Sprayable Thin and Robust Carbon Nanofiber Composite Coating for Extreme Jumping Dropwise Condensation Performance

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Condensation of water on metallic surfaces is critical for multiple energy conversion processes. Enhancement in condensation heat transfer efficiency often requires surface texturing and hydrophobicity, usually achieved through coatings, to maintain dropwise condensation. However, such surface treatments face conflicting challenges of minimal coating thermal resistance, enhanced coating durability, and scalable fabrication. This study presents a thin (=2 µm) polytetrafluoroethylene–carbon nanofiber nanocomposite coating that meets these challenges and sustains coalescence-induced jumping droplet condensation for extended periods under highly demanding condensation conditions. Coating durability is achieved through improved substrate adhesion by depositing a submicron thick aluminum primer layer. Carbon nanofibers in a polytetrafluoroethylene matrix increase coating thermal conductivity and promote spontaneous surface nanotexturing to achieve superhydrophobicity for condensate microdroplets. The coating material can be deposited through direct spraying, ensuring economical scalability and versatility for a wide range of substrates. No other coating is known for metallic surfaces that is able to sustain jumping droplet condensation for extended periods under highly demanding condensation conditions. Improvement in condensation heat transfer coefficient is achieved compared to conventional filmwise condensation.

1. Introduction

Heterogeneous condensation on solid surfaces is an essential component of a wide range of industrial processes such as power plant condensers,[1] heat pipes in electronics cooling,[2] dew collectors in atmospheric water collection,[3] and in desalination or separation systems.[4] A significant amount of natural resources can be saved, if even a small enhancement in the overall efficiency of such processes can be achieved.[5] This in turn can ameliorate the continuous increase in energy demand, while mitigating greenhouse emissions and raw material consumption.[6]

One important component toward realizing aforementioned improvement consists of enhancing the heat transfer performance in condensers,[7] a key device in many industrial processes. Increased thermal efficiency of the condenser allows reduction in saturation pressure for steam condensation, for example, thereby increasing the enthalpy drop across the turbine and generating the same amount of electricity with less fuel consumption and carbon dioxide emissions.

It is well known that on hydrophobic surfaces, the vapor condenses in the form of discrete liquid droplets instead of a film. This effect is known as dropwise condensation (DWC) and can significantly enhance the heat transfer coefficient (HTC) as compared to filmwise condensation (FWC).[8] Often occurring subsequently, if the condensate drops are not removed periodically under gravity to avoid formation of a continuous film,[1] Furthermore, superhydrophobic surfaces can promote an additional gravity-independent droplet departure mechanism through coalescence-induced droplet jumping that results in the ejection of much smaller droplets, leading to further heat transfer enhancement.[9,10] Compared to DWC, jumping dropwise condensation (JDWC) is known to further improve the HTC by up to ~30%.[11] and reduce the droplet departure size down to 500 nm.[12] Apart from these more common and rather broad condensate removal mechanisms, alternative passive pathways have been demonstrated, such as the cascading coalescence of condensed drops into microchannels,[13,14] lubricated surfaces,[15,16] and biphilic surfaces.[17]
Metallic surfaces in condensers, such as steel, aluminum or copper, are typically hydrophilic and DWC can be achieved on such surfaces by applying hydrophobic coatings. Numerous such coatings have been developed along with a range of coating techniques, including self-assembled monolayers (SAMs)[18,19] spraying,[20] physical vapor deposition (PVD),[21] and chemical vapor deposition (CVD).[22] However, these coatings need to address a number of conflicting challenges, namely, optimal wettability for efficient shedding of condensate, low thermal resistance, long-term mechanical durability, and scalability of the fabrication process. The coating materials are typically poor thermal conductors with thermal conductivities at the scale of $\approx 0.1$–$0.5$ W m$^{-1}$ K$^{-1}$.[23] significantly lower compared to metals. This imposes a restriction on the overall thickness of the coating, due to the associated proportional increase in the thermal resistance. Moreover, minimal thickness requirements also arise from the need to be conformal to micro- and nanotextures required for superhydrophobicity during condensation. Most of these surfaces have been tested under mild conditions (absence of shear flow at increased temperature) with few exceptions,[24,25] lacking indication of the durability over long timescales. Additionally, the simultaneous need for economical scalability remains unaddressed. Therefore, despite the existing promising concepts for improving condensation heat transfer, modern industrial condensation processes remain inefficient, and still rely on the use of uncoated metallic condenser surfaces that exhibit FWC.[26]

2. Results and Discussion

2.1. Coating Development

Our fabrication method consists of a number of simple steps, that can be easily scalable, while their combined result leads to the development of a multifunctional, i.e., hydrophobic, thermally conductive, and robust, passive interface optimized for greatly improving condensation heat transfer. Furthermore, the combined cost of fabrication is maintained low and thus attractive for real-world industrial applications. We estimate the cost of our coating to be around USD 45 m$^{-2}$. For details, refer to Section S1, Supporting Information.

The first step of our process involves the application of a thin metal layer as primer. It is generally known that materials adhere preferentially to different substrates and this makes their applicability limited. Applying such an ultrathin sandwiched metal primer (between our coating and the thermally conductive substrate) alleviates this constraint. We illustrate this by successfully coating a copper substrate with PTFE after depositing a thin aluminum layer ($\approx 150$ nm thick) by evaporation first that acts as a coating primer. Other more scalable methods such as electrodeposition may also be used without affecting final performance. The thermal resistance across the introduced aluminum–copper interface is negligible,[31] so is through the aluminum layer due to its very low thickness and high thermal conductivity. Furthermore, prior to the nanocomposite coating deposition, oxygen plasma is applied to the aluminum primer which helps clean and activate the surface with hydrophilic groups that enhance coating adhesion. These steps significantly improve the adhesion of the coating which otherwise has limited adhesion to copper.[31,32] Section S2, Supporting Information, demonstrates the coating failure without a primer as the copper substrate is exposed after only 5 min of condensation at $\approx 50$ mbar.

This priming process is followed by a spray-coating approach and subsequent thermal annealing. We prepare a dichloromethane suspension of 1 μm PTFE microparticles and CNF of 20–200 μm length, which we spray directly on the Al-coated copper substrate. The thermal annealing is performed at 400 °C in a nitrogen-rich environment to inhibit the oxidation of the metal substrate. This melts the PTFE powder that then diffuses into the CNF network. It is important to mention here that without annealing, the nanocomposite has a powdery, fragile morphology; thus, this step is critical for achieving high durability. In the resulting nanocomposite, 10 wt% CNF is integrated within the PTFE matrix. For the optimization of the CNF concentration, refer to Section S3, Supporting Information. Each of these two components contributes to the desired functionalities of the coating.

PTFE, being a tough, hydrophobic, and chemically resistant fluopolymer, serves as a perfect base material as demonstrated by its already widespread commercial application as a water-repelling coating. On top of this, the nanofibers modify the surface and bulk properties to match our needs for condensation. The addition of CNF introduces micro- and nanostructures to the surface, required for superhydrophobicity. Regarding the bulk of the nanocomposite, the exceptional mechanical strength and thermal conductivity of CNF
reinforces the PTFE matrix and lowers its thermal resistance respectively.[31,32] Although to our knowledge there is no available literature on the increase of the thermal conductivity by the addition of CNF to a matrix of PTFE, subsequent thermal conductivity increases have been observed with the addition of CNF into other polymeric materials.[36–38] Moreover, since the length of the CNF fillers used (20–200 μm) exceeds the coating thickness significantly, these fibers are likely to result in direct thermal paths through the composite, effectively increasing the out-of-plane thermal conductivity,[19] an effect that cannot be captured from typical measurements on bulk composite instead of thin coatings.[37,40] Nevertheless, we apply a model to the nanocomposite and estimate a thermal conductivity in the range of 0.30–5.37 W m⁻¹ K⁻¹. Refer to Section S4, Supporting Information, for details. We term this nanocomposite coating as PTFE/CNF hereafter.

The coating thickness is reduced by tuning the total solid fraction of the spray suspension, while maintaining full substrate coverage with good uniformity and no surface defects as shown later in the SEM images in Section 2.2. This level of thickness is challenging to be achieved via spray coating,[41] especially with the addition of nanofibers in the sprayed dispersion that tend to expand the coating volume. We emphasize here that minimal coating thickness is a key aspect for achieving efficient condensation heat transfer, since a thick polymeric coating can counterbalance the heat transfer benefit gained from DWC on hydrophobic surfaces.[39] This is a subtle but important point in the design of heat-transfer-enhancing interface materials, since efforts towards minimizing the thickness of hydrophobic coating layers are typically accompanied with significant loss of long-term performance due to the lack of material durability.

We observe cross sections of the coating by the means of focused ion beam scanning electron microscopy (FIBSEM) of a pure PTFE and a PTFE/CNF coating that are both sprayed as 1 wt% suspensions in dichloromethane. For further details on this characterization technique, refer to Section S5, Supporting Information. The determined coating thickness is 0.85 ± 0.30 μm for PTFE and 2.04 ± 0.35 μm for PTFE/CNF. The higher coating thickness of PTFE/CNF than that of PTFE with the same total used weight of materials can be attributed to the rather sparse packing of nanofibers. By weighing the surfaces before and after spraying, the area density of the PTFE/CNF coating is determined to be 70 ± 3.9 μg mm⁻², and for a coating thickness of 2 μm, the volume density is 3.5 ± 2.0 mg mm⁻³. Thus, our careful spray optimization allows us to achieve a spray coating significantly thinner than conventionally expected.[41] We also find that this 2 μm-thick PTFE/CNF coating enables significant condensation heat transfer enhancement through JDWC while maintaining exceptional surface roughness as we show in the following sections. Other approaches to achieve thin hydrophobic coatings have either limited robustness (e.g., SAMs) or unproven economical scalability.[32] An additional fundamental advantage of our approach compared to many existing ones is that with this method, no separate surface structuring is required (e.g., chemical etching or lithography), since all the hierarchical surface morphology required for superhydrophobicity is formed spontaneously upon spraying and subsequent annealing.

2.2. Surface Characterization

The images obtained with SEM of the surface before and after annealing are shown, respectively, in Figure 1a–d. Prior to annealing, the as-sprayed PTFE/CNF is present in the form of discrete microparticles (PTFE powder) and fibers (CNF), with high porosity (Figure 1a,b). After annealing, the molten PTFE particles blend together and lock the CNF in place (Figure 1c,d). Still, after annealing, a high degree of hierarchical surface roughness (microscale and nanoscale) can be observed. In particular, the PTFE has formed microscopic flakes (Figure 1c) that enclose the high-aspect-ratio CNF. The nanofibers, randomly dispersed and bound by the polymer matrix, achieve the nanostructured requiring to transition condensate microdroplets to mobile Cassie-like state.[42]

We choose two reference surfaces for our study, namely, 1) a CuO superhydrophilic surface,[43] to represent typical FWC on industrial condensers; and 2) a flat hydrophobic surface, to delineate the performance changes by the addition of CNF to PTFE. The superhydrophilic surface (Figure S5.1b, Supporting Information) consists of -1 μm-tall CuO nanoblades fabricated with a hot alkali process,[43] and it serves as a stable reproducible control case for FWC on copper surfaces. On the other hand, the flat hydrophobic surface is composed of only PTFE (Figure 1e). Its fabrication process is similar to the PTFE/CNF nanocomposite, except that the CNFs are excluded from the PTFE. The superhydrophilic surface (Figure 2b) is fabricated by hot alkali process, and it serves as a stable reproducible control case for FWC on copper surfaces. On the other hand, the flat hydrophobic surface is composed of only PTFE (Figure 1e). Its fabrication process is similar to the PTFE/CNF nanocomposite, except that the CNFs are excluded from the PTFE.

Measurements with contact angle goniometry confirm the superhydrophilic properties of our PTFE/CNF nanocomposite. Specifically, the advancing contact angle (ACA) is measured to be 161.1° ± 1.8° while the contact angle hysteresis (CAH) is 1.5° ± 0.6°. These values show that the PTFE/CNF surface is significantly more water-repellent than PTFE alone without CNF, which exhibits an ACA of 132.6° ± 2.5° and a CAH of 34.0° ± 2.9°. The low water adhesion of PTFE/CNF is necessary for the phenomenon of coalescence-induced droplet jumping during condensation. Details on contact angle measurements are available in the Experimental Section.

2.3. Microscale Condensation Dynamics

To evaluate the microscale condensation behavior, we place our surfaces horizontally on a cooling stage and observe events with optical microscopy at room conditions. In Figure 2a–c, we can see how condensation evolves on the superhydrophilic CuO reference surface, the PTFE flat reference surface and the PTFE/CNF surface respectively. A film of water is seen on the CuO surface in Figure 2a, and non-circular droplets with their contact lines pinned by the structures form on top of the film of water. On the other hand, on the flat PTFE surface in Figure 2b, distinct circular droplet contact lines are present, indicating that the droplets have shapes of spherical caps and are generally free from pinning by the surface, a key factor.
for droplet mobility to facilitate DWC. Coalescence-induced droplet jumping is observed only on the PTFE/CNF surface as shown in Figure 2c. Three droplets (indicated by arrows in panel Figure 2c-i) grow by condensation, coalesce, and leave the surface spontaneously due to the conversion of the excess surface energy into upwards kinetic energy from a low-adhesion surface.[44] The empty space without water droplets, left behind after a coalescence jumping event (enclosed region in panel Figure 2c-ii), enables new nucleation events to occur on the surface without undesirable thermal resistance from existing liquid water. As we will show afterwards, JDWC is the predominant departure mechanism for droplets condensed on PTFE/CNF. Details on these observations with optical microscopy are available in Section S6, Supporting Information.

We further observe the condensation behavior on PTFE/CNF in situ with an environmental scanning electron microscope (ESEM) (Video S1, Supporting Information). As seen in Figure 2d, the condensed droplets exhibit nearly spherical shapes, suggesting high contact angles and a high repellency for small droplets during condensation, a condition not necessarily met on all superhydrophobic surfaces.[45] The inset in Figure 2d clearly shows the high contact angle for an individual condensate droplet. While a superhydrophobic surface may exhibit water repellency for deposited droplets, condensation nuclei may grow within the micro- and nanostructures to result in Wenzel-state droplets.[10,46,47] However, it is evident that the PTFE/CNF nanotexture is able to repel condensate droplets of the smallest size observable by our means of microscopy.[44] This is crucial to condensation heat transfer as discussed in the next section.

2.4. Condensation Heat Transfer Characterization

A host of studies exists for novel micro- and nanostructures and coatings that facilitate DWC[48–52] and JDWC.[11,53,54] Yet, the vast majority is limited to surface wetting characterization, sometimes accompanied by measurements of the volume of
condensed water collected from these surfaces. However, these metrics do not necessarily directly correlate with heat transfer performance in terms of challenging but very valuable measurement of HTCs, which in the end is the decisive parameter for evaluating condenser efficiency. In other studies where the condensation HTCs are reported, the testing conditions are often mild and far from a realistic industrial environment, where long-term performance is necessary. Here we investigate the heat transfer efficiency of PTFE/CNF coatings with direct measurements of HTCs for a range of steam temperatures and velocities.

2.4.1. Heat Transfer Measurements at Low Pressure

We first expose the surfaces to saturated steam at 30 mbar (corresponding saturation temperature 24.08 °C) in the low-pressure chamber. The surfaces are oriented vertically while the steam flows horizontally across at ≈4 m s⁻¹ over the samples, which are placed on one end of a copper block, with its other end actively cooled with a recirculating chiller set at different temperatures. Condensation heat flux, steam temperature, and sample surface temperature are measured as discussed with other experimental details in Section S8, Supporting Information.

The heat transfer performance of PTFE/CNF coatings with direct measurements of HTCs for a range of steam temperatures and velocities.

We test the surfaces in two in-house steam flow experimental facilities, with the chamber of one designed to operate at a sub-atmospheric steam saturation pressure of 30 mbar, and the chamber of the other to operate at a steam saturation pressure above atmospheric of 1.42 bar. While the low-pressure chamber mimics realistic operating conditions of industrial condensers used in thermal power plants, the high-pressure chamber provides insights into the ability of PTFE/CNF to withstand more hostile conditions and provides an accelerated aging test for the coating, challenging its performance limits in conditions much harsher than those encountered in the majority of industrial settings. We believe that by evaluating the surfaces under varied environments, a comprehensive picture can be pieced together in terms of the applicability of the surfaces in different contexts.

Figure 2. Optical micrographs showing the condensation behavior of the surfaces placed horizontally at room conditions, a) superhydrophilic CuO; b) hydrophobic PTFE; and c) superhydrophobic PTFE/CNF, i) droplets 1, 2, and 3 coalesce and leave the surface spontaneously, ii) leaving the empty space enclosed by the dashed line. Schematic illustrates the droplet jumping process. d) Condensation on PTFE/CNF under ESEM. Sample held at 45° with respect to the electron beam and maintained at ≈2 °C with a cooling stage. Water vapor pressure is gradually increased to initiate nucleation. The nearly spherical shapes of condensate droplets suggest that the superhydrophobicity is maintained for condensed water and the surface is suitable for condensation heat transfer enhancement. Scale bar: 150 μm. Inset: sample held at 86.5° during earlier stages of the condensation when the droplets are smaller. Inset scale bar: 10 μm.
where the heat transfer improvement brought by PTFE/CNF can be seen from a different perspective. In general, for the same subcooling, PTFE/CNF permits a higher heat flux across the interface. Images of the surfaces during condensation are shown as insets in Figure 3b. The average droplet size on PTFE/CNF is visibly smaller than that on PTFE, a desirable indication of a more efficient removal of condensate droplets before they grow to significant larger sizes, critical for enhancing heat transfer. This efficient condensate shedding for the case of PTFE/CNF is caused by frequent coalescence-induced droplet jumping from the surface as shown by the paths of the jumping droplets viewed from the side in Figure 3c and Video S2, Supporting Information. While coalescence-induced droplet jumping is the predominant mechanism for droplet removal on PTFE/CNF, gravity-assisted droplet removal, which is also underpinned by the much larger departure diameters, is the sole mechanism on PTFE. To quantify our observations, we measure the droplet diameters at their departure from PTFE/CNF and PTFE, as shown in Figure 3d. As droplet jumping departure is, in general, much more frequent than gravity-assisted departure, we measure departure diameters for all the droplets we can observe, i.e., above our resolution limit of ~20 µm per pixel. Most of the departing droplets from PTFE/CNF have diameters below 0.5 mm whereas most from PTFE have diameters above 2.5 mm. The subcooling of both surfaces is ~1 K.

2.4.2. Heat Transfer Measurements at High Temperature

To evaluate the performance and resilience of the surfaces in more hostile environments, the three surfaces are subsequently placed vertically in the high-pressure flow chamber and exposed to superheated steam at 111 °C and 1.42 bar, flowing vertically downwards, i.e., in the gravitational direction.[25]
test the surfaces at two steam flow speeds, namely, \( \approx 3 \text{ m s}^{-1} \) (laminar, Reynolds number \( \text{Re} \approx 1300 \)) and \( \approx 9 \text{ m s}^{-1} \) (turbulent, \( \text{Re} \approx 3900 \)), to study the effects of vapor shear on both droplet shedding and the coating. Re calculation is detailed in Section S11, Supporting Information. The principle of HTC determination is similar to that in the low-pressure flow chamber, as we describe the details of the setup in Section S10, Supporting Information.

The performance of the three surfaces under these condensation conditions is compared in Figure 4. At \( \approx 3 \text{ m s}^{-1} \), we observe a 5.6x increase in average HTC for DWC on the PTFE surface compared to FWC on the CuO surface, and a remarkable 9.2x increase for JDWC on the PTFE/CNF surface. The HTCs at \( \approx 9 \text{ m s}^{-1} \) are higher for all three surfaces, as expected, due to higher shear forces to shed non-jumping droplets on the surfaces and convective effects. The improvements of JDWC from FWC follow a similar trend, where we can observe a 4.2x increase in average HTC for DWC on PTFE and an 8.5x increase for JDWC on PTFE/CNF.

2.5. Durability of PTFE/CNF

The main body of available research for the durability of surfaces for DWC and JDWC has mainly focused on testing them in flow-free environments at low steam temperatures, in which both shear and thermal stresses are absent. In studies of durable surfaces under more challenging conditions,[22,24,25,48] only DWC has been achieved. We test our nanocomposite in the high-pressure flow condensation chamber by exposing the surface to 1.42 bar superheated steam at 111 °C, flowing at \( \approx 3 \text{ m s}^{-1} \) for an uninterrupted period of 72 h. We track the changes in the condensation dynamics and the underlying surface degradation with a high-speed camera at several time intervals over the 72 h.

Images of the PTFE/CNF surface are extracted at different times during the 72 h durability test to show the evolution of condensation behavior over time (Figure 5a). At the very beginning of the experiment (0 h), the view is partially obstructed by unavoidable fogging on the viewing window due to condensate droplets jumping from the surface. At 2 h, a stable water film is formed on the viewing window, eliminating the fogging effect and establishing the needed transparency to view clearly the sample surface. The jumping behavior of the droplets from the surface continues uninterrupted. Up until 10 h, JDWC remains the predominant mode of condensation. After that, we observe an increase in the average droplet size on the surface and DWC takes over as the predominant mode. After 50 h
of further continuous exposure, we finally observe a region of FWC emerging at 60 h at the bottom of the surface, enclosed by the red dashed line. This region expands slowly to take up a significant portion of the surface at 72 h, when we assume coating failure has occurred and we stop the experiment. The droplets start to become less circular as they are pinned by the underlying microstructure. Coating failure is decided at 72 h when the FWC region has taken up a significant portion of the surface.

Apart from the long-term sustained JDWC and DWC demonstrated above, we attempt to quantify the strength of the coating by an estimation of the stresses it has tolerated. During the 72 h durability test, the maximum shear stress exerted by the steam flow onto our surface is estimated, from flow calculations, to be at least 65 mPa (mean shear stress at least 57 mPa), which translates to an equivalent mass load of 6.6 µg mm⁻², 94% of the own mass of the PTFE/CNF coating (Section S11, Supporting Information). We note that additional shear stresses are present before the flow chamber is brought into steady operation, and the shear imposed by condensate droplets on the surface is not taken into account in our calculations, which consider only the steam flow (Section S11, Supporting Information). We suspect that as the average droplet diameter on the surface increases during the course of the experiment, the droplets exert a larger stress onto the coating, thus accelerating further deterioration. Thus, the above-stated shear stress tolerated by the coating is a conservative estimate. Moreover, thermal stresses detrimental
to coating adhesion are expected due to the mismatch of thermal expansion coefficients of the concerned materials.\[5\]
We expect such mismatches at all interfaces in the nanocomposite, and accelerate its deterioration in the durability test at elevated temperatures. We observe that both the deterioration transitions from JDWC to DWC and from DWC to FWC start at the bottom of the surface. As non-jumping droplets by gravity, they sweep droplets along their path and reach the largest size at the bottom of the sample. Therefore, the shear stresses experienced at the bottom are constantly higher than the upper regions.

Finally, we compare the surface topography of PTFE/CNF before and after the durability test with SEM (Figure 5b), focusing on the region in which DWC becomes visible after 72 h of steam exposure. The topography of the surface is clearly modified. Despite the CNFs being still present and randomly dispersed over the surface, the PTFE matrix appears to be damaged and there are no longer smooth PTFE flakes bridging across and enclosing the fibers, leaving the skeleton of CNF exposed. The loss of PTFE creates new larger-sized and deeper microstructures in the form of craters on the surface. As nucleation occurs within these deeper craters, droplets may become trapped, resulting in the transition to the Wenzel state. Eventually, the water condensed in the deeper and larger microstructures may interconnect and form a full film of water, much like the case of the superhydrophilic CuO nanostructured surface, thus leading to FWC.

The surface wettability of the PTFE/CNF surface after the durability test is also examined. We measure an ACA of 152.0° ± 1.9° and a CAH of 12.7° ± 2.9° at three random locations on the exposed condensing surface. The decrease in ACA and the increase in CAH are attributed to the change of the surface microtopography as explained above.

Our accelerated durability test proves that PTFE/CNF can withstand harsh conditions for an extended period of time while, in a host of practical applications, the conditions are like the case of the superhydrophilic CuO nanostructured surface, leading to FWC.

3. Conclusion

We developed a versatile, scalable, and economic method to fabricate exceptionally robust, sprayable superhydrophobic PTFE/CNF nanocomposite coating, able to sustain prolonged JDWC under extremely harsh conditions for 10 h and DWC for an additional 50 h. The key advantages of this method are as follows: 1) no substrate prestructuring is required; 2) appropriate surface priming with a metal layer allows for enhanced coating adhesion without compromising the heat transfer; 3) thin and superhydrophobic coating with thermally conductive nanofillers is realized via a facile spray method; and 4) high adhesion to substrate and the formation of the fiber network, together with PTFE annealing, give rise to an extremely robust coating given its minimal thickness (2 μm). In terms of heat transfer, this translates to an order of magnitude (9x) improvement in HTC compared to our FWC reference and almost double the HTC compared to the DWC reference. We can, therefore, conclude that we have carefully designed a passive and multifunctional, i.e., hydrophobic, thermally conductive and robust, material system that proves to be a promising superhydrophobic material for industrial condensing applications. Such a material could enable more efficient processes, for example, in steam power generation and other condensation-based energy conversion systems, thus contributing to the global reduction of carbon dioxide emissions.

4. Experimental Section

Surface Fabrication: Rectangular copper plates (EN CW004A, Cu ≥ 99.9%, Metall Service Menzingen) precision cut to size 50 mm × 20 mm × 1.5 mm were used as the substrates for all the cases. For PTFE/CNF and PTFE surfaces, the copper substrates were first cleaned with acetone, isopropanol, and hydrochloric acid (37%), sequentially, in an ultrasonicated water bath (USC300D, VWR). They were then rinsed thoroughly with deionized water and dried with nitrogen. A 150 nm thick layer of aluminum was then deposited onto the copper by e-beam evaporation (BAK 501LL, Evatec), followed by 3 min of oxygen plasma (Femto, Diener Electronic) at 100 W for surface activation. This thin layer was added to improve the coating adhesion to the substrate. To prepare the suspension for the PTFE/CNF coating, a vial of 90 mg PTFE (in powder form, 1 μm particle size, Sigma-Aldrich) was dispersed in 4.95 g of dichloromethane (Sigma-Aldrich) in an ultrasonicated water bath and 10 mg CNF (98% carbon basis, 100 nm × 20–200 μm, Sigma-Aldrich) was mixed with 4.95 g of dichloromethane with a probe sonicator (Vibracell VCX 130, Sonics) in another vial. The two vials were then mixed together, followed by an ultrasonicated water bath, resulting in a 1 wt% PTFE/CNF suspension in dichloromethane, the suspension weighing a total of 10 g. This suspension was used to spray-coat three samples simultaneously with a VL double action–internal mix–siphon feed airbrush (Paasche Air Brush) at a distance of ~20 cm with an air pressure of 3 bar. To avoid precipitation, the suspension was continuously slightly shaken during spray. The surfaces were subsequently annealed in an atmosphere of nitrogen at 400 °C (FB1310M-33, Thermoline) for 30 min and cooled slowly to room temperature in the nitrogen environment. The preparation of the suspension for the PTFE coating was similar. A total of 100 mg PTFE was mixed with 9.9 g dichloromethane in an ultrasonicated water bath. The suspension was then sprayed and annealed with the same parameters. For the CuO nanostructured surface, the same copper substrate was cleaned in an ultrasonicated water bath with acetone, isopropanol, and deionized water, sequentially, and then dried with nitrogen. The cleaned substrate was then immersed in 2 μM hydrochloric acid for 20–30 s. It was then transferred into a mixture of NaClO₂, NaOH, and Na₃PO₄·12H₂O at 95 °C ± 3 °C for 4–5 min, followed by rinsing with deionized water and drying with nitrogen.[36]

Wettability Measurements: Surface wettability was characterized by measuring advancing and receding contact angles with a goniometer (OCA 35, Dataphysics). For each surface, five measurements were taken at random locations.

Observation of Condensation with Optical Microscopy and ESEM: Refer to Section S6, Supporting Information, for details on the observation of condensation with optical microscopy and Section S7, Supporting Information, for ESEM.

Heat Transfer Characterization and Droplet Departure Measurements: Condensation heat transfer was characterized in two in-house flow chambers. The details on the structure of these chambers and their experimental procedures are available in Sections S8–S10, Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.
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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M.D. and C.W.E.L. contributed equally to this work. A.M., C.S.S., and D.P. conceived the research and provided scientific guidance in all aspects. M.D. and C.W.E.L. performed most of the experiments and processed the data. A.T. performed the FIBSEM observations and measurements. A.Z. helped in the experimental work related to the coating durability evaluation. The manuscript was written through contribution of all authors.

Keywords

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