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New concepts

The prevailing paradigm for constructing superhydrophobic anti-icing surfaces relies on precisely engineering the coating formulation with high nanoparticle loadings, intricate chemical modifications, and complex multi-step processing. This work challenges that paradigm by introducing a substrate-driven design strategy, where the structural outcome is governed not by the spray slurry, but by the received substrate. Using a porous fibrous film as an active assembly medium, nanoparticles are selectively retained and spontaneously organized into a fine nanoporous architecture in a single spraying step. This transforms the substrate from a passive mechanical support into a programmable morphological regulator, enabling robust superhydrophobicity at only 2.5 wt% nanoparticle content. The design principle is generalizable beyond specific materials, as demonstrated by successful structure formation with varied solvents and resins. Furthermore, this strategy seamlessly integrates with the standard manufacturing processes of resin-based composites, unlocking a scalable and cost-effective pathway to high-performance anti-icing solutions for aircraft, wind turbine blades, and cryogenic fuel storage.



All data generated or analyzed during this study are included in this published article and its supplementary information (SI). [View Article Online](#)
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Scalable nanoporous superhydrophobic films toward extreme icing conditions at -141°C and icing wind tunnel

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Abstract

Superhydrophobic surfaces offer a promising passive anti-icing alternative, yet they frequently fail to sustain the non-wetting Cassie-Baxter state under dynamic icing conditions. Conventional approaches for robust superhydrophobic anti-icing coating rely on high nanoparticle loadings (>50 wt%) to achieve the desired nanoporous roughness, often compromising cost efficiency and interfacial robustness. Herein, we proposed a novel and practical substrate-driven spraying strategy to construct fine nanoporous structures, allowing superhydrophobicity at a substantially reduced nanoparticle content of 2.5wt%. The optimized nanoporous superhydrophobic films exhibited excellent dynamic anti-icing performance, effectively repelling impacting droplets at -141°C and suppressing long-term condensation for over 3 h. Furthermore, the dynamic deicing behaviors are confirmed by the high slipperiness of melted ice and coalescence-induced wriggling of melting ice/frost. When integrated into composite airfoils, the film surface exhibits outstanding practical



1 efficacy in icing wind tunnel tests. Only 0.4 W/cm² of power density was required to
2 suppress icing at both the leading edge and runback zone. This work offers a promising
3 pathway for implementing high-performance anti-icing solutions in advanced resin-based
4 composite materials in wind turbine blades, aircraft, and cryogenic fuel storage tanks.

5 **Keywords**

6 anti-wetting, dynamic, anti-icing/deicing, nanostructures, superhydrophobic films,
7 spraying

9 **1. Introduction**

10 Ice accretion poses a severe and persistent threat to resin-based composite materials
11 operating in low-temperature environments, such as wind turbine blades, advanced aircraft,
12 and cryogenic fuel storage tanks, often leading to performance degradation and
13 catastrophic failures.¹ Traditional anti-icing and de-icing technologies based on mechanical
14 or thermal effects are energy-intensive and rely on complex ancillary systems.² In response,
15 the development of passive, energy-free alternatives has become a focal point of research.³
16 ⁴ Among these, superhydrophobic surfaces that leverage the non-wetting Cassie-Baxter (C-
17 B) state to retard water/ice formation have shown considerable promise for static anti-
18 icing.⁵ However, under dynamic icing environments featuring high undercooling, elevated
19 humidity, and ultra-low temperatures, previously reported superhydrophobic surfaces
20 frequently fail to sustain the stable C-B state.⁶ Consequently, they usually fail to pass
21 rigorous icing wind tunnel assessments.⁷ Under these extreme icing conditions, the surface
22 is exposed to both impacting and condensed water droplets. These droplets tend to
23 penetrate and pin within the micro/nanostructures, promoting the formation of tenacious,



1 interlocked ice.^{8, 9} Consequently, enhancing the robustness of the superhydrophobic state
2 under extreme dynamic icing conditions remains a paramount challenge.¹⁰

3 The wetting state under icing conditions is governed critically by the vapor-liquid
4 phase transition and the subsequent dynamics of condensate water.¹¹ Various engineered
5 surfaces have been developed to manipulate these dynamic processes for applications such
6 as atmospheric water harvesting and dropwise condensation.^{12, 13} In most cases, these
7 reports together highlight the importance of nanostructures in facilitating the highly
8 slippery C-B state.¹⁴ Indeed, nanostructures consistently exert their effect in inhibiting the
9 formation and accumulation of both water and ice.^{15, 16} Specifically, during condensation,
10 they have been demonstrated to inhibit the nucleation of condensate droplets,¹⁷ enhance
11 droplet mobility,¹⁸ and facilitate rapid shedding.¹⁹ While under water impact conditions,
12 nanostructures contribute to minimizing contact angle hysteresis and energy dissipation,²⁰
13 thereby increasing the possibility of droplet rebound. Therefore, the superhydrophobic
14 surface incorporating with fine nanostructures exhibits a dual-repellency capability,
15 effectively shedding water at both the micro-scale condensate water and the macro-scale
16 impacting droplets.

17 However, the scalable and portable preparation of the requisite fine nanostructures
18 presents another significant hurdle. Existing top-down techniques like corrosion²¹ and
19 photolithography,²² as well as bottom-up methods such as sol-gel,²³ self-assembly,²⁴ and
20 physical vapor deposition,²⁵ can create nanostructures on the flat or micro-structured
21 surfaces. However, these techniques are often hampered by complexity, high cost, and
22 time-consuming.^{26, 27} Notably, candle soot, multi-wall/single-wall carbon nanotubes, and
23 fumed silica are common nanomaterials for fabricating fine nanostructures.^{28, 29} Air-



1 assisted spraying enables the deposition of structured superhydrophobic coatings onto
2 diverse substrates using these nanoparticles.^{30, 31} Given this versatility, along with its
3 inherent scalability, the technique is a promising candidate for the large-scale surface
4 engineering of composite materials. Nevertheless, adding binders to enhance adhesion
5 strength may reduce the exposure of nanostructures at the coating surface.³² Advanced
6 technologies have been developed to regulate the deposition morphology, such as
7 electrostatic spraying,³³ ultrasonic spraying,³⁴ flame spraying,³⁵ and thermal spraying.³⁶
8 However, achieving binder-minimized superhydrophobic surfaces in a facile and scalable
9 manner remains elusive.

10 In this work, we examine the critical requirements for superhydrophobic surfaces to
11 achieve dynamic anti-wetting and anti-icing, pinpointing fine nanopores and nano-
12 architectures as essential features. We subsequently propose a facile substrate-driven
13 morphology control strategy to construct such desirable nanoporous films, which enables
14 superhydrophobicity at a substantially reduced nanoparticle content of 2.5 wt%. This
15 method breaks through the dependence of the traditional superhydrophobic structure
16 spraying process on high nanoparticle content. The optimized nanoporous
17 superhydrophobic structures exhibit exceptional dynamic anti-icing performance, capable
18 of repelling water droplets impacting on surfaces cooled below -140°C and withstanding
19 prolonged vapor condensation for 3 h. Moreover, we elucidated the superior of nanoporous
20 structures to maintain superhydrophobic stability in the dynamic deicing process under the
21 coupling of gravity and thermal effects. Importantly, the resulting nanoporous
22 superhydrophobic film can be integrated into the resin-based composite airfoil without
23 altering its standard manufacturing process.³⁷ Subsequent icing wind tunnel tests confirmed



1 the practical anti-icing capability with low energy consumption at 0.4 W/cm^2 . Our findings
2 tackle both the scientific and practical bottlenecks in implementing advanced anti-icing
3 technology for resin-based composites, particularly in the demanding fields of aerospace
4 and wind energy.

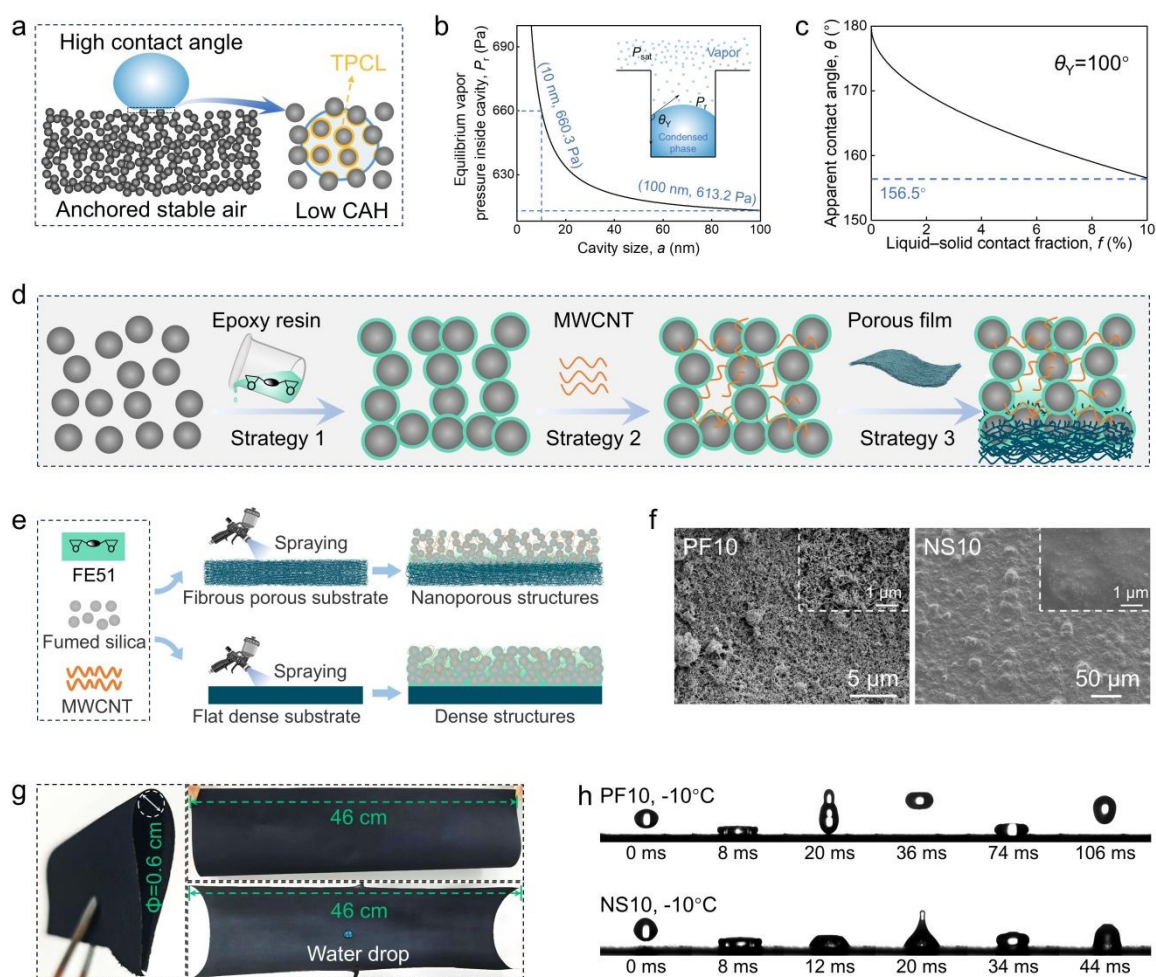
5 **2. Results and Discussion**

6 **2.1. Anti-Icing Performances of Nanoporous Structures**

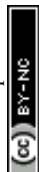
7 Nanoporous structures with fine nanopores and nano architectures hold
8 groundbreaking potential for anti-icing applications through the following anti-wetting
9 mechanisms (Fig. 1a). First, nanoporous structures can inhibit the phase transition of water
10 vapor to condensate droplets by regulating the vapor pressure. For a hydrophobic
11 nanocavity ($\cos\theta < 0$), Kelvin equation dictates that the vapor pressure inside the cavity (P_r)
12 is higher than the ambient saturation vapor pressure (P_{sat}) (Fig. 1b). When the cavity size
13 is smaller than 100 nm, the elevated vapor pressure will help stabilize the vapor phase and
14 suppress condensation (Supplementary Note S1).^{38,39} Second, when water vapor condenses
15 to form liquid water, the fine nanoporous structure also shows strong superhydrophobicity
16 to facilitate water shedding. As shown in Fig. 1c, when a droplet resides on the nanoporous
17 surface in the C-B state, the apparent contact angle increases with decreasing solid-liquid
18 contact fraction. The nanoporous structures enable outstanding superhydrophobicity due to
19 the minimal solid-liquid contact area (Supplementary Note S1). Third, the triple-phase
20 contact lines (TPCL) on such nanoporous structures are short and discontinuous (Fig. 1a).
21 This contributes to very low contact angle hysteresis (CAH),^{40, 41} which is critical for
22 maintaining the non-wetting state under dynamic water exposure. Fourth, nanoporous
23 structures exhibit high thermal resistance to suppress solid-liquid heat transfer, thereby



1 reducing excessive energy dissipation in droplets (Fig. 1a). In contrast to the sparse air
 2 pockets trapped by conventional roughness, the high porosity of nanoporous structures
 3 entraps a much larger air volume. This endows them with superior overall thermal
 4 insulation performance. In fact, owing to the mechanisms discussed above, nanoporous
 5 structures are effective in suppressing the generation, accumulation, and infiltration of
 6 liquid water from the microscopic to the macroscopic scale (Fig. S1). This cross-scale anti-
 7 wetting capability forms the basis for effective dynamic anti-icing.⁴²



8
 9 **Fig. 1** (a) Schematic diagram of the anti-icing mechanisms of nanoporous structures. (b)
 10 The variation of vapor pressure inside the cavity (P_r) with cavity size (a). (c) Change of
 11 the apparent contact angle with the liquid-solid contact fraction for the ideal Cassie-Baxter



1 state. (d) Three complementary strategies for constructing robust nanoporous structures.
2 (e) Schematic diagram of the distinct spray deposition morphology on nonporous substrate
3 (NS) and porous fibrous film (PF) substrates. (f) SEM images of prepared NS10 and PF10.
4 (g) Optical photos demonstrating the flexibility and retained superhydrophobicity of a bent
5 PF10 film. (h) Snapshots of droplets impacting the surfaces of PF10 and NS10 at -10°C .

6 However, the scalable and low-cost fabrication of such fine nanoporous structures
7 remains a significant challenge.²⁷ Commercially available fumed silica nanoparticles, with
8 primary particle sizes of 4-40 nm, serve as an ideal building block for this purpose. Herein,
9 we integrate three complementary strategies to prepare robust nanoporous structures based
10 on these nanoparticles (Fig. 1d). Firstly, fluorinated epoxy resin is added as a binder to
11 construct a cohesive nanoparticle skeleton, the so-called “resin + particle” strategy.⁴³ The
12 resin content is critical as a trade-off must be struck between skeleton strength and porosity.
13 Generally, the nanoparticles are likely to be wrapped and covered with resin, causing
14 nonporous dense structures.⁴⁴ Although higher nanoparticle content can improve surface
15 roughness, it may lead to insufficient adhesion between nanoparticles and between coatings
16 and substrates.⁴⁵ To address this, our second strategy incorporates high-aspect-ratio multi-
17 walled carbon nanotubes (MWCNTs) to reinforce the connectivity and strength within the
18 nano-architecture. Last but not least, we employ the porous fibrous film (PF) as a spraying
19 substrate (Fig. S2a), which represents a departure from conventional formulation-centric
20 approaches.⁴⁶ In this design, the porous fibrous substrate is hypothesized to facilitate the
21 formation of nanoporous structures while simultaneously establishing a robust anchored
22 interface, as shown in Fig. 1e. To implement the above three strategies, the fumed silica,
23 MWCNTs, and fluorinated E51 epoxy resin (FE51) were mixed to obtain a slurry, and
24 followed by assembling it into nanoporous structures through spray process (Fig. 1e).



1 It is important to note that the nanoporous structures are fundamentally distinct from
2 previously reported superhydrophobic coatings on other substrates. Although
3 heterogeneous substrates have been employed in previous studies, they are largely selected
4 either to achieve mechanical flexibility or to improve interfacial adhesion. Consequently,
5 conventional combinations of spray slurries and substrates do not yield the targeted fine
6 nanoporous architecture (Fig. S3). However, this substrate employed in our strategy
7 features a nanoscale porous fibrous structure, which represents not merely a processing
8 method, but a design rationale and a viable strategy for constructing nanostructured
9 coatings.

10 As shown in Fig. 1f, aerosolized slurry with nanoparticle content of only 10 wt% tends
11 to form fine nanoporous structures on the PF film. Dynamic water repellency was
12 characterized by impacting $\sim 10 \mu\text{L}$ water droplets from a 10 cm height. The inherent
13 hydrophilicity of the bare PF substrate led to droplet adhesion (Fig. S4a). In contrast, after
14 depositing a nanoporous coating via spraying, the resulting PF10 surface enables complete
15 rebound of impacting droplet (Fig. S4b). Furthermore, through co-curing and hot-pressing
16 with prepreg, the PF10 can be integrated into a composite airfoil (denoted as PF10-airfoil)
17 with the preservation of excellent dynamic water repellency (Fig. S4c). Additionally, the
18 PF10 sample retains its superhydrophobicity even under severe bending deformation (Fig.
19 1g), highlighting its mechanical robustness and potential for use in conformal or curved
20 aerodynamic components. The critical role of the substrate becomes unequivocally clear
21 when the same slurry is sprayed onto a composite laminate surface (Fig. S2b) as a
22 nonporous substrate (NS). In this case, it yields a dense, nonporous structure (Fig. 1f). At
23 room temperature, the NS10 surface appears superhydrophobic, while this non-wettability



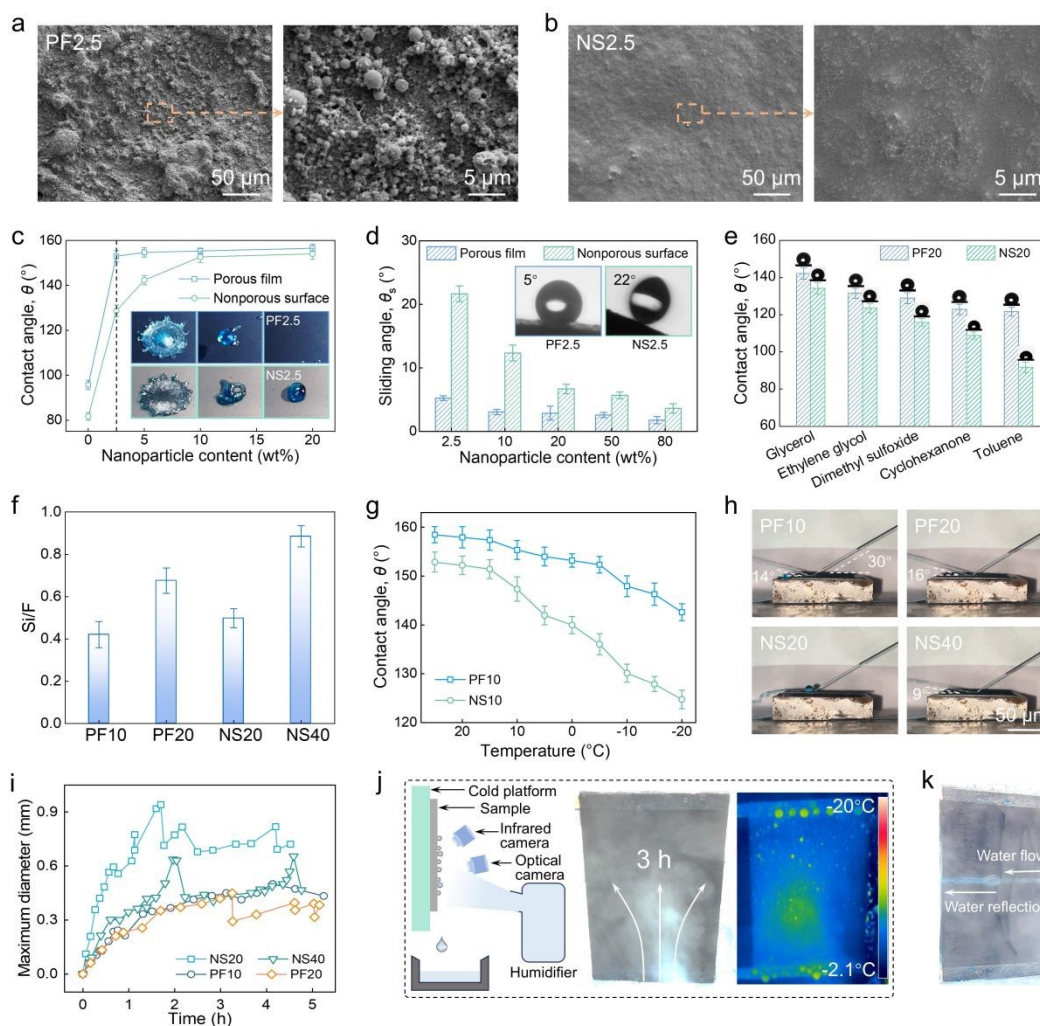
1 severely degrades under low-temperature dynamic conditions. To demonstrate this, both
2 PF10 and NS10 were cooled to -10°C and impacted by droplets from a height of 10 cm.
3 As shown in Fig. 1h, the droplet completely rebounded from the PF10 surface, whereas it
4 was pinned on the NS10 surface. A top-down perspective coupled with infrared
5 thermography further confirmed this anti-wetting difference (Fig. S5, Movies S1 and S2).
6 Notably, the impacting droplet effectively cleared the condensed water from the PF10
7 surface, providing direct evidence of a stable low-adhesion C-B state.⁴⁷ This substrate-
8 dependent divergence in anti-wetting and anti-icing performance is often overlooked but
9 profound. Given the prevalent challenge of superhydrophobic degradation at low
10 temperatures, our substrate-driven spraying strategy represents a groundbreaking, simple,
11 and readily executable advance.

12 **2.2. Substrate-Driven Regulation of Morphology and Wettability**

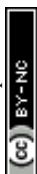
13 Regulating surface morphology through substrate selection presents a facile and
14 highly effective alternative to conventional spraying strategies. This approach circumvents
15 the typical reliance on high nanoparticle loadings to achieve micro/nano-roughness.
16 Remarkably, even at a nanoparticle content as low as 2.5 wt%, PF2.5 exhibits well-defined
17 nanostructures (Fig. 2a), whereas NS2.5 shows a comparatively smooth and dense
18 morphology with insufficient roughness (Fig. 2b). These distinct morphologies, arising
19 directly from the different deposition dynamics of the aerosolized slurry on porous versus
20 nonporous substrates, lead to profound differences in wettability. Achieving spray-coated
21 superhydrophobicity on conventional substrates typically requires a high nanoparticle
22 loading ($>30\%$), along with intricate nano-architectural modifications (Supplementary
23 Note S2, Table S1). Our strategy overcomes this by utilizing a significantly lower



1 nanoparticle content. This reduction translates directly into cost efficiency and enhanced
2 interfacial adhesion strength.



3
4 **Fig. 2** SEM images of prepared surfaces with only 2.5 wt% nanoparticles on (a) porous
5 film (PF2.5) and (b) nonporous substrate (NS2.5). (c) Water CAs and (d) water SAs as a
6 function of nanoparticle content for PF and NS substrates. (e) CAs of various organic
7 solvents on PF20 and NS20 surfaces. (f) Surface Si/F atomic ratio from EDS analysis,
8 indicating nanoparticle exposure. (g) Water CAs of PF10 and NS10 changing with surface
9 temperature. (h) Dynamic water jet repellency test from an incident angle of 30° at -20°C.
10 (i) Variation of the maximum diameter of condensate droplets with time on different
11 sample surfaces. (j) Schematic diagram, optical image, and the corresponding infrared



1 photo of the anti-condensation test in high humidity environment. (k) Optical image of
2 PF10 surface exhibiting waterjet impacting after 3-h anti-condensation test.

3 The influence of the substrate on wettability is quantitatively demonstrated by the
4 water contact angles (CAs) and sliding angles (SAs) of prepared films with varying
5 nanoparticle content (Fig. 2c-d). Sprayed structures on the PF substrate consistently
6 achieve higher CAs and lower SAs than their NS counterparts at equivalent loadings. When
7 the nanoparticle content was reduced to 2.5 wt%, PF2.5 exhibited superhydrophobicity
8 with water CA of $153 \pm 2.5^\circ$ and water SA of $5.2 \pm 0.4^\circ$, hence repelling impacting droplet
9 from the height of ~ 10 cm (Fig. 2c). As a sharp contrast, the NS2.5 failed to reach the
10 threshold of superhydrophobicity with water CA of $128.7 \pm 2.6^\circ$ and water SA of $21.7 \pm 1.2^\circ$,
11 resulting in the final pinning of the impact droplet. Even though differences in water CA
12 and water SA diminish at nanoparticle contents above 10 wt%, the intrinsic wettability
13 contrast persists, as revealed by contact angles of various organic solvents (Fig. 2e). For
14 every solvent tested, PF20 displays a higher contact angle than NS20. Notably, this
15 disparity becomes more pronounced for liquids with lower surface tension. For the toluene
16 with surface tension of 28.9 mN/m, the CAs are $121.7 \pm 2.4^\circ$ for PF20 versus $91.7 \pm 2.8^\circ$ for
17 NS20, underscoring the more effective liquid repellency imparted by the PF-derived
18 nanostructures.

19 To elucidate the mechanism behind this substrate-driven morphology control, we
20 analyzed both the surface topography and the compositional distribution of the coatings.
21 First of all, SEM analysis confirmed that the thermal curing process did not alter the
22 spraying morphology (Fig. S6), indicating that the differentiated topography is dictated
23 solely by the slurry deposition process. Furthermore, when the ethyl acetate solvent was
24 replaced by N, N-dimethylformamide (DMF), or the fluorinated epoxy resin (F-E51) was



1 replaced with polydimethylsiloxane (PDMS), similar nanoporous structures were
2 successfully obtained (Fig. S7). Therefore, the proposed substrate-driven strategy does not
3 depend on a specific slurry formulation, but rather on its regulation of the self-assembly
4 process of the slurry during deposition. Since the actual deposition process cannot be
5 directly observed, we employed EDS to analyze the surface elemental distribution of PF10,
6 PF20, NS20, and NS40 (Fig. S8). We focused on the Si (from SiO₂ nanoparticles) and F
7 (from the fluorinated epoxy resin) signals (Fig. S9). The Si/F ratio serves as a quantitative
8 indicator of the relative surface exposure of nanoparticles. As shown in Fig. 2f, the Si/F
9 ratio increases with nanoparticle content for both NS and PF substrates, which aligns with
10 the expected results. Crucially, for any given content, the Si/F ratio is consistently higher
11 for coatings on the PF substrate than on the NS substrate. This provides direct evidence
12 that the PF substrate promotes greater nanoparticle exposure. This is corroborated by
13 observing early-stage deposition (Fig. S10). A minimal amount of slurry forms a dispersed,
14 nanoparticle-rich porous network on the PF substrate, but a resin-encapsulated, smoother
15 film on the NS substrate. This fundamental difference in initial growth dictates the final
16 morphology, which is preserved with further spraying. These observations support a
17 proposed mechanism in which the PF substrate acts as a filter during spraying. It rapidly
18 absorbs the solvent and partially the resin from the spraying slurry, concentrating and
19 retaining the nanoparticles at the deposition front. This process facilitates the in-situ
20 assembly of a nanoporous structure. Therefore, it should be emphasized that the reported
21 nanoparticle loading refers to the slurry composition as a controlled input parameter rather
22 than a descriptor of the final surface composition.



1 It should be emphasized that the mechanism described above represents a generalized
2 interpretation based on our current observations. The underlying assembly process may
3 also involve Brownian motion of resin molecules and heterogeneous aggregation during
4 the drying of the liquid film. Notably, when other porous substrates were employed,
5 including foam iron, filter paper, wire mesh, and fabric, none were able to produce the
6 desired fine nanoporous structure (Fig. S3). This indicates that simply using a porous
7 substrate to enhance the absorption of resin and solvent does not universally lead to the
8 target coating morphology. The outcome appears to be closely related to the characteristic
9 dimensions of the substrate, because a substrate of carbon nanotube film prepared by
10 vacuum filtration yields a similar nanoporous structure. Collectively, scalable fabrication
11 of such fine nanoporous anti-icing surfaces is far from a straightforward engineering
12 implementation. The underlying mechanisms are highly complex and warrant further
13 investigation.

14 The superhydrophobic superiority of the fine nanostructures on PF substrates is
15 further magnified under low-temperature conditions, which are critical for dynamic anti-
16 icing performance. As expected, both PF10 and NS10 exhibit a reduction in contact angle
17 with decreasing surface temperature (Fig. 2g). This common phenomenon is attributed to
18 condensation within the structures in a supersaturated vapor environment.³⁸ However,
19 PF10 demonstrates far greater resilience, whose CA remains higher than that of NS10 at
20 every temperature, and the decline rate is significantly slower. For instance, the PF10
21 maintained superhydrophobicity at -5°C with a water CA of $152.3 \pm 1.7^{\circ}$, while the NS10
22 fell below this threshold even at 10°C with a water CA of $147 \pm 2.5^{\circ}$. This indicates that the



1 nanoporous structure of PF10 is more effective at resisting water penetration and
2 condensation-induced wetting transitions.

3 Static contact angles alone are insufficient to evaluate anti-icing performance under
4 dynamic icing conditions. Therefore, we assessed the uniformity and effectiveness of
5 dynamic water repellency using a water jet test at -20°C (Fig. 2h). When a water jet
6 impinged on the surfaces at an incidence angle of $\sim 30^{\circ}$, it was cleanly reflected from the
7 PF10, PF20, and NS40 surfaces at angles of approximately 14° , 16° , and 9° , respectively.
8 In stark contrast, the water jet adhered to and accumulated on the NS20 surface. These
9 results unambiguously demonstrate that spraying structures on the PF substrate possess
10 superior dynamic anti-wetting properties under low-temperature icing conditions
11 compared to those on the NS substrate.

12 Vapor condensation in the high-humidity, low-temperature icing environment often
13 leads to superhydrophobic degradation and a loss of dynamic anti-wetting capabilities. We
14 evaluated long-term anti-condensation performance by monitoring droplet growth on
15 surfaces held at $-5\pm 1^{\circ}\text{C}$ for 5 h (Fig. S11a). Tracking the maximum droplet diameter over
16 time reveals distinct shedding behaviors (Fig. 2i), whose abrupt changes represent
17 detachment or coalescence events. For NS20 and NS40, droplets grew to relatively large
18 sizes (~ 0.94 mm and ~ 0.64 mm, respectively) before abrupt detachment (Fig. S11b),
19 exhibiting the characteristic of gravity-driven sliding (Fig. S12a). In contrast, on PF10 and
20 PF20 surfaces, the maximum droplet diameter stabilized at a much smaller value (~ 0.45
21 mm) after about 3.2 h. Clearly, the fine nanoporous structures enables condensate droplets
22 maintaining a low-adhesion C-B state.⁴⁸ Consequently, they depart via coalescence-
23 induced jumping at a much smaller size and earlier stage (Fig. S12b), a more efficient



1 shedding mechanism than gravity-driven sliding. Furthermore, we conducted a
2 macroscopic validation of the superhydrophobic durability against condensation. As shown
3 in Fig. 2j, the surface of PF10 cooled at -5°C was exposed to a flux of humid air for 3 h to
4 promote surface condensation, and the waterjet impact was subsequently utilized to test the
5 surface wettability. As shown in Fig. 2k and Movie S3, the water jet was cleanly repelled
6 without any adhesion, demonstrating that the nanoporous structure of PF10 retains
7 excellent dynamic non-wetting properties even after prolonged exposure to a condensing
8 environment.

9 **2.3. Dynamic Anti-Icing at Extreme Conditions**

10 Maintaining a non-wetting state at ultralow temperatures poses severe challenges for
11 superhydrophobic surfaces, primarily due to drastically increased water viscosity and
12 intensified vapor condensation, both of which compromise the stability of the C-B state.
13 To probe the dynamic anti-icing limits, we employed liquid nitrogen to cool sample
14 surfaces to below -100°C (Fig. 3a). Surface temperature was monitored in real-time using
15 a PT100 thermometer (Fig. S13a, Movie S4). The temperature of the solid-liquid impact
16 zone can't be monitored in real time because such ultralow temperatures lie beyond the
17 operational range of existing infrared cameras. To verify the reliability of the reported
18 temperature, four PT100 sensors were attached at different locations on the sample surface,
19 including the central point where the droplet impact occurred. As shown in Fig. S13b, the
20 temperature of the central location was slightly colder than the peripheral areas, with
21 deviations within 5°C , which most likely arises from faster heat conduction at the edges.
22 These results confirm that the temperature measurement error falls within an acceptable
23 range and that the reported surface temperature is essentially reliable. It is noteworthy that



1 the water impact tests were conducted at a relatively high relative humidity (~55%),
2 significantly exceeding the levels reported in many benchmark studies (Table S2). In this
3 condition, vapor condensation and desublimation are usually inevitable and detrimental to
4 droplet rebound. Strikingly, even when the surface was cooled to an ultra-low temperature
5 of -141°C , a water droplet dropping from a 10 cm height exhibited complete rebound from
6 the PF20 surface (Fig. 3b, Movie S5). In stark contrast, an identical droplet was irreversibly
7 pinned on the NS40 surface at a comparatively higher temperature of -125°C (Fig. 3c,
8 Movie S6). The temperature profiles recorded during these impacts confirm the extreme
9 conditions (Fig. 3d). To contextualize this achievement, we benchmark our results against
10 the state of the art (Fig. 3e, Table S2). Previous reports on superhydrophobic surfaces with
11 single or hierarchical textures demonstrate droplet rebound only at temperatures above
12 approximately -30°C . Our nanoporous surfaces (PF10 and PF20) dramatically extend this
13 limit. To our knowledge, this work is the first to achieve complete rebound of impacting
14 water droplets from surfaces cooled below -100°C .



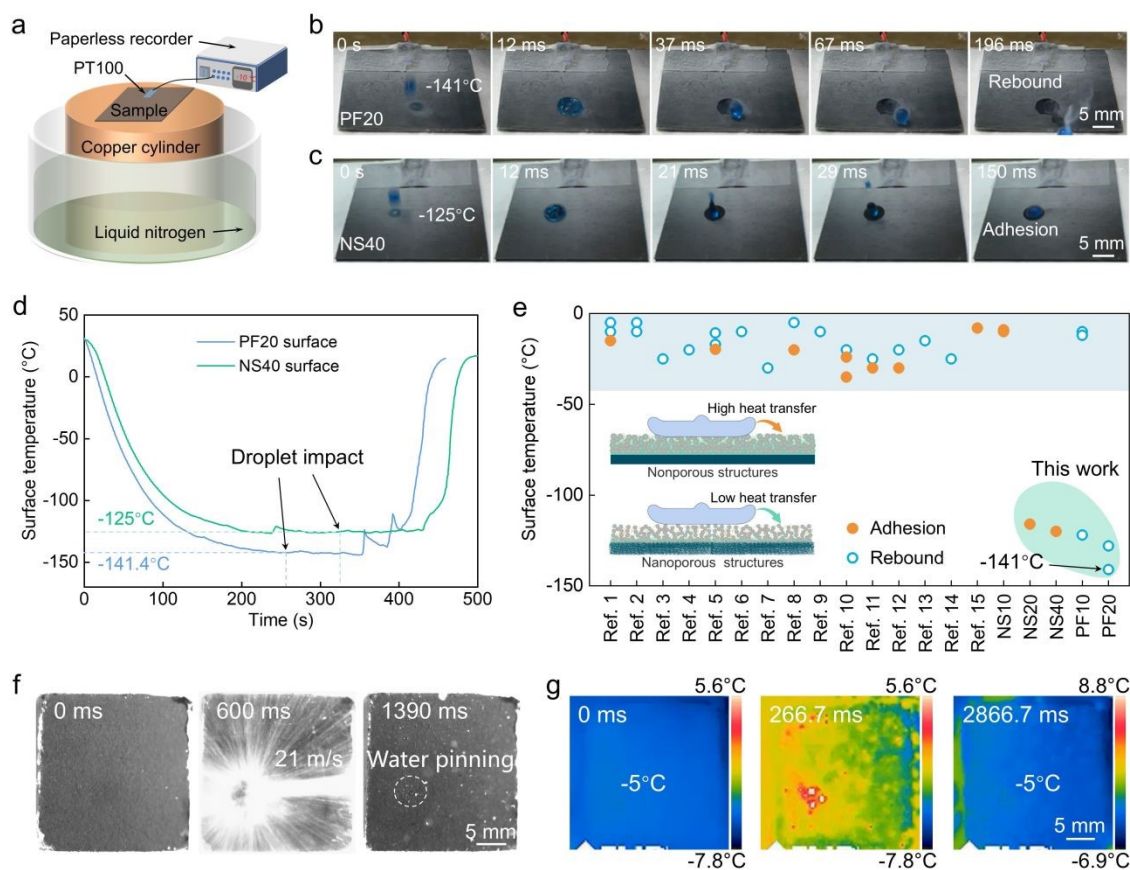


Fig. 3 (a) Schematic diagram of the ultra-low temperature droplet impact test setup using liquid nitrogen cooling. Snapshots of water impact on surfaces of (b) PF20 at -141°C and (c) NS40 -125°C , showing the final rebounding and pinning state, respectively. (d) Temperature curves of the PF20 and NS40 surfaces during water impact tests. (e) Comparison of the tested anti-wetting temperature between our work and the current state-of-the-art superhydrophobic surfaces. Hollow dots denote instances of droplet rebound, whereas solid dots signify droplet adhesion. The detailed anti-wetting performances of the literature from ref. 1 to ref. 15 are shown in Table S2. The inserted schematic diagram shows the heat transfer between impacting water and the surfaces of dense structures and nanoporous structures. Snapshots of (f) optical photos and (g) infrared photos demonstrating a high-speed water jet (21 m/s) impacting a PF10 surface at -5°C .

The conventional criterion for droplet rebound is to compare the anti-wetting capillary pressure against the dynamic impact pressure.^{49, 50} At ultralow temperatures, this criterion becomes inadequate due to the influence of viscous and thermal effects. Therefore, we



1 analyze the process through an energy conversion perspective. In fact, the energy balance
2 governing rebound involving adhesion work (ΔE_w) and energy dissipation (ΔE_{vis}) can be
3 expressed by (Supplementary Note S3):

$$E'_k = E_k - (\Delta E_{vis-vol} + \Delta E_{vis-int} + \Delta E_w)$$

4
5 where E'_k and E_k are the kinetic energies of the impacting droplet and recoil droplet,
6 respectively. $\Delta E_{vis-vol}$ and $\Delta E_{vis-int}$ are volume part and surface part of energy dissipation
7 caused by viscous friction, respectively (Fig. S14), both of them are proportional to water
8 viscosity.⁵¹ The adhesion work ΔE_w is contingent upon intrinsic contact angle and contact
9 angle hysteresis (Supplementary Note S4). To meet $E'_k > 0$ for droplet bouncing, the
10 energy dissipation and adhesion work should be minimized as much as possible. The
11 exceptional performance of our PF coatings stems from their unique structure, which
12 addresses both terms. First, the fine nanoporous structures exhibit ultralow thermal
13 conductivity of 58.1 ± 0.4 W/K, with an approximately 24.6% reduction compared with
14 pristine PF substrate (Fig. S15). This severely limits heat transfer from the droplet
15 according to the Fourier heat conduction equation,⁵² thereby preventing a drastic rise in
16 droplet viscosity and suppressing energy dissipation.⁵³ Second, the nanostructures
17 contributed to reducing contact angle hysteresis, hence decreasing the kinetic energy loss.⁵⁴
18 Consequently, the impacting droplet can rebound from the surface even at an extremely
19 low surface temperature.

20 Owing to the reduced cost, enhanced mechanical robustness, and greater potential for
21 practical application, PF10 was selected as the primary sample for the following tests. As
22 shown in Fig. 3e (Movie S7), PF10 was able to repel 1.4 m/s impact droplets even when



1 cooled to -122°C . To further assess the resilience against more severe dynamic conditions,
2 the PF10 was cooled to -5°C using a cold platform and subjected to a water jet at 21 m/s.
3 The interaction was captured simultaneously by high-speed and infrared cameras at 200
4 and 30 frames per second, respectively. After ~ 900 ms of continuous jet impingement, only
5 minimal water adhesion was observed on the PF10 surface, with the largest residual droplet
6 being merely ~ 0.5 mm in diameter (Fig. 3f). Although the infrared and high-speed images
7 were not perfectly synchronized due to the lower frame rate of the thermal camera, the
8 infrared sequences still clearly recorded the surface temperature evolution before and after
9 impact, as evidenced in Fig. 3g. These results indicate that PF10 maintains effective
10 dynamic anti-wetting performance across an exceptionally broad spectrum of conditions
11 from ultra-low temperature droplet impact to high-speed water jet impingement,
12 highlighting its potential for real-world anti-icing applications.

13 **2.4. Dynamic Deicing Induced by Gravity**

14 Gravity-driven ice removal exploits a fully passive physical process, offering a low-
15 cost and sustainable deicing strategy that requires no chemicals or external energy input.
16 However, the ice adhesion strength between ice and superhydrophobic surfaces typically
17 exceeds 10 kPa,⁵⁵ a value that cannot be overcome by gravitational force alone. In contrast,
18 water droplets on superhydrophobic surfaces exhibit extremely low adhesion, enabling
19 them to slide off at tilt angles below 5° or even 1° .⁵⁶ Therefore, transforming the solid-solid
20 interface into a solid-liquid interface through the heating effect may enable gravity-induced
21 dynamic deicing. We first conducted freezing-melting tests on different sample surfaces
22 (Fig. S16). Water droplets were frozen at -15°C and subsequently allowed to melt during
23 natural warming. The measured icing time can be determined as PF20>PF10>NS40>NS20



1 (Fig. 4a), which correlates directly with their dynamic anti-wetting performance observed
2 in waterjet-impacting tests (Fig. 2h). Thus, the nanoporous structures of PF10 and PF20
3 confer superior performance in both static ice delay and dynamic anti-icing compared to
4 NS20 and NS40. Subsequently, we measured the sliding angles (SAs) of the melted
5 droplets by directly tilting the cold platform. The SAs followed the order
6 PF20<PF10<NS40<NS20, inversely correlated with the freezing delay performances.
7 Notably, only PF10 and PF20 surfaces retained their superhydrophobicity after the
8 complete freezing-melting cycle, with SAs below 10°.

9 This divergence in deicing outcome is governed by the degree of
10 superhydrophobicity recovery after melting. The nanoporous structures of PF10 surface
11 coatings favor recovery of the C-B state for two synergistic reasons. First, its fine structure
12 inherently resists water penetration and mitigates irreversible wetting transitions during
13 freezing (Fig. 2g).¹⁷ Second, the extended freezing time and high interfacial thermal
14 resistance promote a pronounced temperature gradient within the melting ice droplet. This
15 gradient drives a Marangoni flow, which facilitates the transport of air bubbles to the solid-
16 liquid interface, actively replenishing the air layer and restoring superhydrophobicity.⁵⁷



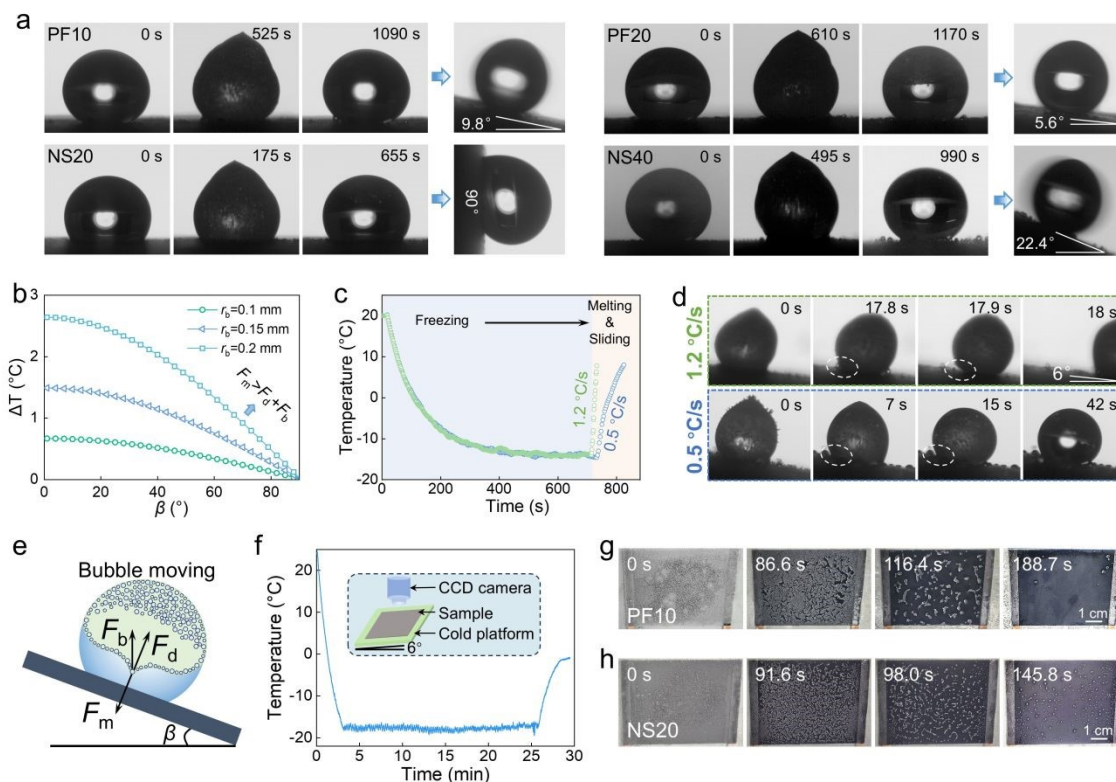


Fig. 4 (a) Images of droplets on PF10, NS20, PF20, and NS40 surfaces during the freezing/melting cycle. The right panel shows the sliding angles of the melted droplets. (b) Variation of critical temperature difference between the surface and the top unmelted ice with surface inclination angle for different bubble sizes. (c) Temperature curve of the PF10 surface with different warming rates after freezing on a cold platform. (d) Corresponding optical images showing the dynamic behaviors during the melting process of ice droplets on the PF10 surface at different warming rates. (e) Schematic diagram of force analysis of bubbles inside a melted ice droplet on inclined surfaces under the Marangoni effect. (f) Temperature curve of the sample surface during the freezing/melting cycle for frost removal tests. The inserted schematic diagram represents the test device. Snapshots of coalescence-induced wriggling of melting frosts on (g) PF10 and (h) NS20 surfaces with an inclination angle of 6° .

In the real world, ice removal is driven by the thermal-mechanical coupling effect rather than their independent action discussed above. When ice melts on an inclined surface, the condition for ice drop sliding can be expressed as:⁴²



$$mg \sin \beta > \begin{cases} F_{\text{ice-solid}}, & \text{initial melting} \\ Kd(\cos \theta_{\text{trial}} - \cos \theta_{\text{lead}}) + F_{\text{ice-solid}}, & \text{intervening state} \\ Kd(\cos \theta_{\text{trial}} - \cos \theta_{\text{lead}}), & \text{interface ice melting} \end{cases}$$

where β is the surface inclination angle, m is the mass of the droplet, g is the gravitational constant, K is a dimensionless factor associated with droplet shape, d is the width of the three-phase contact line, θ_{trial} is the trial contact angle, and θ_{lead} is the lead contact angle.

$F_{\text{ice-solid}}$ is the solid-solid resistance caused by adhesion between ice and the sample surface, while $Kd(\cos \theta_{\text{trial}} - \cos \theta_{\text{lead}})$ represents the liquid-solid resistance from static contact line pinning. There are two critical sliding conditions for melting ice. In the initial melting regime, the ice-substrate interface is only partially molten, and the contact line is largely immobilized. Thus the $Kd(\cos \theta_{\text{trial}} - \cos \theta_{\text{lead}})$ can be ignored. Sliding occurs if the gravitational shear stress overcomes the residual ice adhesion, i.e., $mg \sin \beta > F_{\text{ice-solid}}$. In the interface ice melting regime, the ice-substrate interface is fully liquefied and $F_{\text{ice-solid}}$ vanishes. The sliding of the melted droplet is determined by the depinning of the contact lines, i.e., $mg \sin \beta > Kd(\cos \theta_{\text{trial}} - \cos \theta_{\text{lead}})$, which typically depends on a well-recovered superhydrophobicity. Real-world dynamic deicing represents an intervening state between these two conditions above. Clearly, the restoration of superhydrophobicity will simultaneously reduce the deicing resistance of both solid-solid and solid-liquid interfaces.

The underlying mechanism of superhydrophobic recovery under thermal-mechanical coupling effects can be attributed to Marangoni effects at the inclined surface. The force exerted on the bubble along the direction perpendicular to the surface is given by:⁵⁷

$$F = F_m - F_b - F_d = \int_0^{2\pi} \frac{d\gamma}{dT} \Delta T \cdot r_b d\alpha - \frac{4\pi}{3} \rho g r_b^3 \cos \beta - \frac{\pi}{2} C \cdot \rho v_b^2 r_b^2$$



1 where F_m , F_b , and F_d are the Marangoni force, buoyancy, and water drag, respectively;
2 $\frac{d\gamma}{dT}$, ρ , g , and C are the change rate of water's surface tension with temperature, water
3 density, gravitational constant, and resistance coefficient of water, respectively. The
4 temperature difference between surface and the top unmelted ice (ΔT), bubble radius (r_b),
5 surface inclination angle (β), and moving velocity of bubble (v_b) are the four key variables
6 affecting bubble movement towards the interface or vice versa. In the critical condition for
7 downward motion of a bubble, the relationship between the required temperature gradient
8 and the inclination angle of the surface is shown in the Fig. 4b. Clearly, the temperature
9 gradient directly governs bubble migration efficiency. An inclined surface reduces the
10 required temperature gradient to drive bubbles toward the interface, especially for larger
11 bubbles (Figs. 4b and S17). Then the PF10 was cooled from room temperature until the
12 sessile droplet froze, then the surface was tilted to 6° and warmed at different rates (Fig.
13 4c). Surprisingly, when the PF10 surface was warmed at a high heating rate ($\sim 1.2^\circ\text{C/s}$), the
14 ice droplet slid off the surface with a remained peach-like shape (Fig. 4d). However, at a
15 lower warming rate of $\sim 0.5^\circ\text{C/s}$, the meltwater wetted and pinned on the surface. In fact,
16 the faster heating establishes a steeper temperature gradient, which intensifies the
17 Marangoni flow, allowing more and larger bubbles to impact the interface, facilitating the
18 replenishment of the air layer (Fig. 4e).

19 We further extended this concept to frost removal. As shown in Fig. 4f, the same
20 freezing/melting cycle was performed to investigate gravity-induced dynamic defrosting.
21 During natural warming of a frosted PF10 surface tilted at 6° , the melting frost layer
22 underwent pronounced coalescence-induced wriggling, culminating in spontaneous, large-
23 scale detachment (Fig. 4g, Movie S8). In this case, the dynamic behaviors of melting ice



1 may overcome $F_{\text{ice-solid}}$ before complete interface melting, which has been confirmed by
2 our previous work.⁴² Conversely, under identical conditions, the NS20 surface exhibited
3 higher adhesion with water/ice with more subdued coalescence-induced wriggling of
4 chain-like water, leaving numerous water droplets on the surface (Fig. 4h, Movie S9). This
5 comparative study conclusively demonstrates that the fine nanoporous structure of PF10
6 ensures not only outstanding anti-icing performance but also superior recovery of a low-
7 adhesion state during melting, enabling efficient gravity-driven deicing and defrosting.

8 **2.5. Icing Wind Tunnel Assessment**

9 The icing wind tunnel is designed to produce high-speed supercooled microdroplets,
10 thereby replicating in-flight icing conditions at high altitudes. As shown in Fig. 5a, the
11 reflux icing wind tunnel is composed of a cooling system, water atomization system,
12 compressor system, aerodynamic system, and test section. Test samples were fabricated as
13 thin-walled composite airfoils that were connected to the fixture of the test section. We
14 designed three configurations and only the leading edge was heated (Fig. S18). For PF10-
15 PF10, both the leading edge and the downstream runback zone were coated with PF10. To
16 compare the capabilities of different samples for suppressing overflow ice, PF10-NS20 was
17 prepared by replacing the non-heating zone of PF10-PF10 with NS20. Additionally, PFac-
18 NSac was fabricated as a control group that was coated with aviation paint but not
19 superhydrophobic slurry. Infrared imaging confirmed that all heated leading edges
20 exhibited uniform temperature distribution under a power density of 0.1 W/cm²,
21 establishing a consistent thermal baseline for comparative testing (Fig. 5b).



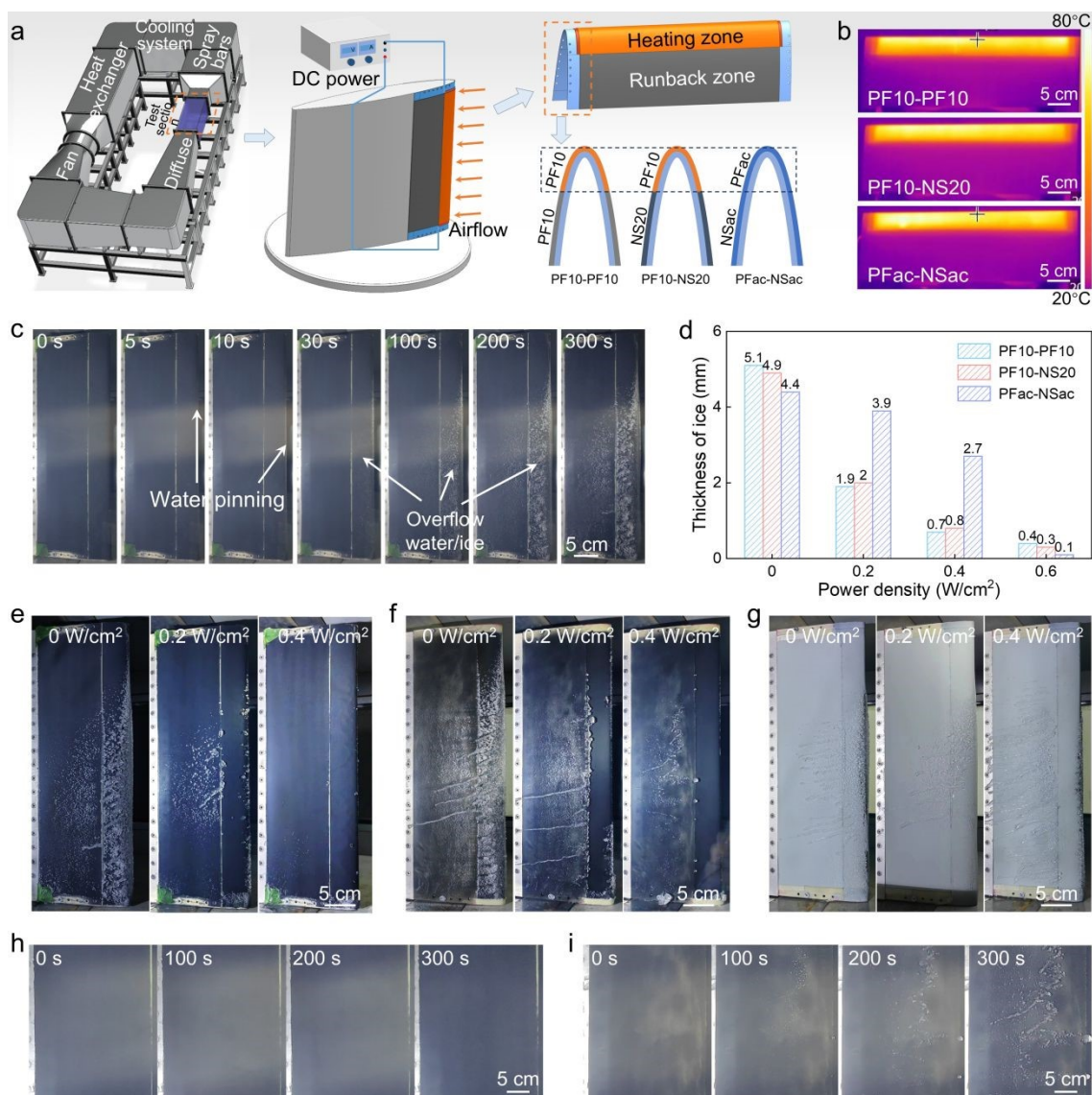


Fig. 5 (a) Schematic diagrams of icing wind tunnel test of three composite airfoil configurations: PF10-PF10, PF10-NS20, and PFac-NSac. (b) Infrared images confirming uniform temperature distribution on the heated leading edges at 0.1 W/cm². (c) Optical images of the icing process of PF10-PF10. (d) Variation of ice accretion thickness on the leading edge with supplied power densities. Optical images of (e) PF10-PF10, (f) PF10-NS20, and (g) PFac-NSac after icing wind tunnel tests under different electric power supplies. Optical photos of runback zones of (h) PF10-PF10 and (i) PF10-NS20 during icing wind tunnel tests.

To assess the anti-icing performance in simulated aviation conditions, these three samples were positioned in the icing wind tunnel, which was cooled to the predetermined



1 temperature before turning on the spraying system. During the initial spray period of 5-10
2 s, only sporadic adherent droplets/ice patches were observed on the leading edges of PF10-
3 PF10, without the formation of a continuous water film or rivulet flow (Fig. 5c). However,
4 under prolonged exposure (30-100 s) to the high flux of supercooled droplets, significant
5 ice accretion occurred on the PF10-PF10 leading edge despite its excellent
6 superhydrophobicity. This demonstrates that under the extreme water collection rates
7 typical of leading edges, passive superhydrophobicity alone is insufficient to prevent ice
8 accretion, a well-documented challenge in the field.⁷ Furthermore, after a 300 s icing test
9 at different power supplies, ice accretion thickness on different airfoil leading edges was
10 measured. In the absence of an electrical power supply, the ice thickness reached 5.1 mm
11 and 4.9 mm on the leading edges of PF10-PF10 and PF10-NS20, respectively (Fig. 5d),
12 which were comparable to that of PFac-NSac (4.4 mm). However, upon applying a low
13 power density of only 0.2 W/cm², ice accretion on the leading edges of both PF10-PF10
14 and PF10-NS20 was effectively inhibited (Fig. 5e-f), resulting in a sharp reduction in ice
15 thickness of approximately 60% compared to their unpowered state. At a higher power
16 density of 0.4 W/cm², only discontinuous, small ice particles adhered to the PF10 surfaces
17 of the leading edges (Fig. 5e-f). These particles could be readily removed by airflow
18 following further accumulation and growth (Movie S10). When the aviation coating was
19 applied to the leading edge of the control group (PFac-NSac), a power density of 0.4 W/cm²
20 achieved only a ~39% reduction in ice thickness. The suppression of ice accretion on this
21 control surface required a higher power density of 0.6 W/cm². Therefore, the PF10-based
22 leading edge enables a reduction in energy consumption of at least 33% relative to the
23 conventional aviation coating. It is worth noting that the nanoporous structure exhibits a



1 higher thermal resistance than the sprayed aviation paint, yet it still delivers higher deicing
2 efficiency and lower energy consumption. This result demonstrates that the contribution of
3 the stable air layer to reducing ice adhesion outweighs the thermal resistance penalty it
4 introduces. This observation is consistent with our previous report on the dual role of the
5 interfacial air layer and its dominant contribution to lowering ice adhesion.⁵⁸

6 Importantly, the runback zone of the airfoil usually faces milder icing conditions than
7 the leading edge, thereby often being expected to achieve passive anti-icing without a
8 power supply.⁵⁹ As shown in Fig. 5e-f, the runback zone of PF10-PF10 exhibited less ice
9 accretion than that of PF10-NS20 at each supplied power density. While the aviation
10 coating on PFac-NSac failed to suppress overflow ice formation across the tested power
11 range (Fig. 5g). In fact, the water collection coefficient at the runback zone is relatively
12 low, thus the surface ice accretion is mostly caused by water flow from the leading edge.
13 Due to the excellent dynamic anti-wetting capabilities of PF10, the overflow water can be
14 removed easily due to the highly slippery C-B state (Fig. 5h-i, Movies S10-11). Therefore,
15 our nanoporous superhydrophobic films demonstrate a dual-mode application strategy: (1)
16 as a low-energy enhancer for electro-thermal systems at critical areas like leading edges to
17 drastically reduce power consumption, and (2) as a stand-alone passive solution for areas
18 prone to runback icing.

19 We also collected state-of-the-art literature involving the investigation of the anti-
20 icing/deicing performance of superhydrophobic surfaces under icing wind tunnel
21 conditions. As shown in Table S3, without active electric heating, passive anti-icing cannot
22 be achieved solely by the superhydrophobic effect. When combined with electric heating,
23 the superhydrophobic effect shows a significant reduction in the required power supply.⁶⁰



1 Notably, the anti-icing power density of the prepared PF10 in this work is only 0.4 W/cm²,
2 which is the lowest value among these reports. Although the energy saving percentage is
3 only 33%, which appears modest compared to the enhancements reported in existing
4 literature. This can be attributed to the specific properties of the control group, a
5 commercial mature aviation paint that features a low surface energy and reduced intrinsic
6 ice adhesion. These results above conclusively demonstrate the practical anti-icing
7 capability of PF10 under simulated realistic icing conditions and highlight its promising
8 application potential for resin-based composite materials.

9 **3. Conclusions**

10 In summary, this work theoretically and experimentally demonstrated the subversive
11 advantage of nanoporous structures in inhibiting the formation and accumulation of water
12 and ice. We elucidated the often-overlooked influence of the substrate on spray
13 morphologies. A novel spraying strategy to construct fine nanoporous structures utilizing
14 a porous fibrous substrate was proposed. The extreme anti-wetting properties of the
15 resulting nanoporous films were emphasized, including their ability to repel impacting
16 water on surfaces at ultralow temperatures (−141°C) and withstand prolonged vapor
17 condensation (3 h). The shedding of melting and melted ice from the PF10 surfaces at tilt
18 angles below 10° confirmed the dynamic dewetting after icing/melting cycles. Additionally,
19 the PF10 surface exhibited excellent anti-icing performances in the icing wind tunnel,
20 effectively suppressing leading-edge and overflow icing under an electric power density of
21 0.4 W/cm². Our earlier work centered on the superhydrophobic/electrothermal
22 modification of fiber reinforced polymer-based composites with these PF films as substrate,
23 and confirmed their superhydrophobic durability and mechanical properties of the



1 composites.³⁷ This facile fabrication presents a promising pathway toward practical anti-
2 icing and deicing applications used in wind turbine blades, aircraft, and liquid hydrogen
3 and liquid oxygen storage tanks.

4 **4. Experimental Section**

5 *Materials:* The bisphenol-A epoxy resin (E51) was purchased from Yueyang Baling
6 Petrochemical Company. Multiwalled carbon nanotubes (MWCNTs, TNM3) were
7 purchased from Chengdu Organic Chemicals Co., Ltd. (China). Fumed silica (SiO₂, 4-40
8 nm in diameter) was supplied by GRACE Davison (America). The glass fiber prepregs
9 (1502T/EW220B) were supplied by Weihai Mingyue New Materials Co., Ltd. Organic
10 solvents such as ethyl acetate, glycerol, ethylene glycol, methylene blue, dimethyl
11 sulfoxide, cyclohexanone, and toluene were all bought from Macklin Biochemical
12 Technology Co., Ltd (China). T31 curing agent was bought from Tianjin Ningping
13 Chemical Products Co., Ltd. The porous fibrous films (CNTF1414-1, PF film) were
14 purchased from Kunming Natai Technology Co., Ltd. The aviation paint (TS 96-75) was
15 supplied by Tianjin Lighthouse Paint Co., LTD. All raw materials above were used without
16 further treatment, and deionized water (18 MΩ) was used throughout the experiments.

17 *Preparation of Nanoporous Superhydrophobic Films:* Firstly, the E51 epoxy resin
18 was fluorinated following the methodology outlined in our previous work.⁶¹ The
19 fluorinated E51 epoxy resin (FE51) was subsequently mixed with ethyl acetate, T31 curing
20 agent, and nanoparticles consisting of equal proportions of SiO₂ and MWCNTs. After
21 magnetic stirring for 10 min and ultrasonication for 20 min (VOSHIN-250W), the slurry
22 was transferred into a spray gun. Then, taking the PF film as substrate, the spraying was
23 implemented from a distance of ~10 cm at a pressure of ~0.3 MPa. The resin-based



1 composite materials were used as a nonporous substrate (NS) for the same spraying process
2 that was fabricated by bag pressing four layers of glass fiber preregs. For subsequent tests,
3 the sprayed PF was integrated on the surface of the composite material by laying it on the
4 preregs and molding as described in previous work.^{37, 62} The spraying coatings on PF and
5 NS are designated as PF_x and NS_x, respectively, where x represents the content of mixed
6 nanoparticles (measured in percentages). In addition, the sprayed commercial aviation
7 coatings (ac) on PF and NS substrates are designated as PF_{ac} and NS_{ac}, respectively. To
8 prepare the composite airfoils for icing wind tunnel tests, 16 layers of prepreg were laid on
9 the surface of the mold, followed by laying the PF10 film on the specific zones before air
10 bagging. The samples for the subsequent icing wind tunnel tests have a projected size of
11 150 mm in chord length and 470 mm in wingspan length. The heating zone in the leading
12 edge (with ~30% of the surface area) has a projected size of 45 mm in the chord length and
13 430 mm in the spanwise length (Fig. S18).

14 *Characterizations:* The microlevel morphologies were characterized by scanning
15 electron microscopy (SEM, Tescan Maia 3, Czech Republic) along with EDS. The thermal
16 conductivity was measured by the thermal constant analyzer (TPS2500S, Sweden) using
17 hotdisk method according to ISO 22007-2. Contact angle (CA, represented by θ) and
18 sliding angle (SA, represented by θ_s) were measured by the optical measuring meter
19 (SL200KS Solon, China). At least 3 randomly different locations were tested to
20 demonstrate the repeatability of the measurements. For the tests of CA and SA at low
21 temperatures, the sample was placed on the cold platform and cooled to the set temperature,
22 followed by performing the same measurement procedure. The surface temperature was
23 monitored by the PT100 thermometers, whose probe was a patch-type and could be



1 adhered to the sample surface. Alternatively, the infrared images/videos were captured with
2 an infrared camera (FOTRIC 626CH) to obtain the macroscopic temperature distribution.

3 *Water Impact Test:* To investigate the dynamic anti-wetting performances, a water
4 droplet was released from ~10 cm to impact the sample surfaces (Fig. S19). The impacting
5 process was recorded by a high-speed camera (SH3 Mini, Shenzhen SINCEVISION
6 Technology Co., Ltd.). The humidity of the test environments was $55\pm 3\%$, and the room
7 temperature was 20°C . The surface temperature of the sample was controlled by the cold
8 platform (TEC1-12706) and tested by the PT100 or infrared camera. For the anti-wetting
9 test in the ultralow-temperature icing environments, liquid nitrogen was used to cool the
10 samples on the copper cylinder, which was tilted to $\sim 5^\circ$ to facilitate the observation of the
11 dynamic behavior of droplets. The temperature of the sample surface was monitored by the
12 PT100 thermometer. To investigate the long-term anti-wetting performance in
13 condensation environments, the test setup was sealed, and a humidifier was employed to
14 maintain a relative humidity at $60\pm 5\%$. Then the sample surface was controlled at $-5\pm 1^\circ\text{C}$,
15 and the evolution of surface condensation was observed by optical microscope (HG-3101U,
16 Wuxi Hanguang Optics Co., Ltd).

17 *Icing and Deicing Test:* The freezing time of droplets ($\sim 20\ \mu\text{L}$) on the low-temperature
18 surfaces was tested by the contact angle meter (Fig. S20). Firstly, the samples were cooled
19 to the predetermined temperatures on a cold platform before placing the droplet at room
20 temperature. The testing environment was maintained at a relative humidity of $\sim 20\%$ and
21 an ambient temperature of $\sim 20^\circ\text{C}$. After the droplets froze, the cold platform was turned
22 off to observe the melting behaviors of ice droplets. Then the sliding angle was tested by
23 tilting the cold platform after the sample surface returned to room temperature.



1 Additionally, to investigate the effect of the high-humidity environment ($55\pm 3\%$) on the
2 freezing/melting process, droplets were placed on the sample surfaces at room temperature
3 before turning on the cold platform. After the droplets were frozen, turn off and tilt the cold
4 platform by 6° to observe the dynamic behavior of the melting ice droplets. The warming
5 rate of the sample surface was controlled by the electric heating substrate. The surface test
6 temperature was monitored by a patch-type temperature sensor (PT100). In addition, the
7 dynamic behavior of melting ice droplets was directly observed through an optical
8 microscope.

9 *Icing Wind Tunnel Test:* The icing wind tunnel was used to assess the dynamic
10 icephobic properties in a simulated flight icing environment. Every test follows the same
11 experimental parameters, i.e., air temperature of $-6\pm 0.5^\circ\text{C}$, wind speed of 20 m/s, liquid
12 water content (LWC) of 2.82 g/m^3 , and median volume diameter (MVD) of $20\text{ }\mu\text{m}$. After
13 turning on the electric heating for ~ 5 min to reach a relatively stable working state, the
14 water spray system was turned on for 300 s to evaluate the effectiveness of various anti-
15 icing/deicing strategies. To optimize the supply of electric heating power, the heated
16 leading edge constitutes 30% of the total airfoil surface area. The icing behaviors of the
17 test surface were captured by a digital camera. A power supply (LW-K3010D) was used to
18 perform controlled electric heating. The reported power densities represent the power
19 supplied to the heating element and are calculated from the output voltage and current
20 displayed by the power supply.

21 **Author contributions**

22 **Yunyun Meng:** Conceptualization, Data curation, Formal analysis, Investigation,
23 Methodology, Validation, Visualization, Writing - Original draft, Writing - Review &





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4 & Editing. **Suli Xing**: Conceptualization, Methodology, Project administration, Resources,
5 Supervision, Writing - Review & Editing. **Xian Yi**: Conceptualization, Project
6 administration, Resources, Writing - Review & Editing. **Song Wang**: Conceptualization,
7 Methodology, Project administration, Supervision, Writing - Review & Editing. **Senyun**
8 **Liu**: Methodology, Resources, Supervision, Writing - Review & Editing. **Nan Wu**:
9 Conceptualization, Formal analysis, Funding acquisition, Methodology, Project
10 administration, Supervision, Writing - Review & Editing.

11 **Data Availability**

12 All data generated or analyzed during this study are included in this published article
13 and its supplementary information (SI).

14 **Declaration of Competing Interest**

15 The authors declare that they have no known competing financial interests or personal
16 relationships that could have appeared to influence the work reported in this paper.

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