論文の内容の要旨

論文題目　Bouncing behavior of a water droplet on a super-hydrophobic surface near freezing temperatures
（氷点付近における超撥水面上の水滴の動的挙動に関する研究）

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In recent years, super-hydrophobic surfaces (SHSs) fabricated through mimicking surface structures of plants and animals in nature have fascinated a lot of interests among researchers and engineers. Due to low surface energy of SHSs, they have demonstrated outstanding potentials to mitigate ice accumulation and exceptional capabilities to repel water droplets for anti-icing applications. However, the underlying physics dominating the rebounding behavior of an impact water droplet on an SHS near the freezing temperatures is still poorly understood. Hence, to understand the ice-phobic nature of SHS, this research focuses on conducting experiments to explore the bouncing mechanism of a water droplet on a cold SHS. The SHS is controlled under the condition of large temperature difference between the SHS and the impinging water droplet. The influence of surface temperature of SHS, initial temperature of a water droplet, which is the same as the ambient temperature, and droplet size on the bouncing behaviors is investigated.

The SHS utilized in this study is fabricated by spray-coating of a suspension of acetylene black and trimethylsiloxysilicate on a copper substrate. To evaluate the dynamics of water droplet during impact, the contact time and rebounding height are measured and employed as performance parameters. The ice-phobic nature of SHS is evaluated for a wide range of SHS temperature maintained around the freezing point of water (283 K-248 K). In addition, the effects of increasing the droplet temperature (278 K-293 K) and droplet size (2.07 mm-2.99 mm) on the droplet rebounding behavior are also analyzed.

Experimental results show that when the droplet initial temperature is at 278 K, the contact time increases and the rebounding height decreases or even to zero (adhesion to SHS) as the surface temperature of SHS is reduced from 283 K to 248 K. Besides, as the initial temperature of the droplet is increased from 278 K to 293 K, the impinging droplet presents the tendency to adhere to cold SHS. With an increase in droplet size from 2.07 mm to 2.99 mm, these trends become more prominent.

The experimental results are elucidated by the fact that when an impinging water droplet of relatively higher temperature comes into contact with an SHS maintained at much lower temperature, the rapid evaporation from the droplet could take place during the droplet impact process. As a result, the space between the droplet and micro/nano surface textures of SHS might become supersaturated. At low temperature of SHS, the empty space inside the hierarchical micro/nano surface textures of SHS could be instantly filled with water owing to the local condensation of evaporated water vapor.

Consequently, as the condensed water accumulates inside micro/nano textures of SHS water bridges linking the droplet and SHS could occur, the wetting transition from the Cassie-Baxter state to the Wenzel state takes place, and the super-hydrophobicity of the surface could no longer be preserved. The formed water bridges also yield the increase of droplet-SHS adhesion. To overcome the adhesion between the impinging droplet and water bridges within micro/nano surface cavities, a larger amount of kinetic energy was spent during the droplet rebound. Therefore, for the impinging droplet, a noticeable decrease in the residual energy occurs, resulting in an extended contact time and a reduction in rebounding height.

At a lower SHS temperature or a higher water droplet temperature, an increment of the rate of water condensation on SHS is observed. In addition, with an increase in droplet size there is an extended droplet-SHS contact time as well as an increase of the amount of condensed water. Under different experimental conditions, the amount of condensed water is evaluated via liquid-vapor phase transport model and a detailed energy analysis is elucidated during droplet rebounding process, which verify the proposed mechanism.

In addition, this study investigates the wetting transition of a sessile water droplet on a cold SHS from the Cassie-Baxter state to Wenzel state induced by the condensation of evaporated water vapor inside SHS hierarchical micro/nano textures. The receding contact angle of a sessile water droplet with the initial temperature of 278 K on an SHS with different temperatures (283 K-258 K) is measured and selected as the performance parameter. Compared with SHS at 283 K and 278 K, there is a significant decrease in receding contact angle when SHS temperature is reduced to 268 K, which could be caused by the existence of condensed water inside SHS micro/nano structures. When SHS is changed from 268 K to 258 K, the receding contact angle demonstrates a weak dependency on surface temperature owing to the sufficient time for vapor condensation to completely fill SHS micro/nano structures with condensed water.

To further interpret the dynamics of an impinging droplet on SHS near freezing temperatures, computational fluid dynamics simulations through the volume of fluid method are applied. A body force based on the continuum surface force model is adopted in the momentum equation to account for the effect of surface tension. The wetting transition observed in experiments is added as a boundary condition via the wall adhesion model and quasi-dynamic contact angle mode. The numerical modeling is validated through comparing the side-view profiles of impact droplet, time-course contact length, contact time, and rebounding height between experiments and simulations.

To analyze the dominant factor determining the rebounding or sticking physics of an impact water droplet on SHS near freezing temperatures, parametric study is carried out in consideration of surface characteristics (i.e., droplet-surface adhesion in terms of contact angle) and water droplet properties (i.e., viscosity and surface tension coefficient). As the droplet-surface adhesion increases (i.e., receding contact angle decreases), the droplet recoiling decelerates and the rebounding height becomes lower or even 0. When the droplet-surface adhesion increases, there is a reduction in the surface tension force near the surface, particularly in vertical direction. Besides, non-wetting condition is considered to evaluate the threshold energy loss due to viscosity for an impact water droplet. When the initial potential energy is insufficient to overcome the summation of threshold energy loss due to viscosity and threshold energy loss due to adhesion, the droplet forfeits rebounding capability on SHS. Within capillary-inertial regime, contact time shows an irrelevant relationship with water viscosity. But with the increase of water viscosity, the impact droplet bounces to a lower height because of the increment of viscous loss. As the increase of surface tension coefficient, there is a decrease in contact time because the capillarity is equilibrated with the inertia. Meanwhile, there is an increase in rebounding height owing to reduction in in viscous loss as the larger surface tension restricts droplet spread on surface. The parametric study demonstrates that under the experimental conditions of this work, the dominant mechanism affecting the impact behaviors of a water droplet on an SHS near freezing temperatures is the wetting transition induced by the water condensation inside SHS micro/nano textures.

In summary, the experimental findings indicate that the wetting transition caused by the accumulation of condensed water within micro/nano textures of an SHS near freezing temperatures may significantly alter the droplet rebounding behaviors. The numerical simulations reproduce droplet impacting performance observed from experiments and validate the significance of wetting transition. When considered in anti-icing applications, SHSs are expected to repel impinging water droplets under various conditions. The present research explores the significance of condensed water from the impact water droplet within micro/nano surface textures to the rebounding capability of droplet on an SHS near freezing temperatures. The substantial understanding of this droplet rebound mechanism will provide valuable insights on the rational design of SHSs for anti-icing or de-icing purposes.