and the roughness height exceeds a critical value. In the work of Mimmi Eriksson et al. [15], a certain functional relationship between the measured adhesion force and the TPCL line tension was summarized. The wetting tension $\gamma\cos\theta$ showed a linear relationship with the calculated adhesive force-to-contact radius ratio. This work also used laser scanning confocal microscopy to measure the existence of gas capillary forces on rough surfaces, which can be described by thermodynamic curves. Finally, this work defined the phenomena of superhydrophobic, superoleophobic, and superamphiphobic as transitions between the forces acting on the solid surface and the interfaces between the phases.

Understanding the forces is beneficial for guiding the development of theories and the design of superhydrophobic surfaces, especially when superhydrophobicity requires self-cleaning characteristics like the lotus effect. In Chen's work [16], the adhesive forces between water droplets and hydrophobic and superhydrophobic materials were measured using atomic force microscopy (AFM). It was found that the adhesive force on superhydrophobic surfaces is much smaller compared to hydrophobic surfaces. Under constant surface tension, a larger contact angle results in a greater upward force on the droplet, making it easier for the droplet to detach from the surface and promoting self-cleaning phenomena. Based on these findings, it was determined that the critical radius for achieving self-cleaning on superhydrophobic surfaces is related to the particle density: the greater the particle density, the smaller the critical radius.

In summary, understanding the forces is beneficial for guiding the development of theories and the design of superhydrophobic surfaces. However, force measurement is currently a challenging task as it involves microscopic intermolecular forces. In terms of measurement, there are high requirements for instrument equipment and operational precision. Measurement methods that have been proven practical include atomic force microscopy, micro-electro-mechanical balance systems, and the study of microscale interactions between superhydrophobic surfaces and interfaces, which is still a relatively new field.

2.2.2. Dynamic Contact – Impact. When a droplet impacts the surface of a horizontally superhydrophobic solid, its motion resembles that of a small water-filled balloon. Based on previous work [17], as shown in Figure 6, the movement of a droplet impacting a superhydrophobic surface can be divided into four stages: falling, spreading, contracting, and rebounding.

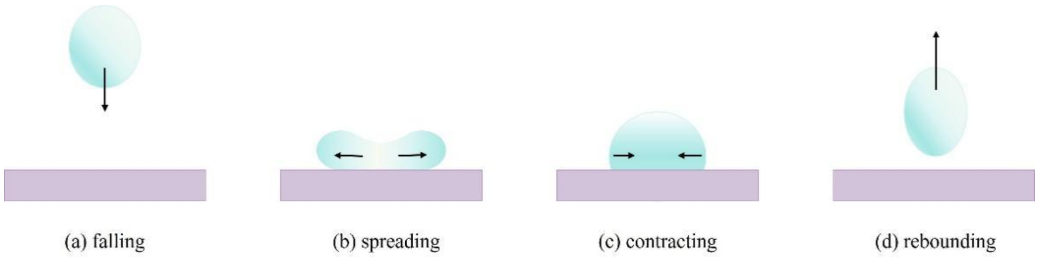

Figure 6. The motion process of droplet impact on superhydrophobic surfaces.

The four stages of the impact process are influenced by various factors. The stages of contact between the impact process and the surface are spreading and recoiling. The forces acting on the droplet during these two stages are not only related to the wetting properties of the surface but also influenced by the droplet collision velocity and surface tension. In addition, the collision process is non-ideal and involves adhesive forces and other resistances, resulting in energy losses. An analysis of energy losses in this process can be attributed to air resistance, thermodynamic losses during spreading, and adhesive forces. According to the experimental analysis by Hu et al. [18], the adhesive force accounts for the dominant energy loss during the spreading stage. The work by Kannan's team [19] summarizes the formula for adhesive force as:

$$W = \frac{1}{4}\pi D_0^2 \sigma_{lg} \frac{(W_e + 12)(\cos\theta_R - \cos\theta_A)}{3(1 - \cos\theta) + \frac{4W_e}{\sqrt{R_e}})} \quad (6)$$

where σ_{lg} is the liquid-gas surface tension, θ_A is the advancing angle during the spreading stage, θ_R is the receding angle during the recoiling stage, and D_0 is the initial diameter. From this formula, it can be deduced that the value of adhesive force is directly related to the dynamic wetting parameters of the solid surface.

In addition to qualitative research on the impact process between droplets and superhydrophobic surfaces, significant progress has been made in simulating dynamic processes through the development of computer software. Bu [18] used Fluent software to numerically simulate the process of droplet impact on superhydrophobic surfaces and summarized the results through dynamic observation of simulated droplet shapes and calculations. During the recoiling-rebounding stage, a concave "cavity" is formed on the bottom surface of the droplet due to the velocity difference between the droplet edge and the central region. Throughout the entire process of droplet impact on the surface, the internal velocity and pressure of the droplet are symmetrically distributed along the central axis. During the rebounding process, high pressure regions are located at the top and bottom of the droplet, causing the droplet to oscillate in a wave-like form.

2.2.3. Dynamic Contact and Flow. A prominent characteristic of superhydrophobic surfaces is their large slip length, which contributes significantly to reducing drag. Numerous experimental results confirm that the nano gas layer between the solid/liquid interface is the main reason for the large slip length. However, ultimately, whether it is the surface roughness, wetting properties, or flow shear rate,

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the influence on slip length is fundamentally the result of molecular interactions between the solid/liquid surfaces. The principles and influencing factors of slip length on two typical surfaces are described below:

1) Slip length on smooth surfaces

Zhu et al. [20] investigated the relationship between surface roughness and the interaction forces between liquid surface molecules and their effects on boundary conditions. Under the condition of both surfaces being hydrophobic, according to the no-slip boundary, the critical shear rate on the surface increases exponentially with increasing roughness. In smooth conditions, intermolecular forces play a major role, while in rough conditions, roughness plays a major role.

The theory of slip length due to the nanoscale effect can be divided into apparent slip theory and gas-liquid composite slip theory. Lauga et al. [21] proposed:

$$\delta = \frac{R}{4}\left(\frac{Q_{slip}}{Q_{non-slip}} - 1\right) \tag{7}$$

Where R is the radius of the pipe, Q_{slip} and $Q_{non\text{-}slip}$ represent the flow rates with and without slip velocity, and δ is the slip length. Experimental studies have shown that for smooth surfaces, the slip length is generally on the order of hundreds of nanometers.

2) Slip length on surfaces with spherical particles

Gu Chunyuan [22] assumed a single-layer adsorption and established a slip model for nanoscale particle adsorption microchannels. The following expression for slip length was derived:

$$\delta = \sqrt{\frac{(r_0 - d_p)^2}{2} - \frac{4\mu q}{\pi (r_0 - d_p)^2 \nabla p}} - r_0 + d_p \tag{8}$$

where r_0 is the inner radius of the microchannel, q is the flow rate of a single channel, d_p is the particle diameter, ∇p is the pressure gradient between the two ends of the microchannel, and μ is the fluid viscosity. This equation reflects the significant slip characteristics of hydrophobic nanoparticles adsorbed on microchannels, which effectively increase the effective radius of the microchannel, increase the injection volume, and reduce the injection pressure at both ends of the microchannel. This is the basic concept of reducing pressure and drag using hydrophobic nanoparticle adsorption.

Currently, there are various interpretations for the causes of slip, and with the discovery of the slip effect on hydrophobic surfaces, research on new drag reduction technologies based on the slip effect of hydrophobic surfaces is gaining attention.

3. Current Issues and Future Directions

Based on the research status of superhydrophobic surfaces, this paper presents the current issues and future research directions in this field, divided into theoretical research and surface preparation aspects, as follows:

3.1. Issues and Research Directions in Theoretical Research

1) Limited measurement methods for interfacial forces:

Due to the immaturity of equipment and technology, the methods and types of force measurement are still relatively limited, and the analysis of forces is currently in the laboratory research stage. Future development directions can utilize computer simulations to develop dynamic contact test programs that simulate experimental data under complex conditions. This can be combined with actual experimental measurements to analyze and summarize the experimental results.

2) Lack of systematicity in biomimetic theory:

In the observation, research, and preparation of biomimetic micro/nanostructures, many new research structures are described mainly using examples such as lotus leaves, petals, and gecko feet. However, for such a large number of newly discovered micro/nanostructures, a systematic and comprehensive classification is still needed. This includes factors such as the range of apparent contact angles, apparent rolling angles, height of surface micro-protrusions, presence of groove structures, groove structure periodicity, etc.

3) Lack of a universal thermodynamic model for guiding surface design:

Currently, researchers have only studied simple linear relationships between some thermodynamic parameters/curves and capillary forces on rough surfaces. The underlying mechanisms have not been deeply investigated, and a universal thermodynamic model for guiding surface design has not been proposed. This is one of the directions for further research in the future.

3.2. Current Issues and Research Directions in Superhydrophobic Surface Preparation

1) Need for further improvement in the lifespan of superhydrophobic surface micro/nanostructures:

For the external surfaces of infrastructure or large mechanical equipment with superhydrophobic properties, exposure to external substances such as dust, precipitation, particles, and chemical corrosion can cause wear and failure of the nanostructures over time. Therefore, more research experiments are needed to enhance the robustness of structures in terms of the degree of wear on the surface exposed within a unit of time. In the future, composite structures of micro and nanostructures can be attempted, using different types of reinforcing materials, to simulate surface wear, and detect and compare the improvement in working lifespan. Alternatively, research can be conducted on micro/nanocomposite structure materials that can self-repair to enhance the robustness of surface structures and extend their lifespan.

2) Difficulty and low efficiency in large-scale preparation of superhydrophobic structures:

According to the overview by Xu [23], the current methods for preparing superhydrophobic materials can be summarized into three categories: chemical coatings, liquid lubrication layers, and micro-nano structures. The chemical coating method is currently the simplest process, but the use of expensive and environmentally polluting chemicals such as silanes and fluorinated compounds is a drawback. Liquid lubrication layers are prone to loss, failing in the superhydrophobic effect. For example, Wong et al. [24] first proposed the concept of superlubricated surfaces based on the pitcher plant effect (SLIPS), which involves filling a porous polymer with a certain amount of lubricating liquid to obtain a stable and defect-free liquid lubrication layer. When the material surface freezes, the lubricating liquid acts as a barrier between the ice and the substrate, greatly reducing adhesion. However, in the long term, there can be loss of the lubricating liquid. Micro-nano structures are currently mostly prepared using molding methods, but the complex process of molding makes large-scale production difficult. In recent studies, laser etching [25] has been used to prepare micro-nano structures, which shows great potential for large-scale production. However, this method requires advanced laser equipment due to its high precision requirements.

Overall, due to current technological and cost limitations, the preparation of various new superhydrophobic materials and anti-icing surfaces mostly remains in the laboratory stage. In practical applications, coating and molding methods still dominate the industrialization and commercialization of superhydrophobic and anti-icing surfaces.

4. Conclusion

The application scope of biomimetic superhydrophobic surfaces is extremely wide, and different types of superhydrophobic surface structures can have different application functions. Superhydrophobic and super slippery anti-icing surfaces not only have broad prospects in aircraft anti/de-icing technology but also have significant application demands in large-scale infrastructure self-cleaning surfaces, water collection device surfaces, and even drag reduction equipment. This paper, through the research and analysis of existing superhydrophobic applications and theoretical models, proposes the current issues and future research directions in the field of biomimetic superhydrophobic research from both theoretical and preparation aspects. This is of great significance for the subsequent research in this field.

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