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Static and Dynamic Wetting Behaviors of Droplets on Micro-Nano Pillar-Structured Superhydrophobic Surfaces

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Extended Abstract

Liquids demonstrate various unique behaviors on superhydrophobic surfaces with microstructures, such as facilitating rapid droplet rebound and delaying ice formation, which have attracted significant attention from researchers. In this paper, theoretical analysis and experimental methods are combined to investigate the static and dynamic wetting behaviors of droplets on micro-nano scale secondary array-distributed pillar-structured surfaces.

Firstly, a thermodynamic analysis of the static wetting characteristics of secondary micro-nano scale square pillar microstructures is conducted. Furthermore, the universal expressions for the dimensionless geometric parameters (relative pillar height and relative pillar spacing of microstructures and nanostructures), wetting rate (k), intrinsic contact angle (θ_Y), and apparent contact angle (θ), which encompass nine wetting modes including complete wetting (Wenzel state), partial wetting (between Wenzel and Cassie state), and complete non-wetting (Cassie state) of both primary and secondary structures are derived. Among these, the Cassie-Cassie (C-C), Cassie-Wenzel (C-W), Wenzel-Cassie (W-C), and Wenzel-Wenzel (W-W) modes demonstrate stability, while the others are metastable transitional states. Based on this, the transformation conditions between composite and non-composite wetting states are further explored, and distribution maps of the four stable wetting states with respect to relative pillar height and relative pillar spacing are constructed. It is also revealed that the roughness factor has an amplifying effect on wettability under non-composite wetting conditions.

Next, the dynamic wetting characteristics of secondary-structured superhydrophobic surfaces are analyzed from the perspective of dynamics. The relationship between wetting pressure, anti-wetting pressure, and geometric parameters of microstructure was established. It has been confirmed that the reduction of the solid-liquid contact area and the concomitant increase in the solid-gas contact area beneath the liquid are crucial factors in enhancing superhydrophobicity. Furthermore, the differences and temporal sequence of anti-wetting pressures in micro and nano scale structures are analyzed. The findings reveals that nanostructures have a significant advantage in anti-wetting properties, thereby reducing the number of wetting states of droplets in contact with the surface to six modes. On this basis, the impact of structural parameters on the anti-wetting energy barriers of structures of two scales is compared, and the anti-wetting energy barriers provided by the micro-nano structures exhibit a synergistic effect during the wetting process is proposed, leading to a micro-nano hierarchical protection phenomenon in the wetting behavior of liquids.

Finally, combining experiments and theoretical analysis, the dynamic characteristics of droplet impact on cold superhydrophobic surfaces are studied. The qualitative relationships between the maximum spreading factor (α), contact time (t_c), maximum rebound factor (β), and Weber number (We) are determined. It has been demonstrated that superhydrophobic surfaces with secondary-scale microstructures exhibit significantly enhanced rebound and adhesive properties, surpassing those of conventional surfaces and surfaces with only primary structures. Based on the classical nucleation theory, the mechanism by which superhydrophobic surfaces delay ice formation is elucidated: a larger contact angle results in a greater critical nucleation work for the surface, making nucleation more difficult; the air layer trapped within the microstructures of the superhydrophobic surface weakens the heat transfer between the droplet and the surface, hindering the formation of critical nuclei and thus delaying ice formation.

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