Watching fluid flow at nanometer scales: Researchers find that tiny nanowires can lift liquids as effectively as tubes

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Imagine if you could drink a glass of water just by inserting a solid wire into it and sucking on it as though it were a soda straw. It turns out that if you were tiny enough, that method would work just fine—and wouldn't even require the suction to start.

New research carried out at MIT and elsewhere has demonstrated for the first time that when inserted into a pool of liquid, nanowires—wires that are only hundreds of nanometers (billionths of a meter) across—naturally draw the liquid upward in a thin film that coats the surface of the wire. The finding could have applications in microfluidic devices, biomedical research and inkjet printers.

The phenomenon had been predicted by theorists, but never observed because the process is too small to be seen by optical microscopes; electron microscopes need to operate in a vacuum, which would cause most liquids to evaporate almost instantly. To overcome this, the MIT team used an ionic liquid called DMPI-TFSI, which remains stable even in a powerful vacuum. Though the observations used this specific liquid, the results are believed to apply to most liquids, including water.

The results are published in the journal *Nature Nanotechnology* by a team of researchers led by Ju Li, an MIT professor of nuclear science and engineering and materials science and engineering, along with researchers at Sandia National Laboratories in New Mexico, the

University of Pennsylvania, the University of Pittsburgh, and Zhejiang University in China.

While Li says this research intended to explore the basic science of liquid-solid interactions, it could lead to applications in inkjet printing, or for making a lab on a chip. "We're really looking at fluid flow at an unprecedented small length scale," Li says—so unexpected new phenomena could emerge as the research continues.

At molecular scale, Li says, "the liquid tries to cover the solid surface, and it gets sucked up by capillary action." At the smallest scales, when the liquid forms a film less than 10 nanometers thick, it moves as a smooth layer (called a "precursor film"); as the film gets thicker, an instability (called a Rayleigh instability) sets in, causing droplets to form, but the droplets remain connected via the precursor film. In some cases, these droplets continue to move up the nanowire, while in other cases the droplets appear stationary even as the liquid within them flows upward.

The difference between the smooth precursor film and the beads, Li says, is that in the thinner film, each molecule of liquid is close enough to directly interact, through quantum-mechanical effects, with the molecules of the solid buried beneath it; this force suppresses the Rayleigh instability that would otherwise cause beading. But with or without beading, the upward flow of the liquid, defying the pull of gravity, is a continuous process that could be harnessed for small-scale liquid transport.

Although this upward pull is always present with wires at this tiny scale, the effect can be further enhanced in various ways: Adding an electric voltage on the wire increases the force, as does a slight change in the profile of the wire so that it tapers toward one end. The researchers used nanowires made of different materials—silicon, zinc oxide and tin oxide, as well as two-dimensional graphene—to demonstrate that this process applies to many different materials.

Nanowires are less than one-tenth the diameter of fluidic devices now used in biological and medical research, such as micropipettes, and one-thousandth the diameter of hypodermic needles. At these small scales, the researchers found, a solid nanowire is just as effective at holding and transferring liquids as a hollow tube. This smaller scale might pave the way for new kinds of microelectromechanical systems to carry out research on materials at a molecular level.

The methodology the researchers developed allows them to study the interactions between solids and liquid flow "at almost the smallest scale you could define a fluid volume, which is 5 to 10 nanometers across," Li says. The team now plans to examine the behavior of different liquids, using a "sandwich" of transparent solid membranes to enclose a liquid, such as water, for examination in a transmission electron microscope. This will allow "more systematic studies of solid-liquid interactions," Li says—interactions that are relevant to corrosion, electrodeposition and the operation of batteries.

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