Wen et al. demonstrate sustainable anti-frosting with high-efficiency heat transfer on a frost-free surface with a highly thermally conductive 3D nanowire network by a counterintuitive strategy: accelerating the nucleation-to-departure cycle of subcooled micro-droplets. These findings may hold promise for increasing the efficiency of thermal systems while inspiring the designs of frost-free surfaces.

Wen et al., Cell Reports Physical Science 3, 100937
July 20, 2022 @ 2022 The Author(s).
https://doi.org/10.1016/j.xcrp.2022.100937

Highlights

- Anti-frosting strategy is proposed to accelerate micro-droplet nucleation-to-departure
- 3D nanowire network is used to manipulate nucleation and reducing thermal resistance
- Sustainable anti-frosting with high heat flux subcooled condensation is demonstrated
- 10-fold heat transfer enhancement is maintained for 5 h under −15 °C and 75% humidity
Sustainable anti-frosting surface for efficient thermal transport

Rongfu Wen,1 Yushan Ying,1 Xuehu Ma,1 and Ronggui Yang2,3,4,*

SUMMARY
Inhibiting frost formation is of fundamental importance for many industrial applications, ranging from various infrastructures to thermal systems. Sustaining a frost-free surface without reducing heat transfer efficiency is a great challenge. We hereby propose a counterintuitive approach to achieve sustainable anti-frosting under high heat flux subcooled condensation by accelerating the nucleation-to-departure cycle of condensed liquid, demonstrated by manipulating initial nucleation and reducing thermal resistance using a three-dimensional nanowire network. High heat flux subcooled condensation is maintained without frost formation on the frost-free surface at a low surface temperature of \(-15^\circ C\) for more than 5 h in humid air with a relative humidity of 75%. More than 10 times enhancement in the steady-state heat flux is obtained on the frost-free surface compared with the state-of-the-art low solid fraction non-wetting nanostructured surfaces. This passive frost-free surface may hold promise for increasing the efficiency of thermal systems while inspiring the design of frost-free surfaces.

INTRODUCTION
In humid environments, ice crystals could form on a solid surface when the temperature is below the freezing point. There exist serious economic and safety concerns associated with frost formation and accumulation for various infrastructures such as aircraft, power lines, wind turbines, and marine vessels, as well as many commercial and residential energy systems such as refrigerators, air conditioners, and air source heat pumps (ASHPs).1–9 Frosting on a heat transfer surface in a humid environment can lead to up to a 75% reduction in energy efficiency of heat exchangers and even system malfunction.10 Common strategies for removing frosts primarily involve mechanical removal, chemical reagents, and active heating.11 However, most of the de-icing and anti-frosting techniques are expensive, time-consuming, and even environment damaging.

Compared with the prevalent energy-intensive active techniques, the passive frost-free surface could be a safer and more economical approach to reducing frost accumulation. The physical mechanisms for state-of-the-art frost-free surfaces can be categorized as delaying the onset of ice nucleation with the use of antifreeze agents, suppressing frost growth and accumulation on non-wetting surfaces with superhydrophobic (SHO) nanostructures or lubricant-infused layers, and decreasing frost adhesion strength with low interfacial toughness materials1,12–20 (see Note S1 and Figure S1). For heat transfer surfaces in low-temperature energy systems, frost formation is mainly due to the freezing of liquid condensate on the subcooled surface where water vapor in the humid air condenses on the cold surface and subsequently freezes. By achieving a non-wetting state of subcooled droplets on a solid surface with trapped air or lubricant pockets,21–24 the...
contact area between the solid substrate and liquid condensate can be decreased by using the low solid fraction (LSF) nanostructures to minimize surface adhesion.\textsuperscript{25–27} Recently, the SHO heat exchangers covered with non-wetting nanostructures have been demonstrated to delay frost formation and maintain higher heat transfer rates under realistic operating conditions of electric vehicles when compared to that with higher surface energies.\textsuperscript{9} The delayed frost formation results in a system efficiency benefit in the first frosting cycles but diminishes in later cycles due to incomplete defrosting on the surface. The trapped air or lubricant between the sparse nanostructures also intrinsically serves as a thermal barrier layer due to their low thermal conductivity, reducing heat transfer while suppressing condensation and frost accumulation on the cold surface (Figure 1A). Despite that these frost-free surfaces with an LSF non-wetting layer can suppress frost formation and accumulation,\textsuperscript{16,23} such passive strategy suffers from anti-frosting failure, which is caused by either nucleation-induced high adhesion or slow growth-induced long-term residence of subcooled droplets on the cold surface, as well as surface degradation due to lubricant depletion after many frosting-defrosting cycles.\textsuperscript{7,28} According to the classical nucleation theory and experimental observations recently reported,\textsuperscript{13,29} the energy barrier of heterogeneous ice nucleation can exhibit a significant increase only when the feature size of surface structure is comparable to or smaller than the critical nucleation size for ice formation (less than several nanometers), indicating that most of the state-of-the-art LSF frost-free surfaces can only delay frosting but cannot completely prevent frosting, especially under low surface temperature or high air humidity.\textsuperscript{15,30,31} Furthermore, the existence of a low thermal conductivity LSF layer between the substrate and liquid condensate (e.g., the air, lubricant pockets) not only increase the freezing probability of subcooled liquid due to longer residence times, but also limit the potential heat transfer application of such frost-free surfaces in many energy systems.\textsuperscript{32}
Recent studies on the hybrid surfaces with large wettability contrast structures have demonstrated that frost accumulation in the frost-free zone can be reduced by spatially controlling initial nucleation to form discontinuous frost patterns. Due to the lowered vapor pressure of ice relative to liquid water, the frost-free zone can be maintained dry, resulting in a passive frost-free area of up to 90% of a surface under low air humidity. Inspired by the biological morphology in nature, initial ice nucleation on a solid surface can also be controlled by creating localized surface roughness to form discontinuous patterns for weakening frost propagation. Creating a low-energy interface on the magnetic slippery surface can also reduce the anti-icing temperature to as low as \(-34^\circ C\), close to the homogeneous limit \((-38^\circ C)\), which is attributed to the suppressed heterogeneous ice nucleation on the magnetic liquid-liquid interface. More recently, it was shown that coupling solar heating with surface superhydrophobicity can achieve frost-free performance even under an environmental temperature as low as \(-60^\circ C\). However, for many thermal systems, it is vital to suppress frosting but not degrade heat transfer performance due to the introduction of frost-free coatings themselves.

Ideally, heat transfer surfaces in low-temperature thermal systems, such as ASHPs and refrigerators, should maintain efficient heat transfer, especially under high humidity and low surface temperature. A critical step toward a passive frost-free surface that can sustain high-flux heat transfer performance is to rapidly remove the subcooled liquid condensate from a cold surface before ice crystal formation. Due to the higher surface energy on the solid-condensate interfaces when compared to the vapor-condensate interfaces, completely avoiding heterogeneous nucleation of ice crystals in high humidity environments is not a viable solution, no matter whether it is on the state-of-the-art frost-free surfaces (e.g., non-wetting SHO surfaces), lubricant-infused surfaces, hybrid wettability surfaces, or solar-heated frost-free surfaces reported recently. Furthermore, the non-condensable gas (NCG) in humid air forms a low-flux diffusion boundary layer of water vapor near the surface, leading to slow growth and long-term residence of subcooled liquid on the cold surface, and subsequently increasing the freezing probability.

We hereby demonstrate a completely counterintuitive approach (Figure 1B) to achieve sustainable anti-frosting for high-flux heat transfer through accelerating the nucleation-to-departure cycle of subcooled droplets—in other words, by spatially promoting the nucleation and growth of subcooled micro-droplets on the top of the high thermal conductance non-wetting surfaces before the onset of freezing. This necessitates a uniquely designed surface that has a three-dimensional (3D) nanowire network with high thermal conductivity, which can not only suppress ice crystal formation but also reduce the thermal resistance of frost-free coating itself for efficient heat transfer. The 3D nanowire network named here is used to emphasize the nano-bumps bridged randomly between the straight nanowire arrays, which together form an interconnected network covering the substrate. The narrow gaps with a size only in tens of nanometers among 3D nanowire networks can promote initial vapor nucleation on the top of nanowires, but suppress ice formation and growth in the nano-gaps between nanowires. Furthermore, the closely spaced 3D nanowire network with a high solid fraction, together with high thermal conductivity of copper, ensures efficient subcooled condensation heat transfer when compared with other frost-free surfaces reported previously. Benefiting from the strategy to shorten the residence time of subcooled droplets on the frost-free surface by accelerating both the growth and removal, we show that high heat flux subcooled condensation is maintained for more than 5 h without frost formation at the low surface temperature of \(-15^\circ C\) in humid air with relative
humidity at 75%. Compared with the state-of-the-art frost-free surfaces, more than 10 times enhancement in the steady-state heat flux is obtained on the frost-free surface with the 3D nanowire network.

RESULTS
Design and fabrication of sustainable frost-free surfaces
The interfacial thermal resistance between humid air and solid surface needs to be minimized for achieving high flux heat transfer on a frost-free surface. Once the surface temperature decreases below the freezing point on a cold plain hydrophobic (HO) surface (Figure 2A), the subcooled droplets could rapidly freeze. Subsequent frost propagation and accumulation increase frost layer thickness and thus increase additional thermal resistance over time (Figure 2D). In addition, an NCG diffusion boundary layer near the air-solid interface additionally contributes a mass transfer-induced thermal resistance to the overall heat transfer from the humid air to the solid surface. Compared with the plain HO surface, an LSF nanostructured SHO surface (Figure 2B), which incorporates low surface energy coating with the air pockets between nanostructures, can suppress frost formation by reducing heterogeneous nucleation in addition to the minimized contact area of heat transfer from

Figure 2. Sustainable frost-free surface with high thermal conductivity 3D nanowire network
(A) On a plain hydrophobic (HO) surface, slowly growing droplets in accumulated non-condensable gas (NCG) layer could rapidly freeze when surface temperature decreases below the freezing point. (B) State-of-the-art LSF nanostructured superhydrophobic (SHO) surface can suppress condensation due to the low thermal conductivity LSF layer; however, the nucleation-induced high adhesion, together with the slow droplet growth in the NCG layer, can significantly increase freezing probability. (C) Rapid nucleation-to-departure cycle of subcooled droplets on the SHO surface with 3D copper nanowire network can sustain frost-free and high flux, which is attributed to rapid growth and jumping removal by controllable nucleation and increased vapor mass flux by the disturbance. (D) Conceptual illustration of the overall thermal resistance between the solid surface and humid air for the plain, LSF nanostructured SHO, and SHO surface with 3D nanowire network. (E) Cross-sectional scanning electron microscopy (SEM) images of closely spaced 3D copper nanowire network. A high-magnification SEM image shows the nano-bumps covering the wall surface of copper nanowires, which bridge randomly between the straight nanowires.
the growing droplets to the cold substrate. However, the slow droplet growth rate increases the residence time of subcooled droplets on the cold surface, resulting in an increased probability of droplet freezing. In addition, initial nucleation inside the LSF nanostructures can change droplet dynamic behaviors from the highly mobile state to the undesired pinning state, significantly increasing the residence time and freezing probability of condensed droplets. Once a subcooled droplet starts to freeze, a frost layer can form, extend, and even cover the entire LSF nanostructured surface, leading to a strong frost-solid contact with the solid surface and the failure of anti-frosting performance (Figure 2D). The additional thermal resistance due to frost buildup can significantly degrade the thermal efficiency of energy systems.

To avoid the large interfacial thermal resistance and long-term droplet residence on the subcooled surfaces as mentioned above, we present here a non-wetting surface with a highly thermally conductive 3D nanowire network (Figures 2C and 2E) that can increase the growth rate of subcooled droplets to minimize residence time on the cold surface. Contrary to the anti-frosting strategies by suppressing condensation in previous studies, a closely spaced 3D copper nanowire network is grown directly on a copper substrate, which can promote subcooled condensation heat transfer through both the rapid growth and high mobility of micro-droplets. The micro-droplets formed on the top of the 3D nanowire network due to the nucleation control with narrow nano-gaps can greatly shorten the residence time of subcooled droplets in the form of self-jumping in the size of tens of micrometers when compared to the slow-growing suspended droplets or high-adhesion pinned droplets on the previous frost-free surfaces. Spontaneous jumping of subcooled micro-droplets can frequently disturb the NCG boundary layer near the air-droplet interface and reduce the thermal resistance that is caused by vapor diffusion. In short, accelerating the nucleation-to-departure cycle of subcooled droplets that is achieved by manipulating initial nucleation and droplet growth on the highly thermally conductive 3D nanowire network can be expected to reduce the overall thermal resistance between the humid air and cold solid surface to a much smaller value when compared to the state-of-the-art frost-free surfaces with LSF nanostructures (Figure 2D).

Similar to our previous work, our innovative 3D porous anodic alumina oxide (AAO) template with ultra-high-density nanopores is used to fabricate the thermally conductive frost-free surface (see Note S2 and Figure S2). Figure 2E shows the cross-sectional scanning electron microscopy (SEM) image of copper nanowires with a length (height) \( h \) of \( \sim 5 \mu m \) and a diameter \( d \) of 80–100 nm, respectively. High-density nano-bumps inside the nanowire networks enable the nano-gaps between the nanowires smaller than 20–50 nm (inset of Figure 2E), which further increases the solid fraction of 3D nanowire network \( \varphi \), larger than 0.6, and suppresses ice crystal formation in the nano-gaps. Based on thermal conductivity and solid fraction of the nanostructures on the SHO surface, the effective thermal conductivity of the LSF nanostructure layer and 3D copper nanowire network layer is 1 and 238.8 W/m \( \cdot \) K, respectively, which is calculated by the copper oxide species with a solid fraction of 0.04 and thermal conductivity of 25 W/m \( \cdot \) K, and the copper with a solid fraction of 0.6 and thermal conductivity of 398 W/m \( \cdot \) K. The apparent contact angle and contact angle hysteresis of a 4-\( \mu \)L water droplet on the surface with 3D nanowire network are 161° \( \pm \) 3° and 4° \( \pm \) 3°, respectively. For comparison, a plain hydrophilic (HI) copper surface (bare smooth copper), a plain HO surface (self-assembled coating on the plain copper surface), and an LSF nanostructured SHO surface (copper oxide nanograsses on the plain copper surface with an HO coating, \( \varphi < 0.04 \), that is widely used to promote droplet departure and frost
removal\(^{50,52,53}\) are also fabricated (see the details of surface fabrication and characterization in Note S2 and Figure S2).

**Sustainable anti-frosting and high-flux heat transfer**

Anti-frosting experiments are conducted on the vertically mounted test surfaces in a custom-made humid air frosting chamber with built-in optical visualization capability (see the details of experimental setup and procedure in Note S3 and Figure S3). All of the experiments are performed at atmospheric pressure and humid air temperature of \(T_{air} = 20^\circ C\) in the chamber with a relative humidity of 75%. Throughout the experiments, the pressure and temperature of humid air in the chamber are continuously monitored and adjusted to establish stable operating conditions. The surface temperature is independently controlled via a cooling liquid (water-glycol mixture) loop in which the inlet and outlet temperature and flow rate of the cooling liquid are measured in real time to determine the heat transfer rate from humid air to the surface. With a surface area of 12.57 mm\(^2\) measured in this work, the self-similarity feature results in average values of the thermal resistance, and heat flux on the entire surface can be measured.\(^{54,55}\) As the surface temperature decreases, the transition from subcooled condensation to frosting is observed and recorded by a synchronized high-speed camera through the optical window on the chamber. The uncertainties of the heat transfer data are calculated using the error propagation method (see the details of data reduction and uncertainty analysis in Note S4 and Table S1).\(^{56}\)

Figure 3 shows the heat transfer performance of humid air on the four test surfaces under different operating conditions, including plain HI copper surface, plain HO surface, LSF nanostructured SHO surface, and SHO surface with 3D nanowire network. The temporal evolution of heat flux on the surface is continuously monitored for 50 min from the beginning of condensation on the fresh surface to study the effect of frost formation on the heat transfer performance. As expected, all four surfaces remain frost-free at the surface temperature of \(T_w = -1^\circ C\) (Figure 3A). Once humid air condenses on the surface, the heat flux increases rapidly to a maximum, which is due to the vast fresh surface available for initial humid air condensation. With the increase in time, the differences among the heat transfer curves become apparent for the four surfaces. Specifically, the heat flux on the plain HI surface decreases over time after a maximum of 58 kW/m\(^2\) and then reaches a steady-state value of 30 kW/m\(^2\). This is because the exposed fresh surface area decreases with time before a continuous liquid film is formed. Once a stable liquid film covers the whole plain HI surface, the heat flux reaches a steady state that is mainly determined by the thermal resistance of liquid condensate film.\(^{57}\) Similar heat flux reduction to a steady-state value of 41 kW/m\(^2\) after a maximum of 76 kW/m\(^2\) is observed on the plain HO surface. Compared with the plain HI surface, both the maximum heat flux and steady-state heat flux are increased on the plain HO surface due to the expected better heat transfer performance of dispersed small droplets.\(^{42,58}\) For the LSF nanostructured SHO surface, the steady-state heat flux is further enhanced to 68 kW/m\(^2\), which is attributed to the jumping droplet removal at a smaller size and higher frequency when compared with that on the plain HO surface. However, the time required to reach the steady-state heat flux is increased due to the larger nucleation energy barrier and larger thermal resistance of the LSF nanostructure layer. A steady-state heat flux of 98 kW/m\(^2\) is rapidly reached on the SHO surface with 3D nanowire network, which is the largest value among all of the measurements. This is attributed to the shortened nucleation-departure cycle enabled by the enhanced droplet growth and jumping on the high thermal conductivity 3D nanowire network. When the surface temperature is decreased to \(-10^\circ C\), the transition from subcooled condensation to the frosting process significantly
degrades the heat flux on both the plain HI surface and HO surface (Figure 3B). Although the LSF nanostructured SHO surface can delay heat transfer degradation at the beginning, the steady-state heat flux is decreased to less than 10 kW/m² after the frost layer formation at 35 min. Different from the frost-induced heat transfer degradation on the other three surfaces, an unprecedented high steady-state heat flux of 130 kW/m² is maintained without frosting on the SHO surface with 3D nanowire network within a duration of 50 min heat transfer measurement at the surface temperature as low as -10°C. Such a high heat flux obtained on the SHO surface with 3D nanowire network is precisely due to the sustainable subcooled condensation without a frost layer formation when compared with other test surfaces. It is noted that the experimental conditions of subcooled condensation of humid air on a sub-zero surface in this work are completely different from that in the research of condensation heat transfer enhancement, such as high-temperature pure steam.
or with low concentration NCIs. The comparison of heat transfer performance with the reported frost-free surfaces can be found in Note S5 and Figure S4. Such a stable high heat flux subcooled condensation at ultra-low surface temperature is due to the rapid growth and departure of micro-droplets before the onset of ice nucleation, which can significantly shorten the residence time of subcooled droplets to reduce the freezing probability.

Figure 3C shows the maximum heat flux $q_{\text{max}}$ and maximum heat transfer coefficient (HTC) $h_{\text{max}}$ on the four test surfaces as a function of surface temperature $T_w$. The maximum heat flux and HTC are collected by referring to the heat flux peak as shown in Figures 3A and 3B before the start of frost formation during the temporal evolution of heat flux over time. As the surface temperature decreases from $-1^\circ\text{C}$ to $-10^\circ\text{C}$, the maximum heat flux is increased monotonically for all four surfaces due to the increased driving force for heat transfer (i.e., the temperature difference between humid air and solid surface). The maximum HTC of the test surface is almost independent of the surface temperature, and the largest maximum HTC is obtained on the SHO surface with 3D nanowire network. Compared with the maximum heat flux and maximum HTC, the steady-state heat flux and steady-state HTC are collected by referring to the heat flux after the formation of the frost layer, which is highly dependent on whether the liquid condensate is frozen (Figure 3D). On the plain HI surface, once the liquid condensate freezing occurs at a surface temperature of $-3^\circ\text{C}$ and lower, the steady-state heat flux and steady-state HTC are significantly decreased even with an increasing surface subcooling, which is due to the large thermal barrier of the porous frost layer covering on the solid surface. For the plain HO surface with the segmentation of the gaps between dispersed droplets, the frost propagation is reduced to a surface temperature of $-3^\circ\text{C}$, leading to an increase in steady-state heat flux and HTC with the decrease in surface temperature. As the surface temperature is further decreased to $-8^\circ\text{C}$ and lower, the frosting-induced reduction of steady-state heat flux and HTC is observed on the plain HO surface. Compared to the plain HI and plain HO surfaces, droplet jumping on the LSF nanostructured SHO surface expands the operating surface temperature without frosting to $-8^\circ\text{C}$. As the surface temperature is further decreased to $-10^\circ\text{C}$, the steady-state heat flux is reduced to approximately 6.5 kW/m² and the steady-state HTC is reduced to 0.2 kW/m²K (Figure 3D), which is, again, due to the dominant thermal barrier of the accumulated frost layer. On the SHO surface with 3D nanowire network, the steady-state heat flux is increased monotonically as the surface temperature decreases (i.e., the driving force increases for subcooled condensation). The largest steady-state heat flux and HTC are obtained on the SHO surface with 3D nanowire network under the same surface temperature (Figure 3D).

Mechanisms of sustainable anti-frosting performance
To unlock the physical mechanisms for the sustainable anti-frosting and high flux heat transfer on the surface with the 3D copper nanowire network, we quantitatively...
analyzed the heat transfer characteristics through subcooled droplets and experimentally characterized the growth rate, departure size, and residence time of the subcooled droplets on the test surfaces (Figure 4). Defined as the droplet from nucleating to leaving a vertical test surface, the residence time of subcooled droplets on each surface is averaged for more than 10 droplet events under each operating condition. Driven by the temperature gradient between the vapor and the substrate, heat flux is transferred from the vapor to the droplet (Figure 4A). The latent heat of the condensation process is delivered to the liquid primarily through phase change at the liquid-vapor interface. The mass flux associated with the heat flux leads to a growing droplet, which is related to the surface wettability and droplet wetting states. To study the effect of the wetting state on the growth and departure, the infiltration factor $f$ is defined to describe the wetting state of the subcooled droplet on the LSF nanostructured SHO surface, where $f = 0$ is used to characterize the Cassie state (the nano-gaps are filled with air pockets) and $f = 1$ is for the Wenzel state (the nano-gaps are flooded with liquid condensate), respectively. The thermal resistance of the composite liquid condensate-nanostructure layer is...
dependent on the infiltration factor $f$, solid fraction $\varphi$, thermal conductivity of the solid structure $k_s$ and liquid condensate $k_l$. Figure 4B shows the growth of subcooled droplets on the four surfaces as a function of time at the surface temperature of $T_w = -1^\circ C$ and the air humidity of RH (relative humidity) = 75%. When the droplet grows to a critical size larger than the feature size of the surface nanostructure, the average droplet growth rate can be fitted as $r_d = \eta t^\alpha$, where $t$ is time and $\alpha$ is the power-law exponent ranging from 0 to 1. The details of droplet growth measurements can be found in Note S6 and Figures S5 and S6. It is shown that the theoretical predictions from the droplet growth model are in excellent agreement with the experimentally measured results on the test surfaces. Due to the limitations of the custom-made experimental chamber in this work, the droplet behaviors cannot be obtained directly from the side view. The growth, residence, and departure of subcooled droplets on each test surface are compared based on the front view imaging by a high-speed camera.

The residence time of subcooled droplets on the surface is dependent on both droplet growth rate and droplet departure size. On the plain HO surface, the power-law exponent of droplet growth rate $\alpha$ is 0.54. However, to be removed by the gravity, the subcooled droplets need to grow to a critical departure radius of $r_{de} = 1.1–1.3$ mm, resulting in a long residence time of $t_re = 760–960$ s on the cold surface (Figure 4C). Such a long-term residence increases the freezing probability of subcooled droplets on the plain HO surface. As a comparison, the departure radius of the subcooled droplets in the Cassie state ($f = 0$) is significantly reduced, to only approximately 20 $\mu$m due to the efficient jumping removal on the LSF nanostructured SHO surface (Figure 4C). However, the growth rate of the subcooled droplets in the Cassie state is decreased due to the much larger thermal resistance of the air pockets underneath the growing droplets. As a result, the residence time $t_w$ for the jumping droplets on the LSF nanostructured SHO surface is only reduced to $t_w = 15–20$ s. Although the replacement of the air pockets with liquid condensate for the droplets in the Wenzel state ($f = 1$) can increase the thermal resistance of the LSF nanostructure layer, the departure radius of the pinned droplets is greatly increased up to $r_{de} = 1.5–1.8$ mm, leading to a large residence time of $t_re = 1,050–1,400$ s, which is even longer than that on the plain HO surface. Thus, the LSF nanostructured SHO surface suffers from the long-term residence of subcooled droplets on the cold surface, which is caused by either trapped air-induced slow droplet growth for the Cassie state or nucleation-induced high adhesion droplet for Wenzel state. As a comparison, the high-density 3D nanowire network comprising high thermal conductivity copper nanowires not only has a smaller thermal resistance for droplet growth but also enables more efficient droplet jumping at the smallest departure radius $r_{de} = 12–18$ $\mu$m for the removal of subcooled liquid condensate (Figure 4C). Furthermore, the jumping-induced frequent disturbance to the vapor diffusion boundary layer can enhance the mass flux of vapor molecules for humid air subcooled condensation on the surface (Figure 4B). Due to the improvements in both growth and removal of subcooled micro-droplets, the residence time on the SHO surface with 3D nanowire network is greatly reduced to $t_re = 3–6$ s.

**Long-term anti-frosting experiments**

Figure 5 summarizes the microscopic frosting characteristics of the four test surfaces in humid air at $T_{aw} = 20^\circ C$ and RH = 75% under various surface temperatures in a range of $-15^\circ C$ to $-5^\circ C$. For each test surface, the frosting experiments are performed with a beginning surface temperature of $5^\circ C$, where the surface temperature is then decreased by $1^\circ C$ and stabilizes for 20 min until the frosting is observed on the test surface. On the plain HI surface (Figure 5A), the vapor in the humid air nucleates and condenses to form a liquid film that covers the entire surface at $T_w = 5^\circ C$. As the...
surface temperature $T_w$ decreases to $-3^\circ$C for 0.2 h, the liquid film on the plain HI surface begins to freeze and then forms a porous frost layer. A further reduction of surface temperature can exacerbate frost formation and growth on the plain HI surface. On the plain HO surface (Figure 5B), vapor condensation occurs on the surface at $T_w = 5^\circ$C, where a large number of discrete droplets nucleate and grow to a feature size approaching the capillary length ($\sim 2.2$ mm) before gravity removal. However, as the surface temperature is decreased to $-6^\circ$C for 0.2 h, droplet freezing occurs, starting from large droplets, which is shown as the black color of the droplets in the optical image due to the light absorption by ice crystals. Because the gaps between isolated droplets slow down the percolation-induced frost propagation, the frosting is observed at a deeper cooling of $-6^\circ$C on the plain HO surface. Figure 5C shows that the subcooled droplet jumping occurs and is maintained on the LSF nanostructured SHO surface as the surface temperature reduces to $-8^\circ$C or lower. However, the subcooled droplet jumping can only remain at a surface temperature of $-8^\circ$C or higher. Further decreasing the surface temperature to $-8^\circ$C or lower for 0.3 h leads to the onset of droplet freezing and the anti-frosting failure on the surface. Significantly different from the anti-frosting failure on the other three surfaces above, sustainable jumping of subcooled micro-droplets is achieved on the SHO surface with 3D nanowire network even when the surface temperature is reduced to $-15^\circ$C and maintained for 5 h without frosting (Figure 5D).
Figure 6 shows the macroscopic view of frost evolution and coverage on the test surface in humid air. The temporal evolution of subcooled condensation and frosting processes on the surface with a diameter of 4 cm is continuously observed and recorded for 6 h from the beginning of humid air subcooled condensation for quantitatively evaluating the anti-frosting performance. To cope with the stochastic nature of heterogeneous nucleation of the ice from subcooled liquid for a droplet on the cold surface, a large number of condensed droplets of different sizes are formed and simultaneously grow on the test surface in each experiment, which greatly reduces the uncertainty of random heterogeneous nucleation that occurs for a single droplet in one experiment. In addition, three experiments are performed for each operating condition on the test surface.

Figures 6A–6D shows the frost formation and propagation at the surface temperature of $-15^\circ C$ on the four surfaces. As humid air begins to condense on the plain HI surface (Figure 6A), liquid condensate rapidly freezes and transitions to frosting within 0.05 h. Further frost growth causes frost propagation and expansion, leading to the entire surface being covered by the frost layer within 0.1 h. Compared with the plain HI surface, the frosting on the plain HO surface is suppressed due to the dispersed droplets.
(Figure 6B). The frost propagation from the edge to the center of the cold surface is slower due to the discontinuous path between the isolated droplets. The whole HO surface is covered by a continuous frost layer after 0.5 h and further frost growth can thicken and densify the frost layer.²⁵ For the LSF nanostructured SHO surface, the spontaneous micro-droplets jumping accelerates the removal of subcooled liquid condensate, further suppressing the frost layer formation until 1 h later (Figure 6C). Compared with the frost morphology on the plain HI and plain HO surfaces, the ice crystal branches of the frost layer on the LSF nanostructured SHO surface are finer and looser due to the lower adhesion between the micro-droplets and nanostructured surface. Figure 6D shows the continuous 5 h jumping of subcooled micro-droplets and the onset of freezing after 6 h on the SHO surface with 3D nanowire network. Such a long-time anti-frosting performance at the surface temperature of −15°C under high humidity environment is attributed to the much shorter nucleation-to-departure cycle, which is enabled by both the ultra-low thermal resistance and nucleation-controllable nanowire networks on the sustainable frost-free surfaces.

Figures 6E–6G shows the long-time temporal evolution of frost coverage on the 4 surfaces at the surface temperature of −3°C, −10°C, and −15°C, respectively. The frost coverage ratio is defined as the proportion of surface area covered by the frost layer over the entire surface. At the surface temperature of −3°C (Figure 6E), the frost layer can cover the entire plain HI surface within 1 h, while most of the surface area can be kept frost-free on the plain HO surface and LSF nanostructured SHO surface. As the surface temperature is decreased to −10°C (Figure 6F), more than 80% of the surface area is covered by the frost layer on the plain HI surface, plain HO surface, and LSF nanostructured SHO surface within 0.5 h. As the subcooled condensation time increases up to 1 h, the entire surface area is almost completely covered by the frost layer for the three surfaces. Even when the surface temperature is reduced to −15°C, the entire SHO surface with 3D nanowire network can maintain frost-free and the onset of frosting is observed at the edge of the surface only after 6 h of experimental observation (Figure 6G).

DISCUSSION
A counterintuitive strategy for achieving sustainable anti-frosting and high-flux heat transfer is proposed in this work by accelerating the nucleation-to-departure cycle of subcooled micro-droplets. Different from the previous frost-free surfaces reported in the literature that weaken frosting by minimizing heat and mass transfer and suppressing condensation,⁸,¹⁵,¹⁷,⁶⁴ sustainable subcooled condensation without frosting has been demonstrated on the SHO surface with 3D nanowire network to achieve high heat flux for low-temperature thermal systems.

Figure 7 compares the anti-frosting performance of SHO with the 3D nanowire network with state-of-the-art frost-free surfaces reported in the literature, including the SHO surfaces (nanostructured, micropore arrays, and hierarchical), the surfaces with hybrid bi-philic patterns, lubricant-infused surfaces (silicone oil, K100-F13, and K100-F13-PPy), and PSL (phase-switching liquid)-infused surfaces.³,⁸,¹²,³³,⁶⁵ For all of the experimental data collected here, the surface temperature ranges from −15°C to −2°C and the supersaturation of humid air varies 1.5–10. The supersaturation of humid air is defined as the ratio of the ambient partial pressure of water vapor Pw to the saturated vapor pressure corresponding to the surface temperature Pw,s that is S = Pw/Pw,s. Note that the experimental data of frost-free surfaces collected and compared in Figure 7A are measured under different operating conditions, such as the surface temperature and supersaturation. Most previous frost-free surfaces can suppress frost formation but rapidly degrades...
during a 1-h test (Figure 7A). Specifically, the frost-free area of the surface reduces over time even in low-humidity environments. As a comparison, the anti-frosting performance of frost-free surfaces with infused PSL, e.g., SD (solidified dimethyl sulfoxide), SCt (solidified cyclooctane), and SG (solidified glycerol) can be further improved with time due to the release of trapped latent heat of the condensation process. On a hybrid surface with different wettability patterns reported recently, up to 90% of the frost-free surface can exhibit frost-free under the surface temperature of \(-10^\circ\text{C}\) and supersaturation of 1.5. This is attributed to the preferred initial nucleation and frosting of humid air on the micro-stripes across a plain surface, leading to a low diffusion rate of water vapor for maintaining the intermediate surface areas frost-free. Note that the adjacent ice stripes can maintain uncrosslinked with one another even after 24-h measurement under chilled and supersaturated conditions. For the SHO surface with 3D nanowire network studied in this work, the surface can maintain nearly 100% frost-free within the 5-h test, and the onset of frosting is only observed at the edge of the surface after 6 h of the test. Figure 7B compares the frost-free area on the various frost-free surfaces after a 1-h experiment from the beginning of humid air subcooled condensation on the fresh surface. Compared with the reported frost-free surfaces, the SHO surface with 3D nanowire network can maintain frost-free on the entire surface under a lowest surface temperature of \(-10^\circ\text{C}\) and a highest supersaturation of 10. The systematic comparison with the
state-of-the-art frost-free surfaces shows excellent anti-frosting performance obtained on the surface with the 3D nanowire network.

The efficient passive anti-frosting strategy through accelerating nucleation-to-departure cycle demonstrated in this work provides a potential solution for addressing the economic and safety concerns in various infrastructures. Such sustainable frost-free surfaces with high-flux heat transfer performance could tackle the longstanding challenge of pushing the passive frost-free surfaces into many thermal system applications, such as the refrigerators, air conditioners, and ASHPs. The application of the sustainable frost-free surface into the evaporator of ASHP systems can eliminate the degradation of energy efficiency, up to 50%–70%, which is caused by the frost formation and accumulation on the current surfaces for electric vehicles and industrial systems. For an ASHP system that transfers heat from outside air to an indoor space, it consists of an evaporator for extracting heat from ambient air to vaporize refrigerant, a compressor for pressurizing gaseous refrigerant, a condenser for releasing the latent heat of refrigerant to indoor air, and an expansion valve for lowering the pressure of the liquid refrigerant. The impact of the frost-free surface on the energy efficiency of ASHPs is analyzed by using an existing heat pump system model and taking into account the additional thermal resistance due to frost formation on the evaporator. Different from the conventional ASHP system with the plain HI surface, the sustainable frost-free surface with 3D nanowire network can keep the evaporator surface frost-free during the whole day, resulting in an improved average coefficient of performance (COP) of the ASHP system from 2.6 to 3.7. In addition, avoiding periodic intermittent operations can increase the life of the ASHP system (see Note S7, Table S2, and Figures S7–S10). It is noted that the actual efficiency of the applications of frost-free surfaces to mitigate frosting/icing problems is determined by a combination of many factors. In addition to the high heat flux performance and low-temperature operating, high-humidity environment that is focused on in this work, more roles to consider for anti-frosting applications include surface/edge defects, droplet size mismatch, and surface orientation. For example, jumping droplets from a horizontal substrate could return to the surface, which shortens delay frosting time and weakens subcooled condensation heat transfer performance.

In summary, sustainable anti-frosting and high-flux heat transfer performance are demonstrated on a frost-free surface with a highly thermally conductive 3D nanowire network, at an ultra-low surface temperature of −15°C and RH of 75%. Compared to the state-of-the-art frost-free surfaces, more than 10 times enhancement in the steady-state heat flux is obtained on the novel frost-free surface at the surface temperature of −10°C. The excellent thermal and anti-frosting performances are attributed to a counterintuitive strategy: accelerating nucleation-to-departure cycle of subcooled micro-droplets for minimizing residence time on the cold surface. By increasing the growth rate and accelerating departure, the droplet residence time on the SHO surface with 3D nanowire network is shortened to less than one-20th of that on the LSF frost-free surfaces. The remarkable frost-free surface not only holds great promise for a significant increase in the thermal efficiency of many low-temperature energy systems but also creates a new venue for designing sustainable frost-free surfaces in a variety of industrial applications.

**EXPERIMENTAL PROCEDURES**

**Resource availability**

**Lead contact**

Further information and requests for resources and procedures should be directed to the lead contact, Prof. Ronggui Yang (ronggui@hust.edu.cn).
Materials availability
This study did not generate new unique materials.

Data and code availability
All of the data supporting the findings are presented within the article and supplemental information. All other data are available from the lead contact upon reasonable request.

Fabrication of anti-frosting surfaces
3D porous AAO templates are used to fabricate the frost-free surface proposed in this work. The 3D copper nanowire network is fabricated on a plain copper surface by a template-assisted electrodeposition approach. To minimize the nano-gaps between 3D nanowire networks, the electrolyte has been changed from phosphoric acid (H₃PO₄, 0.3 M) to oxalic acid (H₂C₂O₄, 0.3 M). The optimized oxidation voltage of 60 V and electrolyte temperature of (2–4°C) are used to obtain the AAO templates with higher density and smaller diameter nanopores when compared with the AAO templates fabricated in our previous work.⁴² As a comparison, a plain HI surface is fabricated by polishing the copper block surface, then cleaned in an ultrasonic bath with acetone for 10 min, and rinsed with isopropyl alcohol, ethanol, and deionized (DI) water. The plain HO surface is fabricated by dipping the polished copper block sample into an ethanol solution of 2.5 mM n-octadecanethiol at 70°C for 1 h. The self-limiting chemical oxidation process is used to fabricate nanograsses on a plain copper surface.⁵⁰ The polished and cleaned copper block sample is dipped into an alkaline solution composed of NaClO₂, NaOH, Na₃PO₄·12H₂O, and DI water (3.75:5:10:100 wt %) at 80°C for 20 min. HO functionalization of the surface is obtained by dipping the sample into an ethanol solution of 2.5 mM n-octadecanethiol (96% n-octadecyl mercaptan, Sigma-Aldrich) at 70°C for 1 h.

Surface characterization
To obtain the surface morphology of the frost-free surfaces, microstructural characterization is performed using SEM (FEI Quanta 450 FEG). A contact angle goniometer (OCAH200) is used to measure the surface wettability by dispensing a 4-μL water droplet, adding volume to the droplets, and sucking back the volume of water.

For the anti-frosting and heat transfer performance, a custom-made experimental setup is built to measure supercooled condensation on the vertically mounted surface with the visualization capability for in situ experimental imaging. The experimental setup consists of a humid vapor generator, an air pump, a condensation chamber, a chilled liquid bath, and a data acquisition subsystem (N5771A, Agilent). The ambient air is supplied into the humid air generator by an air pump, humidified to the experimental humidity, and then flowed into the condensation chamber. The humidity and temperature of the humid air are controlled by the humid air generator. The test surfaces are mounted vertically in the chamber and three thermocouples are designed in parallel on the copper block to measure the temperature distribution in the copper block for obtaining the surface temperature of the sample. The measurement point of humid air temperature is located 2 cm from the test surface in the chamber. The chilled liquid bath (HAAKE Phoenix II, Thermo Fisher Scientific) is used to dissipate the heat from the sample surface for lowering the surface temperature to be below zero. The inlet and outlet temperature and the flow rate of the cooling liquid (water-glycol mixture) are recorded to determine the heat flux of the sample surface. The relative humidity of the air in the chamber is measured by the humidity sensor (HX94, Omega). The visualization of condensation and frosting
characteristics is conducted using a high-speed camera (Photron FASTCAM SA4) through a transparent window in front of the test surface.

**SUPPLEMENTAL INFORMATION**
Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2022.100937.

**ACKNOWLEDGMENTS**
The authors acknowledge funding from the National Natural Science Foundation of China (nos. 52006025 and 52036002) and the Fundamental Research Funds for the Central Universities (no. DUT20RC(3)016). We thank H. Zhang from Stanford University for her participation in the initial experimental proof of the concept. R. Wen thanks Q. Wang from Dalian University of Technology for helpful discussions and suggestions.

**AUTHOR CONTRIBUTIONS**
R.W. and R.Y. conceived the research. R.Y. supervised the research. R.W. designed and carried out the surface fabrication. R.W. and Y.Y. carried out the anti-frosting and heat transfer experiments. R.W. and R.Y. analyzed the data and wrote the manuscript. All of the authors have approved the final version of the manuscript.

**DECLARATION OF INTERESTS**
The authors declare no competing interests.

Received: January 21, 2022
Revised: April 11, 2022
Accepted: May 18, 2022
Published: June 13, 2022

**REFERENCES**

1. Kreder, M.J., Alvarenga, J., Kim, P., and Aizenberg, J. (2016). Design of anti-icing surfaces: smooth, textured or slippery? Nat. Rev. Mater. 1, 15003. https://doi.org/10.1038/natrevmats.2015.3.

2. He, Z., Liu, K., and Wang, J. (2018). Bioinspired materials for controlling ice nucleation, growth, and recrystallization. Acc. Chem. Res. 51, 1082–1091. https://doi.org/10.1021/acs.accounts.7b00528.

3. Schutzius, T.M., Jung, S., Maia, T., Eberle, P., Antonini, C., Stamatopoulos, C., and Poulikakos, D. (2015). Physics of icing and rational design of surfaces with extraordinary icephobicity. Langmuir 31, 4807–4821. https://doi.org/10.1021/la502586a.

4. Hou, Y., Yu, M., Shang, Y., Zhou, P., Song, R., Xu, X., Chen, X., Wang, Z., and Yao, S. (2018). Suppressing ice nucleation of supercooled condensate with biphilic topography. Phys. Rev. Lett. 120, 075902. https://doi.org/10.1103/physrevlett.120.075902.

5. Wu, S., He, Z., Zang, J., Jin, S., Wang, Z., Wang, J., Yao, Y., and Wang, J. (2019). Heterogeneous ice nucleation correlates with bulk-like interfacial water. Sci. Adv. 5, eaat9825. https://doi.org/10.1126/sciadv.aat9825.

6. Boyina, K.S., Mahvi, A.J., Chavan, S., Park, D., Kumar, K., Lira, M., Yu, Y., Gunay, A.A., Wang, X., and Miljkovic, N. (2019). Condensation frosting on meter-scale superhydrophobic and superhydrophilic heat exchangers. Int. J. Heat Mass Transf. 145, 118694. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118694.

7. Cebeci, T., and Kafyeke, F. (2003). Aircrafticing. Annu. Rev. Fluid Mech. 35, 11–21. https://doi.org/10.1146/annurev.fluid.35.10101.161217.

8. Chatterjee, R., Beysens, D., and Anand, S. (2019). Delaying ice and frost formation using phase-switching liquids. Adv. Mater. 31, e1807812. https://doi.org/10.1002/adma.201807812.

9. Mahvi, A.J., Boyina, K., Musser, A., Elbel, S., and Miljkovic, N. (2021). Superhydrophobic heat exchangers delay frost formation and enhance efficiency of electric vehicle heat pumps. Int. J. Heat Mass Transf. 172, 121162. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121162.

10. Huang, L., Liu, Z., Liu, Y., Gou, Y., and Wang, J. (2009). Experimental study on frost release on fin-and-tube heat exchangers by use of a novel anti-frosting paint. Exp. Thermal Fluid Sci. 33, 1049–1054. https://doi.org/10.1016/j.expthermflusci.2009.06.002.

11. Zhang, Z., and Liu, X.Y. (2018). Control of ice nucleation: freezing and antifreeze strategies. Chem. Soc. Rev. 47, 7116–7139. https://doi.org/10.1039/c8cs00628a.

12. Kim, P., Wong, T.S., Alvarenga, J., Kreder, M.J., Adorno-Martinez, W.E., and Aizenberg, J. (2012). Liquid-infused nanostructured surfaces with extreme anti-ice and anti-frost performance. ACS Nano 6, 6569–6577. https://doi.org/10.1021/nn30310q.

13. Bai, G., Gao, D., Liu, Z., Zhou, X., and Wang, J. (2019). Probing the critical nucleus size for ice formation with graphene oxide nanosheets. Nature 576, 437–441. https://doi.org/10.1038/s41586-019-1827-6.

14. Golovin, K., Dhyani, A., Thouless, M.D., and Tuteja, A. (2019). Low-interfacial toughness materials for effective large-scale deicing. Science 364, 371–375. https://doi.org/10.1126/science.aav1266.

15. Lu, J., Song, Y., Jiang, L., and Wang, J. (2014). Bio-inspired strategies for anti-icing. ACS Nano 8, 3152–3169. https://doi.org/10.1021/nn406522n.

16. Graeber, G., Schutzius, T.M., Eghlidi, H., and Poulikakos, D. (2017). Spontaneous self-dislodging of freezing water droplets and the role of wettability. Proc. Natl. Acad. Sci. U S A 114, 11040–11045. https://doi.org/10.1073/pnas.1705952114.
17. Irajizad, P., Hasmain, M., Farokhnia, N., Sajadi, S.M., and Ghaseml, H. (2016). Magnetic slippery extreme icephobic surfaces. Nat. Commun. 7, 13395. https://doi.org/10.1038/ncomms13395.

18. Liu, Y.-C., Tocilj, A., Davies, P.L., and Jia, Z. (2020). Mimicry of ice structure by surface hydroxyls and water of a helix antifreeze protein. Nature 406, 322–324. https://doi.org/10.1038/35018604.

19. Liu, K., Wang, C., Ma, J., Shi, G., Yao, X., Fang, H., Song, Y., and Wang, J. (2016). Janus effect of antifreeze proteins on ice nucleation. Proc. Natl. Acad. Sci. U.S.A. 113, 14739–14744. https://doi.org/10.1073/pnas.1614379114.

20. Guo, P., Zheng, Y., Wen, M., Song, C., Lin, Y., and Pan, S. (2012). Icephobic/anti-icing properties of micro nanostructured surfaces. Adv. Mater. 24, 2642–2648. https://doi.org/10.1002/adma.201104412.

21. Golovin, K., and tuteja, A. (2017). A predictive framework for the design and fabrication of icephobic polymers. Sci. Adv. 3, e1701917. https://doi.org/10.1126/sciadv.1701917.

22. Pan, S., Guo, R., Bjornmalm, M., Richardson, J.J., Li, L., Peng, C., Bertleff-Zieschang, N., Xu, W., Jiang, J., and Caruso, F. (2018). Coatings super-repellent to ultralow surface tension liquids. Nat. Mater. 17, 1040–1047. https://doi.org/10.1038/nmat5163.

23. Boreyko, J.B., and Collier, C.P. (2013). Delayed phenomena. J. Chem. Phys. 139, 100203. https://doi.org/10.1063/1.4809369.

24. Sun, Y., and Rykaczewski, K. (2017). Suppression of frost nucleation achieved using the nanoengineered integral humidity sink effect. ACS Nano 11, 906–917. https://doi.org/10.1021/acsnano.0c05705.

25. Attiging, D., Frankiewicz, C., Betz, A.R., Schütz, T.M., Ganguly, R., Du, D.Y., Kim, C.-J., and Megaridis, C.M. (2014). Surface engineering for phase change heat transfer: a review. MRS Energy Sustain. 1, 4–40. https://doi.org/10.1557/mres.2014.9.

26. Wen, R., Zhou, X., Peng, B., Lan, Z., Yang, R., and Ma, X. (2019). Falling-droplet-enhanced filmwise condensation in the presence of non-condensable gas. Int. J. Heat Mass Transf. 142, 6293–6304. https://doi.org/10.1016/j.ijheatmasstransfer.2019.112406.

27. Zhang, H., Zhao, G., Wu, S., Alsaid, Y., Zhao, Y., Yao, B., Ma, Y., Zhu, X., and He, X. (2020). Superhydrophobic photothermal icephobic surfaces based on candle soot. Proc. Natl. Acad. Sci. U.S.A. 117, 11240–11246. https://doi.org/10.1073/pnas.200129117.

28. Zhang, H., Zhao, G., Wu, S., Alsaid, Y., Zhao, W., Yao, X., Liu, L., Zou, G., Lv, J., He, X., et al. (2021). Solar anti-icing surface with enhanced condensate self-removing at extreme environmental conditions. Proc. Natl. Acad. Sci. U.S.A. 118, e200978118. https://doi.org/10.1073/pnas.200978118.

29. Golovin, K., Kobaku, S.P.R., Lee, D.H., Diloreto, E.T., Mabry, J.M., and Tuteja, A. (2016). Designing durable icephobic surfaces. Sci. Adv. 2, e1501496. https://doi.org/10.1126/sciadv.1501496.

30. Yeong, D., and Ma, X. (2016). Drop distributions and numerical simulation of dropwise condensation heat transfer. Int. J. Heat Mass Transf. 98, 1657–1671. https://doi.org/10.1016/j.ijheatmasstransfer.2016.02.005.

31. Peng, R.F., Xu, S.S., Ma, X.H., Lee, Y.C., and Yang, R.G. (2018). Three-dimensional superhydrophobic nanowire networks for enhancing condensation heat transfer. J. Heat Transf. 140, 041103. https://doi.org/10.1115/1.4040062.

32. Mouterde, T., Lehoucq, G., Xavier, S., Checco, N., and Meister, K. (2022). Cryofouling avoidance in the Antarctic scallop Adamussium colbecki. C. R. Physique 17, 1082–1100. https://doi.org/10.1016/j.crhy.2021.08.001.

33. Beysens, D. (2006). Dew nucleation and growth. C. R. Physique 7, 1082–1100. https://doi.org/10.1016/j.crhy.2006.02.005.

34. Frenkel, J. (1939). A general theory of heterogeneous fluctuations and pretransition phenomena. J. Chem. Phys. 7, 536–547. https://doi.org/10.1063/1.1750484.

35. Yang, R.G. (2018). Three-dimensional superhydrophobic nanowire networks for enhancing condensation heat transfer. J. Heat Transf. 140, 041103. https://doi.org/10.1115/1.4040062.

36. Mouterde, T., Lehoucq, G., Xavier, S., Checco, N., and Meister, K. (2022). Cryofouling avoidance in the Antarctic scallop Adamussium colbecki. C. R. Physique 17, 1082–1100. https://doi.org/10.1016/j.crhy.2021.08.001.

37. Beysens, D. (2006). Dew nucleation and growth. C. R. Physique 7, 1082–1100. https://doi.org/10.1016/j.crhy.2006.02.005.
66. Martinez-Frias, J., and Aceves, S.M. (1999). Effects of evaporator frosting on the performance of an air-to-air heat pump. J. Energy Resour. Technol. 121, 60-65. https://doi.org/10.1115/1.2795061.