Dr. Neil Canter / Contributing Editor

Potential for windmills at the microscale

Micro-windmills can operate without even standing up.

THE CHALLENGE IN FINDING LONG-TERM LUBRICATION solutions for wind turbines is well known and documented. One approach that has been discussed involves finding ways to reduce the stress on individual wind turbines in a farm in order to improve their longevity.

In a previous TLT article, researchers used a technique known as Simulator for Offshore /Onshore Wind Farm Applications to examine an existing wind farm and studied five scenarios in which the turbines are spaced in a different manner from each other.[1] The results from these scenarios indicate that staggering wind turbines leads to a significant improvement in the efficiency of each individual unit. A second factor is that reduction of the number of wind turbines also results in greater efficiency.

A good deal of attention has also been paid to determining how lubrication occurs at the nanoscale and what types of materials should be used to improve the performance of devices such as microelectromechanical systems (MEMS). One concern with small electrical devices is how to effectively dissipate the heat they generate.

Developing a device that can assist with this process is one of the reasons why work was initiated to design a turbine that functions on the microscale. J.C. Chiao, Greene and Garrett Professor of Electrical Engineering at The University of Texas-Arlington in Arlington, Texas, says, "We have been working to develop MEMS turbine devices for the past six to seven years. My group is involved in the design of new MEMS platforms and we felt that placing a turbine on a silicon chip will have two benefits. The turbine can harness energy that passed by the chip in the form of air circulation or cool the silicon chips operating in an electrical device."

Initial attempts at developing a micro-windmill did not work. Chiao says, "Our initial micro-windmills were fabricated in silicon, which is a very robust material. But under the conditions of strong wind force, the silicon-based micro-windmill became brittle and shattered immediately once wind speed picked up."

The benefits of a micro-windmill can only be achieved if a more durable material can be used. Such a material has now been found.

KEY CONCEPTS

- Micro-windmills with blades that are approximately 0.9 millimeters in length have been developed from a nickel alloy.
- In contrast to macro-windmills, micro-windmills do not need to stand up and can be placed flat on a surface.
- One important application for micro-windmills is to dissipate heat buildup in MEMS.

NICKEL ALLOY

Chiao and his research associate, Dr. Smitha Rao, produced durable micro-windmills through the use of a nickel alloy. Chiao says, "After consultations by one of our research partners, we found that they fabricated micro-machined devices using a nickel alloy instead of silicon. The advantage of the nickel alloy is that it has a lower Young's modulus and is more flexible than silicon. This property enables the alloy not to shatter when it bends."

'The advantage of the nickel alloy is that it has a lower Young's modulus and is more flexible than silicon. This property enables the alloy not to shatter when it bends.'

Fabrication of the micro-windmill was not easy because there was no existing tool to run simulations to evaluate potential designs. Chiao says, "We tried more than 20 different ideas, but finally settled on a design that was inspired by Dr. Rao's daughter who likes to run around with a pinwheel on her head."

The design combines origami concepts with conventional wafer-scale semiconductor device planar layouts. Chiao says, "We fabricated the nickel alloys in a multilayer fashion. Five layers of the nickel alloy with sacrificial layers provide us with required thickness in 3-D structures."

The manufacturing cost is independent of the number of micro-windmills prepared in a wafer. A micro-windmill blade is approximately 0.9 millimeters in length, which means that it will turn with a diameter of 1.8 millimeters. Figure 1 provides a perspective on the size of a micro-windmill relative to a penny.

The dimensions for the initial micro-windmills are purely intuitive at this point. Chiao says, “We need to optimize the length of the blades. Longer blades will lead to more torque, which will increase the speed and effectiveness of the device. But it will reduce the number of windmills in a defined area. So we need to optimize its size to get the maximum combined power.”

In contrast to macro-windmills that are built vertically above the ground to use wind blowing horizontally, air patterns on the micro level are different. Chiao says, “Air moves orthogonally to the micro-windmill, which means that the device does not need to stand up and can be placed flat on a surface. Holes are placed in the micro-windmill to enable air to flow through.”

Chiao is unsure about how the air velocity fluctuates at the micro-level.

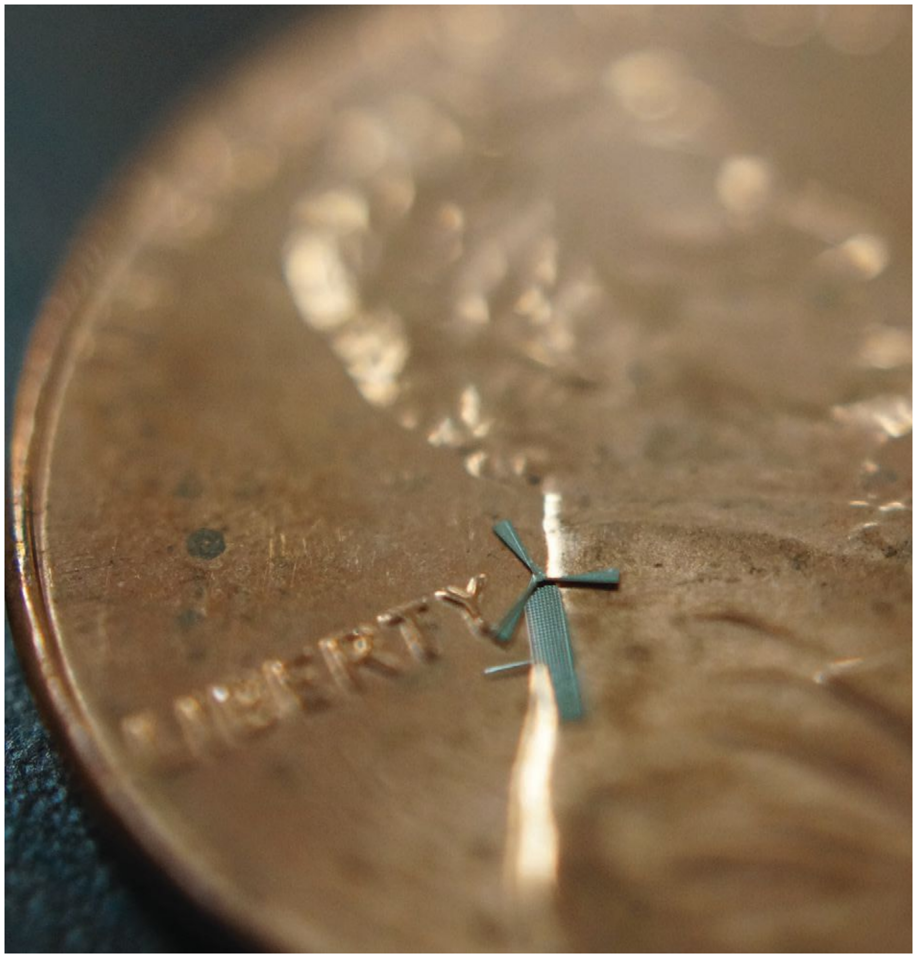

Figure 1 | **The small size of a micro-windmill is shown relative to a penny and means that this device can potentially be used to dissipate the heat buildup in MEMS.** *(Courtesy of The University of Texas-Arlington)*

‘We do not know at this point but believe to maximize the benefit of the micro-windmill in a specific application, the mechanical configuration for that application must be designed around the turbine.’

He says, “We do not know at this point but believe to maximize the benefit of the micro-windmill in a specific application, the mechanical configuration for that application must be designed around the turbine. The wind gradient at the micro-level is much different from what is seen in a conventional wind tunnel that is several meters wide. This is due to the narrower dimensions at the micro-scale.”

Evaluation of the micro-windmill is in progress at this point. Chiao says, “We did some elementary tests to make sure the device works such as using a tiny vacuum tube to blow air on it and also using a hair dryer. Currently, we are in the process of building an apparatus to more systematically evaluate the micro-windmill.”

When asked about the use of lubricants, Chiao indicates that currently none are in use for such MEMS devices. He says, “We believe lubricants will be needed to run the micro-windmills in the future. One area where lubricants will be needed is to protect the micro-windmill from water. Moisture can be a big problem that leads to an increase in friction at the micron or submicron scale.”

Chiao believes that micro-windmills can be used in a number of applications including remote sensors to evaluate the health of infrastructure. He says, “Maintaining infrastructure is a big issue, and the micro-windmills could be used in a wireless sensor to monitor the health of infrastructure such as bridges in a cost-effective manner.”

The researchers have applied for a provisional patent on this technology. Further information can be obtained by contacting Chiao at **jcchiao@uta.edu.**

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Modeling of sudden fluid thickening

A new model explaining discontinuous shear thickening focuses on the frictional contact between particles.

DUE TO THE LARGE NUMBER OF COMPONENTS used in formulating, lubricants can be considered complex fluids. With some of the components in suspension, there can be times when the fluid may suddenly thicken in response to changes in parameters such as shear and viscosity.

In a previous TLT article, a related process in which fast shear or sudden impact to a dense suspension of cornstarch in water was studied.[1] The net effect of applying such stress to a 50 percent suspension of cornstarch in water was the immediate formation of a solid. Stress in the form of an aluminum rod striking the cornstarch suspension leads to the formation of a propagation front of solidification that is similar to how a snow plow operates.

KEY CONCEPTS

- Discontinuous shear thickening (DST) occurs when high shear is applied to a concentrated suspension, leading to a dramatic increase in thickening.
- A new model has been developed to explain that DST involves the formation of a three-dimensional force chain network.
- Once stress is applied, hydrodynamic forces force the particles together to initiate contact and friction.

'DST is very abrupt once sufficient shearing is done to a concentrated suspension. A small, say factor of two, increase in shear rate can lead to orders of magnitude rise in fluid viscosity.'

Application of high shear to a concentrated suspension can lead to a dramatic increase in thickening through a phenomenon known as discontinuous shear thickening (DST). Jeffrey Morris, professor of chemical engineering at The City College of New York in New York, N.Y., says, "DST is very abrupt once sufficient shearing is done to a concentrated suspension. A small, say factor of two, increase in shear rate can lead to orders of magnitude rise in fluid viscosity. There is no intermediate state seen, which means that the fluid either displays low viscosity or high viscosity."

Several mechanisms have been proposed in the past to explain how DST occurs. Morris says, "Two possibilities are the order-disorder mechanism and hydroclustering. Order-disorder describes how a fluid moves from a low-viscosity state in a shear thinning regime to an unstable, disordered viscous state. Hydroclustering was taken directly from fluid mechanics and proposes that the thickening is due to particles clustering together in response to high shear."

Neither of these mechanisms fully explains how DST takes place. A new model has now been proposed to explain the origin of DST. One prominent factor that is extremely important in this model is friction.

THREE-DIMENSIONAL FORCE CHAIN NETWORK

Morris M. Denn, Albert Einstein Professor of Science and Engineering at The City College of New York, along with Drs. Ryohei Seto and Romain Mari, have developed a new model to explain DST that focuses on the frictional contact between particles. This model was prepared through the use of simulations that predict DST.

The numerical modeling simulations were done using Lees-Edwards boundary conditions. Cubic simulation boxes containing 512 particles and rectangular parallelepipeds were used.

Morris says, "For us, DST represented a classical fluid mechanics problem. In a hydrodynamic regime, forces are present to keep two smooth surfaces away from each other. As the surfaces get closer to each other, the film ruptures. This leads to a seizing condition on the local scale in a similar fashion to a journal bearing seizing."

In high concentrations, if one accepts that the particles must be in contact with each other, friction is generated as they rub against each other. The researchers determined how DST might occur from two aspects. Morris says, "Background on the particle interactions comes from analyzing DST, first as a fluid problem and then using ideas from the granular literature to

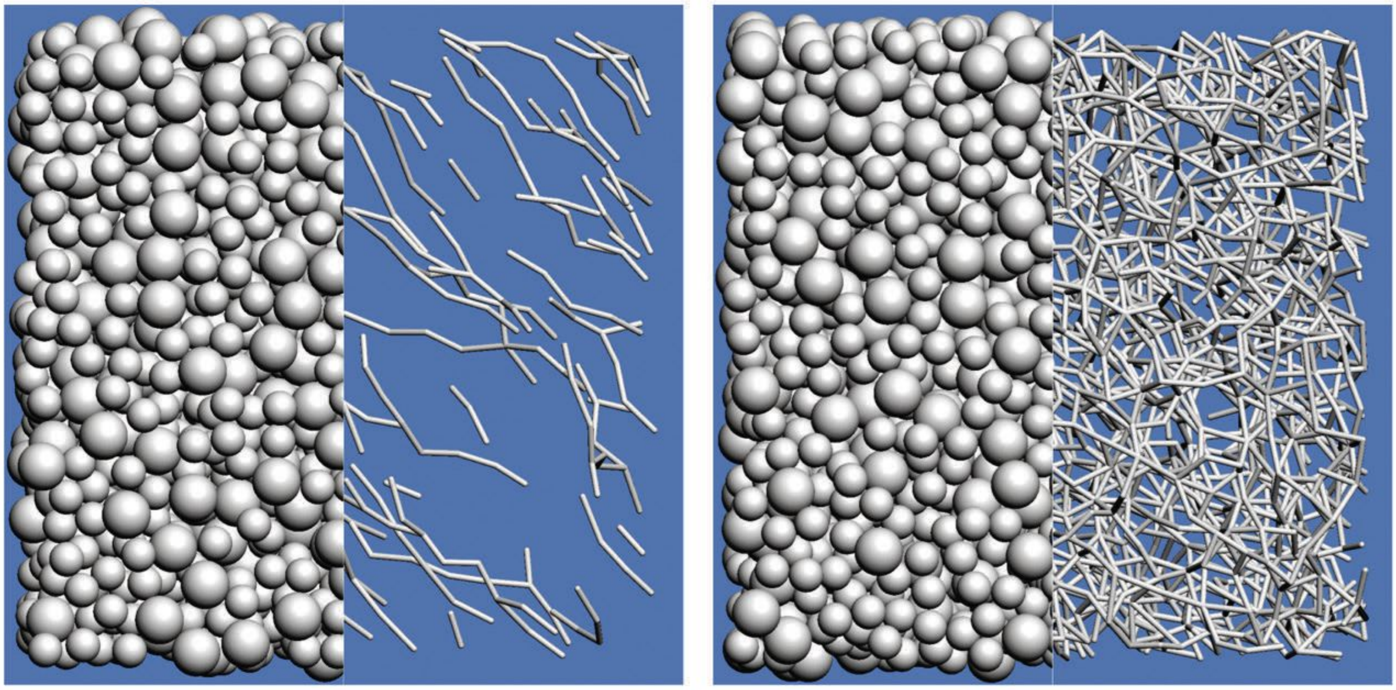

Figure 2 | **A new model for discontinuous shear thickening proposes that particles upon initial application of stress get pushed together and form force chains, as shown on the left side of the figure. Further stress leads the particles to form a three-dimensional force chain network, as shown on the right side of the figure.** *(Courtesy of The City College of New York)*

incorporate friction. We combined these two aspects and introduced the key ideas of friction and viscosity."

Denn added, "A key ingredient of the DST model is the force chain concept derived from the granular literature. Structural transmission of forces moves from particle to particle in a manner that looks like a series of chains."

In the initial fluid state prior to the application of stress, the particles flow at a low viscosity and do not generate any friction because they do not come in contact. As stress is applied, the hydrodynamic forces push the particles together to initiate contact and friction. At this point, they start to act as a single entity. This leads to the formation of force chains that are used by the particles to transmit the stress in one direction. The left image in Figure 2 shows the stressed particles on the left side and the force chains formed as a result are on the right side.

With the increase in stress, the viscosity of the fluid radically increases, and this changes the behavior of the particles. It is not only the viscosity that increases, according to Morris. He says, "The particles want to expand and get more space."

'A key ingredient of the DST model is the force chain concept derived from the granular literature. Structural transmission of forces moves from particle to particle in a manner that looks like a series of chains.'

Eventually, the particles transmit the stress not just in one direction but in all directions. Denn says, "The force developed on the particles is relieved by having chains form in three dimensions, leading to the formation of a dense network." This three-dimensional network is seen in the right side of the right image shown in Figure 2.

Another way to look at DST is by understanding the concept of shear induced jamming. Morris says, "The transition to DST is very similar to a shear jammed state in which shearing a system causes a transition to a solid that becomes so robust that it will stop fluid flow. This effect is seen in such applications as powder-injection molding where the material being forced into a mold can seize up and not move."

Future work will focus on determining the detailed structure for the three-dimensional chains and figure out how they transmit stress. Additional information can be found in a recent article[2] or by contacting Morris at **morris@ccny.cuny.edu**.

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Studying butterfly wings to reduce drag

Butterfly wings exhibit superhydrophobic and self-cleaning properties that might be applicable in real-world applications.

IN THE EFFORT TO IMPROVE THE EFFICIENCY of machinery and to look for factors causing lubrication problems, researchers have looked at Mother Nature for guidance. There are examples in nature where organisms have developed ways to reduce friction and wear to survive in their environments.

One example was provided in a previous TLT article that described how mollusks can produce adhesive gels that enables them to adhere to moist surfaces to such an extent that the amount of force need to remove them is 200 kilopascals.[1] Key components instrumental in the performance of these adhesives are the metals iron, zinc and calcium, which are present in trace quantities.

STLE-fellow and Life-member Bharat Bhushan, Ohio Eminent Scholar and Winbigler Professor of Mechanical and Aerospace Engineering at The Ohio State University in Columbus, Ohio, discusses the properties of the lotus leaf. He says, "The Lotus Effect is attributed to this leaf displaying superhydrophobic properties that enables it to be water repellent and also exhibit the additional benefit of self-cleaning. The latter characteristic is realized due to the ability of water droplets to roll off the leaf, leading to the removal of contaminants that are mainly compatible with water."

'Butterflies are fragile and must have a mechanism in place to repel water and other contaminants in order to maintain their ability to fly.'

Superhydrophobic coatings are also desirable because they can reduce the amount of drag seen in fluid flow, leading to greater efficiency. Two approaches used to develop this effect are to apply a coating to a substrate or to include roughness in the surface structure.

The shark provides an interesting example of a low drag surface through its use of riblets on its skin that reduces frictional drag as the fish moves through the water. Bhushan says, "The shark needs to move through turbulent water at a fast pace to track down its prey. The riblets on the skin lift and pin vortices that can develop in the water, which reduces cross-stream fluid motion and reduces energy loss."

The key for achieving the Lotus Effect is the use of rough, hierarchy structure combined with the presence of a waxy coating on the surface to enhance the superhydrophobic effect, and the key to the shark skin effect is to provide anisotropic riblets to reduce drag. Bharat says, "Several years ago, we came across a new species that seemed to exhibit many of the properties of lotus leaf and shark skin, enabling it to thrive in its environment. We decided to spend time studying this species to see what properties it exhibited that might be applicable for replication in real-world applications. The species is the butterfly."

GIANT BLUE MORPHO BUTTERFLY

Bhushan and his associate, Gregory Bixler, determined that on the nanoscale, butterfly wings exhibit the key combination of superhydophobicity and self-cleaning. Bhushan says, "Butterfly wings are covered with hierarchical scales that exhibit these important properties. They are needed because butterflies are fragile and must have a mechanism in place to repel water and other contaminants in order to maintain their ability to fly."

The researchers chose to study the wings from the butterfly species *Blue Morpho didius*. Bhushan says, "We selected this species because it is a relatively large butterfly with wings that are approximately three-inches long." Figure 3 shows images of the *Blue Morpho didius*.

KEY CONCEPTS

- There are several examples of Mother Nature's work that show species have developed ways to reduce friction and wear in their environments.
- One strategy used is to develop superhydrophobic coatings that can reduce the amount of drag seen in fluid flow and also are self-cleaning.
- Butterfly wings display hierarchical scales that display these superhydrophobic properties.

Replicas of the butterfly wing were produced through the use of a two-step soft lithography molding procedure. Bhushan says, "We started by using a polymer such as dental cement in preparing a negative mold. Then polydimethylsiloxane is applied and cured on the first polymer to produce a precise positive replica. A fluorinated coating is used to separate the positive copy from the mold."

The resulting replicas were characterized using scanning electron microscopy and digital camera images. Oil drag was measured by evaluating the pressure drop determined as white oil is pumped through the replicas. Measurements were taken under low-velocity and high-velocity conditions.

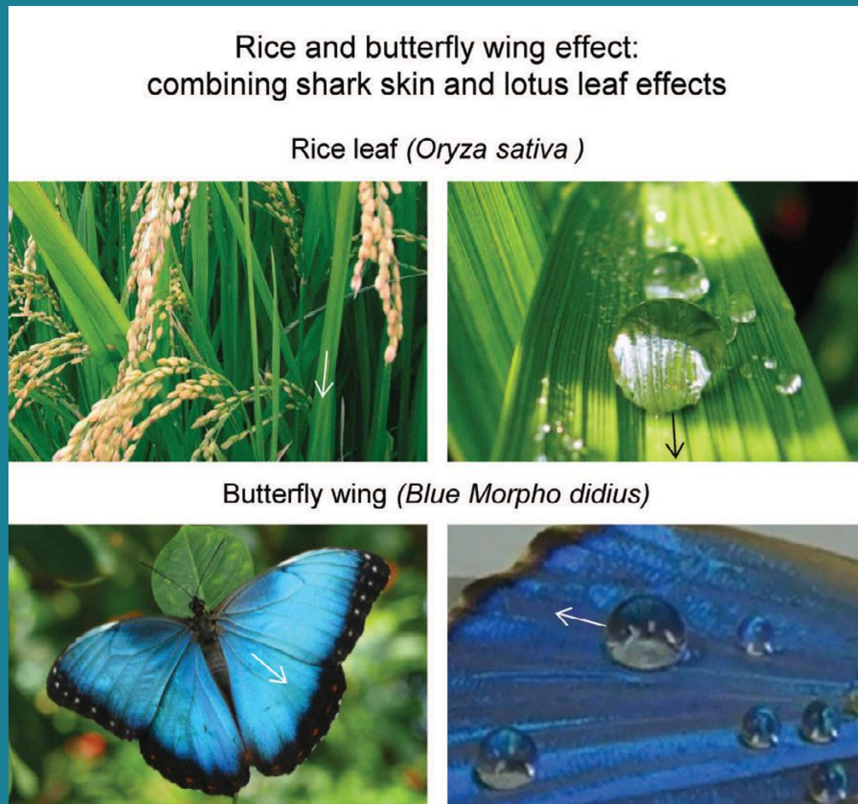

Figure 3 | **The wings of the butterfly species, *Blue Morpho didius* display superhydropobic properties, leading to reduced drag and improved efficiency.** *(Courtesy of The Ohio State University)*

> *'We found that the replicas displayed better performance under high-velocity conditions. This is anticipated because fluid flow under high-velocity conditions can be turbulent, leading to the formation of vortices.'*

Bhushan says, "We found that the replicas displayed better performance under high-velocity conditions. This is anticipated because fluid flow under high velocity conditions can be turbulent, leading to the formation of vortices. Drag reduction is seen at high-velocity due to the formation of a thin oil film on the microstructure surface of the replica." The researchers determined that the butterfly wing replica displayed a drag reduction of 6 percent.

To determine the superhydrophobicity, apparent contact angles were determined on the butterfly wings and their replicas. Differences were seen between butterfly wings and their replicas. Bhushan explains, "The reason is due to the presence of a hydrophobic wax on the butterfly wing creating the conditions for a high contact angle when exposed to water. In contrast, the untreated replicas are not nearly as hydrophobic and have much lower contact angles. This can be adjusted by applying a hydrophobic coating contacting the replicas."

Bhushan believes that the structural information obtained on the butterfly wings can be applied to real-world applications. He says, "There is potential for reducing drag in many applications including moving blood through a nano-channel, pumping crude oil through a pipeline, reducing drag on the surface of an airplane wing and improving the efficiency in which a ship's hull moves through water.

Further information can be found in a recent publication[2] or by contacting Bhushan at **bhushan.2@osu.edu.** TLT

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