Anti-icing strategies are on the way
Zhiyuan He1,* and Jianjun Wang2,3,*

1School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, China
2Key Laboratory for Green Printing, Beijing National Laboratory for Molecular Science, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China
3School of Future Technology, University of Chinese Academy of Sciences, Beijing 101407, China
*Correspondence: hezy@bit.edu.cn (Z.H.); wangj220@iccas.ac.cn (J.W.)
Received: May 26, 2022; Accepted: June 26, 2022; Published Online: June 30, 2022; https://doi.org/10.1016/j.xinn.2022.100278
© 2022 This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Citation: He Z. and Wang J. (2022). Anti-icing strategies are on the way. The Innovation 3(5), 100278.

Ice and snow coat more than 50% of the Northern Hemisphere of our planet in winter and are essential to atmosphere, geology, and life on Earth. However, undesired ice formation on solid surface with different forms, i.e., frost, snow, glaze, and rime, always causes severe energy and safety issues. Ice accretion poses serious problems for dams and locks, aircrafts, express trains, air conditioners, refrigerators, wind turbines, solar panels, power lines, suspension bridges, heat pumps, and offshore oil platforms. These icing problems will increase energy-resource consumption and origin electrical and mechanical malfunctions, reduce operating efficiency of devices, and result in security risks. For this reason, great efforts have been made to develop anti-icing and deicing methods for the following four purposes: (1) resisting the detrimental effects of condensed water, (2) inhibition of ice nucleation, (3) prevention of ice growth and propagation, and (4) reduction of the ice adhesion strength. In general, all the different anti-icing/de-icing strategies have been employed to prevent ice accumulation and to easily remove ice, and they can be classified into two major categories: active and passive approaches (Figure 1).

Until now, many active anti-icing approaches, such as electrothermal melting, chemical anti-freezing agents, mechanical deicing, high voltage direct current, and electro-impulse have still been widely used. Thermally keeping the surface temperature above 0°C by means of electrothermal heating is still an efficient anti-icing method in the aerospace industry and the wind-power-generation area. However, this method is extremely energy- and time consuming, and the electromagnetic disturbance induced by electric flow should be taken into consideration. Thanks to the lower freezing points of chemical anti-freezing agents compared with water, various deicing fluids are applied on the surface of aircrafts, express trains, and vehicles in order to prevent icing. For example, road salting takes advantage of this effect to protect roads from icing over, and salts are widely applied as inhibitor for water freezing. Commonly used NaCl can depress the freezing point of pure water to about –21°C. It is noted that the use of chemical agents has many drawbacks, i.e., the short-lived effectiveness and high costs as well as environmental pollution problems. In addition, direct mechanical removal of ice by shock waves, twisting of conductors, pneumatic boots, vibrations, or scraping devices are applied to break ice accretion on surfaces of apparatuses, express trains, transmission lines, and power networks. Considering the manual operations in complicated and dangerous conditions, these mechanical deicing approaches are neither efficient nor safe. Meanwhile, many other active anti-icing methods have also been applied, e.g., microwave, ultrasound, automatic robots, shape-memory alloys, and electromagnetic technology. Overall, most of these active strategies striving against ice accretion are apparently energy consuming, high cost, inefficient, or environmentally harmful. It is thus crucial to study and develop environmentally harmless, cost-effective, and efficient anti-icing technologies.

To solve these problems, great attention has been paid to develop passive anti-icing strategies for suppressing water condensation, preventing ice nucleation,
inhibiting ice propagation, and reducing ice adhesion. To inhibit condensation freezing and desublimation, great efforts have been made to study the abilities of superhydrophobic surfaces for removing impacting water droplets and condensed water droplets, leaving no water for freezing. The water droplets can slide away from superhydrophobic surfaces when the surfaces are slightly tilted. With the freezing conditions of cold rain, the impacting droplets of freezing rain can be retracted and rebounded on superhydrophobic surfaces to prevent water accumulation before freezing. In a cold and humid environment, coalesced condensed water droplets can be spontaneously removed from superhydrophobic surfaces with optimum hierarchical micro/nanostructures via self-propelled jumping. This self-propelled jumping effect is driven by the released surface energy during water-droplet coalescence after overcoming liquid-solid adhesion strength. Despite the excellent performance of superhydrophobic surfaces in shedding water, the disadvantages of durability, weatherability, UV resistance, anti-fouling ability, and humidity tolerance limit their anti-icing application. Another anti-icing approach that aims to prevent heterogeneous ice nucleation has attracted intensive interest because ice nucleation is the rate-limiting step for ice formation. It is found that ice-nucleation temperatures on different surfaces can be tuned by controlling surface charge and charge density, types of counterion, densities of hydroxyl groups, surface roughness and defects, surface crystallization lattice structures, and local electric field on surface. For example, increasing charge density on positively charged supercharged unfolded polypeptides can promote ice nucleation, whereas increasing charge density on negatively charged supercharged unfolded polypeptides inhibits it. The controllability of ion specificity grants the polyelectrolyte brushes, polyelectrolyte multilayers, polyelectrolyte hydrogels, and polyanlypholates high performance in inhibiting ice-nucleation temperatures as low as $-30^\circ$C. It is also found that heterogeneous ice-nucleation efficiency is correlated with bulk-like interfacial water, and the ice-nucleation temperature can be tuned via simply changing hydroxyl-group density on polyvinyl alcohol, graphene oxide, and highly oriented pyrolytic graphite surfaces. In practical anti-icing application, the undesired ice nucleation is inevitable due to the contaminants and dusts in real-world environments, giving rise to ice growth and propagation across the whole surface. Therefore, control of ice propagation is also critical for anti-icing applications. On surfaces of polyelectrolyte multilayer, polyelectrolyte hydrogels, and multilayer hydrogels, the ice-propagation rates can be tuned up to 3 orders of magnitude via simply changing counterions and the polyelectrolyte types. Take the anti-freeze-protein-inspired multi-functional anti-icing hydrogel as an example. It can prevent ice-propagation rates as low as 0.002 cm$^2$/s; however, the poor mechanical robustness and durability limit its widespread application in real-life conditions. Beyond all the anti-icing strategies above, ice can still inevitably form on even the best anti-icing coatings under extreme conditions (i.e., ultra-low temperatures and high humidity), thus making icephobic materials with ultra-low ice adhesion strength is urgently needed. It is demonstrated that the ice adhesion can be controlled via tuning the structure, mobility, and amount of interfacial water. A number of icephobic surfaces with ultra-low ice adhesion have been demonstrated using a self-lubricating liquid water layer, and the ice formed atop the surface can be easily shed via the action of wind blowing. Besides the high ice-removal efficiency, the existence and availability of a self-lubricating aqueous layer have a valid temperature range, below which the freezing of the lubricating aqueous layer will cause the rapid increase of ice adhesion strength. Instead of trapping water, the slippery liquid-infused porous surface employs organic lubricants trapped inside the surface microstructures, polymeric or porous matrix materials, and leaves a smooth liquid surface with ultra-low ice adhesion strength. However, the depletion of the lubricant will reduce the durability and long-lived anti-icing performance; meanwhile, environmental pollution arising from lost lubricant cannot be ignored either. Over the past few years, a number of materials with enhanced light absorption including ultra-black semiconductors, cermet, conjugated polymers, and carbonaceous materials have been investigated for solar anti-icing applications. These materials harvest solar energy as heat for ice removal. A significant defect still exists in solar anti-icing studies: how to ensure high anti-icing efficiency if there is no sunlight, particularly in the cloud daytime and evening. Though the solar anti-icing surfaces based on phase-change materials were utilized to store and release latent heat for ice removal in the evening, the low solar-energy-storage capacity cannot ensure anti-icing efficiency throughout a whole day.

It is noted that none of these active or passive anti-icing strategies alone can meet the practical application requirements. Ideally, an efficient anti-icing strategy in the future should combine the advantages of both active and passive icephobic materials for having optimum anti-icing performance in different possible conditions. For example, combinations of electrothermal and photothermal anti-icing strategies can make breakthroughs in the wind-power-generation field and achieve all-day continuous ice-free application. The electrothermal anti-icing approach works in the evening, and the photothermal anti-icing approach works in the daytime, thus complementing each other perfectly. Combinations of electrothermal anti-icing films and superhydrophobic coating have a promising application in the areas of aircraft and railroad. The melted ice on electrothermal films can be easily shed from the superhydrophobic coatings, avoiding being re-frozen. Combinations of ultra-low ice adhesion coatings and industrial robot deicing methods may show great potential for anti-icing application in solar panels, power lines, suspension bridges, and offshore oil platforms. Without assistance of mechanical deicing approaches, most of the ultra-low ice adhesion coatings are entirely ineffective because ice cannot fall off under the force of gravity. Combinations of active and passive anti-icing approaches have true versatility and prominent performance in practical anti-icing applications.

Furthermore, from the specific perspective of anti-icing materials, the anti-icing performance, scalability, mechanical durability, and versatility of anti-icing materials should be improved to adapt to harsh environmental conditions in the future. Firstly, we need to identify the formation mechanism of ice crystals at the molecular level, i.e., the molecular mechanisms of ice nucleation, ice structure change, and ice adhesion with different anti-icing coatings. Without knowing more about how ice forms, it is impossible to build highly efficient anti-icing materials. Then, comprehensively considering the complexity of the practical application environment, the demand for material hardness, wear resistance, environmental friendliness, etc., is also a key issue that needs to be paid attention to in the future research of anti-icing materials. In addition, more research is needed on smart surfaces, such as self-healing, flexible, multi-functional surfaces, because compared with ordinary anti-icing surfaces, this type of surface has a longer service life and can suffer worse environmental conditions. Overall, by taking all-round exploration of mechanism and proper selection of materials into account as well as making full use of the flourishing science and technology developments, there will be a promising breakthrough in the anti-icing field.

**REFERENCES**

1. Kreder, M.J., Alvarenga, J., Kim, P., et al. (2016). Design of anti-icing surfaces: smooth, textured or slippery? Nat. Rev. Mater. 1, 15003.
2. Wang, D., Sun, Q., Hokkenen, M.J., et al. (2020). Design of robust superhydrophobic surfaces. Nature 582, 55–99.
3. He, Z., Wu, C., Hua, M., et al. (2020). Biospired multifunctional anti-icing hydrogel. Matter 2, 723–734.
4. Wong, T.-S., Kang, S.H., Tang, S.K.Y., et al. (2011). Biospired self-repairing slippery surfaces with pressure-stable omniphobicity. Nature 477, 443–447.
5. Parent, O., and Ilina, A. (2011). Anti-icing and de-icing techniques for wind turbines: critical review. Cold Reg. Sci. Technol. 65, 88–96.

**DECLARATION OF INTERESTS**

The authors declare no competing interests.