Dr. Neil Canter / Contributing Editor

Relationship between wettability and ice removal

A new study determined that ice growth is dependent on the hydrophobicity of a surface.

AS THIS COLUMN IS READ, those of us in the Northern Hemisphere are dealing with a common winter task—removing ice from windshields. This task can be difficult and time consuming.

To develop an approach for easier ice removal, further information is needed about the structure of ice when it forms on a surface. Clues about how to deal with this issue can originate from research done to repel ice's liquid state, water, from surfaces. This leads to an examination of the concept of superhydrophobicity.

Superhydrophobic surfaces are designed to reject or repel water. This makes them attractive in lubricant systems because water contamination can create premature lubricant failure by causing problems such as corrosion. Repelling water is a popular approach to facilitating water removal from a lubricant system.

In a previous TLT article, researchers defined a superhydrophobic surface as containing microscopic ridges and posts in combination with a hydrophobic coating such as polytetrafluoroethylene.[1] These characteristics enable the contact angle of water droplets impinging on a superhydrophobic surface to be greater than 120 degrees.

About 20 years ago, modeling studies by Xiao Cheng Zeng, Chancellor's University & Willa Cather Professor of chemistry at the University of Nebraska-Lincoln in Lincoln, Neb., determined the structure of ice on a surface. Zeng says, "We found that ice forms a two-dimensional bilayer on a surface that is similar in structure to graphene. The structure is 0.8 billionth of a meter thick and cannot be seen, but it can be measured by spectroscopic techniques. The structure of the two-dimensional ice was designated as Nebraska Ice and was verified experimentally in 2009."

A new modeling study and experimentation has provided further insight into how ice growth is a function of the hydrophobicity of a surface.

KEY CONCEPTS

- Ice growth on a surface is a function of hydrophobicity with along-surface growth occurring at a contact angle below 40 degrees.
- When the contact angle is above 40 degrees, ice grows in an off-surface growth mode.
- Surface roughness lowers the contact angle when ice growth switches from the along-surface to the off-surface mode.

TWO ICE GROWTH MODES

Zeng and colleagues from several China institutions have determined the way ice grows on a surface as a function of the hydrophobicity of the surface. The work was done both through modeling and experimentation.

Surface roughness also can influence ice growth.

The surface used in this study was prepared by depositing a thin aluminum film on a silicon wafer. Hydrophobicity was introduced through chemical vapor deposition of perfluorodecyltrimethoxysilane. The wettability of the surface was varied by adjusting the treatment time. On average, the thickness of this film is approximately 50 nanometers.

Ice was added to this surface, and the samples were added to a cryostage kept at -15 C with humidity adjusted by adding wet air to the cryostage. Zeng says, "We found that ice growth on a surface will differ depending upon the hydrophobicity of a surface. When the contact angle for ice is below 40 degrees, then ice formation will creep along the surface in a manner known as the along-surface growth mode. As part of this process, Nebraska Ice is formed."

Zeng feels that an appropriate term for ice growing in this manner on the surface is iceophilic.

In the presence of a more hydrophobic surface with a contact angle greater than 40 degrees, ice grows in a different manner away from the surface. Zeng says, "We found that ice forms in an off-surface growth

When he was three, Braille accidentally poked himself in the eye with an awl from his father's leather

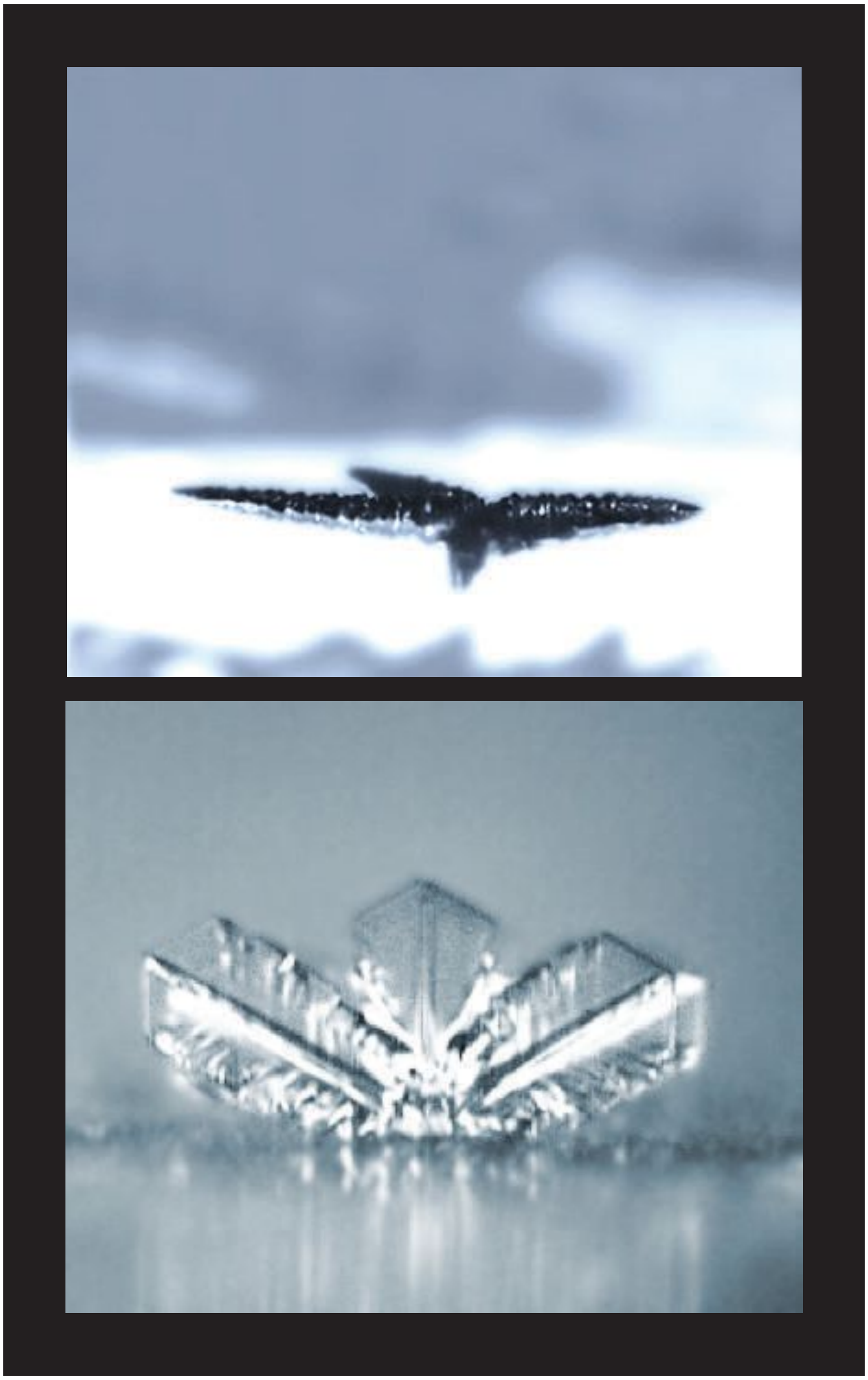

Figure 1 | **Ice forming along the surface is shown on the top, while ice growing off the surface is below. Off-surface growth can ease ice removal from a surface.** *(Figure courtesy of the University of Nebraska-Lincoln.)*

mode, which we term as iceophobic. Ice grows toward the sky in a manner similar to a snow flake and often forming shapes that exhibit beautiful six-fold symmetry."

A particular significant experiment was done to demonstrate how ice grows on a surface that is 50% hydrophilic and 50% hydrophobic. As ice growth progressed from the hydrophilic to the hydrophobic side of the surface, the initial along-surface growth mode changed to off-surface growth mode.

Surface roughness also can influence ice growth. Zeng says, "We determined that the contact angle where ice growth switches from the along-surface to off-surface growth modes drops to a smaller angle. This shift may be due to the ice not really being in contact with the rough surface as readily as a smooth surface. The hydrophilicity of the surface must be more pronounced to enable the ice to act in the along-surface growth mode."

The difference in the two ice growth modes is shown in Figure 1. Off-surface growth improved the ability for ice to be removed as shown on the right, while along-surface growth made it difficult for ice to be removed as depicted on the left. Experiments subjecting both surfaces just to wind blowing at 5.78 meters per second led to rapid ice removal for the hydrophobic surface but no ice removal for the hydrophilic surface.

This work should provide guidance for the development of better ice-repellent surfaces that might make it easier to remove ice from automobiles and also to de-ice airplanes. Zeng says, "We have seen that two-dimensional ice has different types of crystal structures that can range from hexagonal to square surfaces. In the future, we are looking to better understand how these surfaces are formed."

Additional information on this research can be found in a recent article[2] or by contacting Zeng at **xzeng1@unl.edu.**

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Keeping cool with wearable textiles

Researchers have developed a composite textile that can be woven into fabrics.

TECHNOLOGY IS ADVANCING TO ENABLE INDIVIDUALS to better use their bodies as power sources. In a previous TLT article, researchers developed a wearable device that takes advantage of the temperature difference between two objects to generate power.[1] This process is known as thermoelectric generation (TEG) and, in this case, takes advantage of the difference between the temperature of the human body and the ambient environment.

The maximum amount of power generated was 20 microwatts per square meter when the TEG device is placed on the upper arm and the individual using it is walking at a rate of 1.1 meters per second.

One problem that individuals deal with in hot climates or during the summer is dissipating this body heat. We rely on air conditioning to control temperature, but the cost and the increased emissions make it worthwhile to see what can be done for the individual.

The result has been the development of personal cooling technologies. Liangbing Hu, associate professor in the Department of Materials Science and Engineering & Energy Research Center at the University of Maryland in College Park, Md., says, "Personal cooling technologies provide thermal comfort to the individual by directing local heat to the thermal-regulated environment."

'Personal cooling technologies provide thermal comfort to the individual by directing local heat to the thermal-regulated environment.'

For the textile industry, personal cooling technologies offer an approach for simultaneously providing thermal comfort and reducing energy consumption for the individual. Hu says, "This function can enable textiles or garments to have a new function and develop enhanced value."

Personal cooling technologies are commercially available and include moisture management textiles, air-cooled textiles, cold pack textile phase change materials and liquid cooling textiles. But these technologies have limitations.

Hu says, "Moisture management textiles are the most common thermal-management textiles on the market, but its thermal-management mechanism can only be triggered when the microclimate between human skin and fabric is at a high humidity level. The other technologies have limitations such as inconvenience due to the bulky size of the cold pack, massive consumption of power and high cost. These technologies are mainly utilized to reduce the risk of heat-related injuries to the human body and not suitable for general applications."

A key challenge that needs to be overcome is to find a material that exhibits improved thermal conductivity. Such a material in the form of a composite fiber has now been prepared.

BORON NITRIDE NANOSHEETS

Hu and his colleagues developed a new type of textile fiber based on a composite of boron nitride (BN) nanosheets and polyvinyl alcohol (PVA) that can be woven into a fabric. He says, "BN has traditionally been considered as an effective material in thermal management applications due to its high thermal conductivity, yet this material also is an electrical insulator. The BN nanosheets exhibit high in-plane thermal conductivity and are ideal filler materials for fabrication of a thermal conductive composite."

The processing of the BN/PVA composite fiber is shown in Figure 2. Initially, BN and PVA were dispersed in dimethyl sulfoxide prior to 3D printing. Hu says, "PVA has a great interfacial compatibility with BN nanosheets that helps with dispersion in solution."

The next step was preparing the fibers through 3D printing. Hu says, "3D printing, as an efficient additive manufacturing technique, can fast and accurately fabricate an arbitrary and complicated structure. This technique is not only scalable but efficiently fabricates the BN/PVA composite fibers and also can promote the development of new 3D printed textile structures."

The composite fibers are then drawn

KEY CONCEPTS

- Personal cooling technologies are now commercially available but do not exhibit adequate thermal conductivity.
- A new composite fiber based on boron nitride and polyvinyl alcohol exhibits good thermal conductivity when woven into a fabric.
- Composite fibers are efficiently prepared using 3D printing.

at a temperature of 200 C. Hu says, "This process leads to a composite fiber that displays a combination of high mechanical strength (355 megapscals) and favorable heat dispersion. Due to the improved thermal transport property imparted by the thermally conductive and highly aligned BN nanosheets, a better cooling effect (55% improvement over commercial cotton fiber) can be achieved."

In evaluating the performance of the BN/PVA composite fiber, the researchers used a laser-infrared camera and laser input power to determine the temperature distribution of the fiber bundles and fabrics and to evaluate thermal conductivity. Hu says, "BN/PVA was evaluated versus pure PVA and cotton fabrics. We found that the BN/PVA composite fabric displayed the lowest maximum temperature at laser power inputs of 0.047, 0.079 and 0.096 Watts. The BN/PVA composite fabric also demonstrated the highest thermal conductivity of the three fibers tested."

For the future, the researchers will further examine the thermal conductivity of BN/PVA. Hu says, "We plan to use a heated mannequin that is similar to an actual human body to further study the thermal properties of the composite fabric. Newer textile structures will be designed and prepared based on 3D printing technology. We also plan to evaluate other fiber candidates with promising physical properties for thermal management applications."

Additional information on this work can be found in a recent article[2] or by contacting Hu at **binghu@umd.edu**.

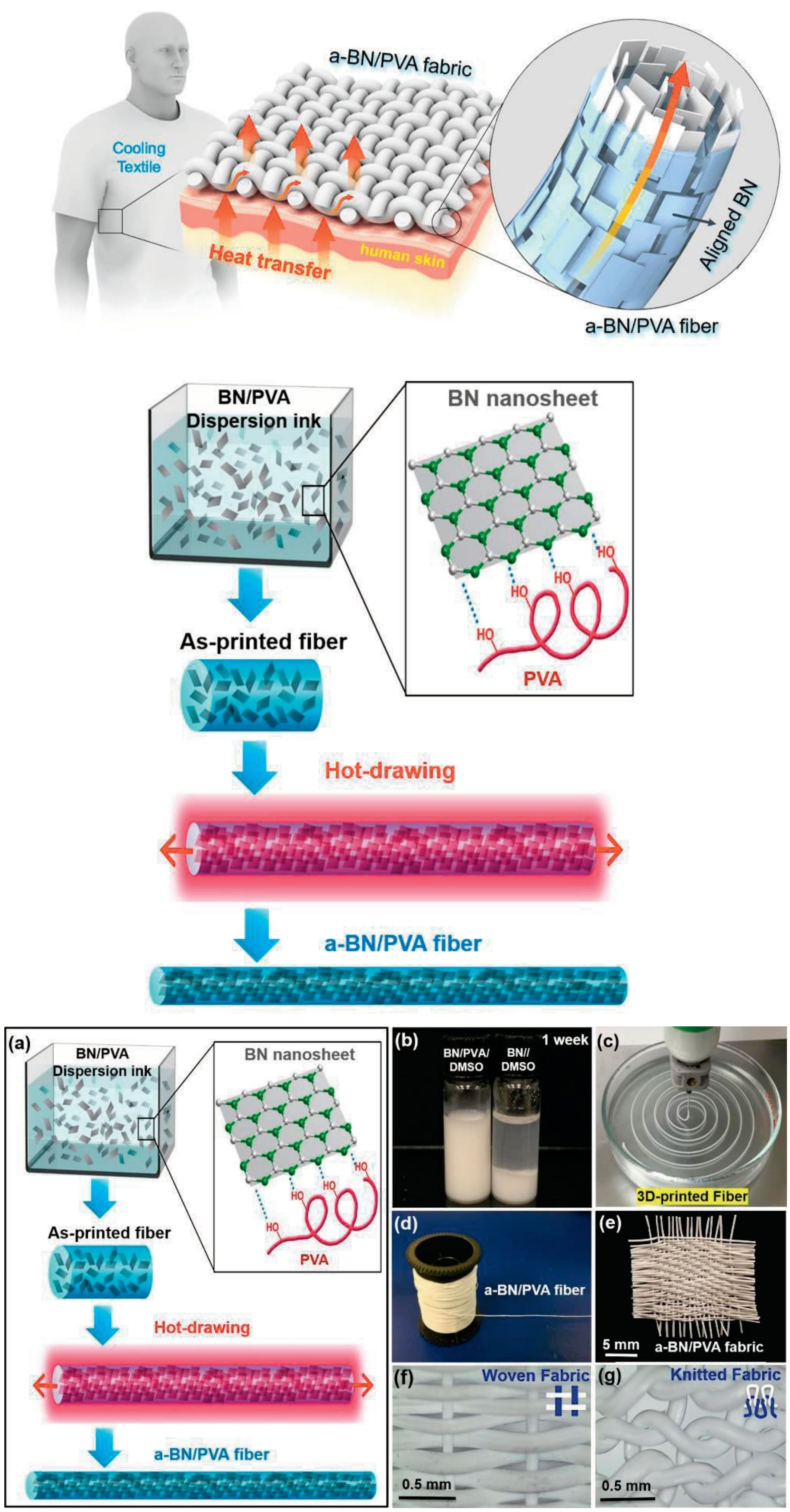

Figure 2 | **A new type of textile fiber based on a composite of boron nitride (BN) and polyvinyl alcohol (PVA) that shows superior thermal conductivity is processed in the manner shown.** *(Figure courtesy of the University of Maryland.)*

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Evaporation as an alternative energy source

A new model evaluates the potential for generating power by placing evaporation engines in natural fresh water sources.

IN THE SEARCH FOR DEVELOPING ALTERNATIVE ENERGY SOURCES to petroleum, this column continues to monitor developments in wind energy and solar power. Research to determine if water can be harnessed in some fashion as an energy source also has been underway. One motivation is that water occupies 71% of the Earth's surface, according to the U.S. Geological Survey.[1]

Almost all of the water (96.5%) is contained in Earth's oceans, which contain varying degrees of salinity. Researchers have been working to use differences in salinity as a means to generate power. In a previous TLT article, the salinity difference between fresh water and seawater was used to produce power using a concentration flow cell where water with a high salinity content flows past one electrode, and water with a low salinity content flows past a second electrode.[2] The average power density achieved was twice what was reported previously.

KEY CONCEPTS

- Evaporation represents a different approach for using water as an energy source.
- A model developed found that 325 gigawatts of power can be generated through using evaporation on all fresh water surfaces in the U.S. greater than 0.1 square kilometer, except for the Great Lakes.
- The model determined that more energy can be realized from evaporation in drier, sunnier, warmer climates than cooler, wetter climates.

A different approach for using water as an energy source is evaporation. Dr. Ahmet-Harndi Cavusoglu, associate director, Academic Venture Exchange and formerly a graduate student in the department of chemical engineering at Columbia University in New York City, indicates that evaporation is a key part of the water cycle. He says, "The water cycle describes how water moves through the Earth's atmosphere. Initially, water condenses and is released onto the Earth as rain (or snow). The water then moves into rivers which then empty into lakes and oceans. This process also occurs on land as water is absorbed into soil. In the final step, water evaporates back into the air completing the cycle."

The possibility exists that evaporation of water may be used as a way to produce energy. Cavusoglu says, "The rate of evaporation's energy transfer or flux was determined to be 80 watts per square meter on average globally. This is a measure of how energy flows up into the atmosphere and then down onto the Earth's surface."

The significant amount of potential power available from evaporation has been examined by Ozgur Sahin, associate professor of biological sciences and physics at Columbia University. Sahin and his research group have developed an evaporation engine to generate energy in the laboratory.[3]

Cavusoglu describes how the evaporation engine works, "An evaporation engine would be placed above a body of evaporating water and acts in a similar manner to a greenhouse over a body of water such as a lake. This device would contain a hygroscopic material that grows and shrinks when in contact with moisture, sandwiched between shutters on top of the engine facing the atmosphere and shutters below in contact with the water surface. In the first step, the upper shutters are closed while the bottom shutters open, enabling water at its highest chemical potential to be absorbed into the engine causing the transparent material to swell. Then the upper shutters open and the lower shutters close, which allows the hygroscopic material to shrink releasing water at a lower chemical potential, thus, generating energy from the difference in chemical potential."

Reducing evaporation will lead to an additional 96.4 billion cubic meters of water recovered per year.

The cycle then repeats itself.

With this background, Cavusoglu and his colleagues then developed a model to evaluate the potential for generating power in the U.S. by placing evaporation engines in natural fresh water sources.

DRIER CLIMATES FAVORABLE

Cavusoglu, Sahin and their co-workers developed a model to demonstrate

Braille continued at school and learned what he could through oral instruction. When

Figure 3 | **A reservoir located near Phoenix, Az., is in a dry, sunny, warm climate that appears to be advantageous for generating power through the use of evaporation.** *(Figure courtesy of Columbia University.)*

the potential for using evaporation to generate energy in the contiguous U.S. Cavusoglu says, “We evaluated the energy flux that can be generated on all fresh water surfaces that are greater in area than 0.1 square kilometer, except for the Great Lakes. The assumption is made that each of these water surfaces is completely covered with an evaporation engine.”

The researchers calculated that 325 gigawatts (2.85 billion megawatt hours per year) of power can be generated from evaporation. A secondary benefit is that the reduction in evaporation will lead to the recovery of an additional 96.4 billion cubic meters of water per year, which is extremely important, particularly in drier climates. The potential power obtained through evaporation is greater than electrical power generation in 15 of the 47 U.S. states evaluated.

The weather in a specific location played a significant role in the amount of power the model predicted can be produced through evaporation. Cavusoglu says, “We found that more evaporation energy can be generated from water sources in drier, sunnier, warmer climates than those in cooler and wetter climates. One other factor is that changes in the seasons also will impact power generated as more will be produced in the summer than in the winter.”

This means that locations such as Phoenix, Az., which is serviced by the reservoir shown in Figure 3, could benefit greatly from evaporation. Cavusoglu points out that locations such as Minnesota also will benefit for a different reason. He says, “Minnesota has a cooler climate that inhibits evaporation energy but compensates for this negative characteristic due to the large number of lakes present. Our model calculated that a large amount of evaporation energy can be generated even though the efficiency as measured by watts per square meter is low.”

While producing power from evaporation can be done as needed and is not directly reliant on the sun or the wind in the case of wind energy and solar power, Cavusoglu envisions evaporation to be a supplemental renewable energy source. He says, “We feel that evaporation energy is an extra tool in the tool box and complementary with other energy sources.”

Future work for Sahin’s group will involve scaling up the evaporation engine. Additional information on this model can be found in a recent article[4] or by contacting Sahin at **sahin@columbia.edu.** TLT

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