Slippery when narrow

An experimental technique has been developed to measure water flow through carbon nanotubes. Measurements reveal that flow can be almost frictionless, posing challenges for computer simulations of nanofluidics.

Carbon nanotubes are hollow cylinders formed from carbon atoms arranged in a hexagonal, graphite-like lattice and have nanometre-scale diameters. It has been suggested that water transport through carbon nanotubes is almost frictionless, and that the flow exceeds predictions made using classical theories by many orders of magnitude (see refs 1–3, for example). However, because of challenges in performing reliable measurements and computer simulations, and because of huge differences in the reported results, claims of rapid water transport have at times been met with scepticism (see, for example, ref. 4). On page XXX, Secchi et al.5 help to resolve this issue by reporting unambiguous measurements of water flow through individual carbon nanotubes. The unprecedented sensitivity of their measurements reveals a strong dependence of water friction on the radius of the carbon nanotube: the narrower the tube, the less friction there is.

Why is water flow through carbon nanotubes of interest? One reason is that increasingly severe shortages of clean water are on the horizon, and so better water-purification and desalination technology is needed. Carbon nanotubes have generated excitement because measurements and computer simulations6 have revealed that water can travel much more rapidly through these tiniest of pipes than salt ions can, for example. Carbon nanotubes might therefore enable higher-performance filters that are more cost effective than the conventional carbon-based filters currently ubiquitous in water-purification devices.
To explore water flow through nanotubes, the authors built nanoscale devices in which two reservoirs of water were separated by a water-tight membrane pierced by an individual nanotube. By raising the pressure on one reservoir, water flows through the nanotube to the other. The flow is incredibly small: about a femtolitre (10–15 litres) per second. To put this in perspective, 1 fl is less than the amount of water in a single human red blood cell. Given the minuscule amounts of water involved, Secchi and colleagues could not track the motion of water itself. Instead, they built on previously reported work7 by monitoring how the jets of water emerging from the nanotube displaced polystyrene nano-particles suspended in the low-pressure water reservoir (Fig. 1). Ignoring the differences in relative size, this is like counting the number of children sliding into a ball pit by watching the motion of the balls. The polystyrene nanoparticles were large enough to be seen with an optical microscope, and, by tracking their motion, ultra-sensitive measurements of water flow through the tubes were possible. This sensitivity is the key methodological advance of the study.

Using this technique, the authors measured flow through carbon nanotubes that have different radii, and through nanotubes built from boron nitride —a technologically promising material that forms nanotubes with a similar atomic structure to that of carbon nanotubes. The key metric commonly used to evaluate flow across surfaces and in confinement is known as slip length (see ref. 8, for example). Essentially, the larger the slip length, the more slippery the surface and the less friction is exerted on a fluid flowing across it. Slip lengths have been measured previously for water flow through aligned arrays of carbon nanotubes of different radius, but the values obtained differed by several orders of magnitude4.

Secchi and co-workers' measurements of flow through individual nanotubes help to reconcile some of the previous measurements by revealing a strong dependence of slip length on nanotube radius. In addition, the measurements confirm that carbon surfaces are indeed unusually slippery, allowing almost friction- less flow through the tubes with the smallest radius (approximately 15 nanometres) in the study. The authors also observed that boron nitride nanotubes are rather sticky compared with carbon nanotubes — for the range of radii considered (about 10 to 30 nm), water does not flow anywhere near as freely through boron nitride nanotubes, and is almost at the detection limits of the experimental set-up.

By providing a deeper understanding of well-defined aqueous interfaces, these measurements might aid the design of improved membranes and nanofluidic devices. The results also pose opportunities and challenges for computer simulations of fluid motion. For example, the quantitative measurements of slip length can serve as a benchmark against which computer simulations can be verified. This is important, because understanding how well computers simulate interfacial water is relevant not just to potential applications such as membranes and water desalination, but also to fields such as the atmospheric sciences, energy, and catalysis.

But an explanation is needed for the relative stickiness of nanotubes made of boron nitride nanotubes compared with carbon. Only modest disparities in the behaviour of water at these two materials are expected on the basis of their similar structures and from previous simulation studies9, including reference-quality quantum-mechanical simulations10,11. The huge differences observed by Secchi et al. imply that factors such as water dissociation (the break-up of water molecules into their constituent parts), ion adsorption to the nanotubes, nanotube defects and defect- induced chemistry, or gating effects at the ends of the nanotubes might have a role in deter- mining water flow. Resolving which factors are involved will require further experiments and high-quality quantum-mechanical simulations.

To extend this work for desalination applications, it will be essential to understand the connection between water flow and (salt) ion motion. More broadly, the authors' experimental approach could readily be applied to nanofluidics in general, by examining the flow of different liquids through different materials. If the sensitivity of the technique can be improved, then studies of water flow through the pores in biological membranes — including the most efficient water filter of all, the aquaporin protein — should also be within reach.

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