Fluid dynamics researchers shed light on how partially submerged objects experience drag

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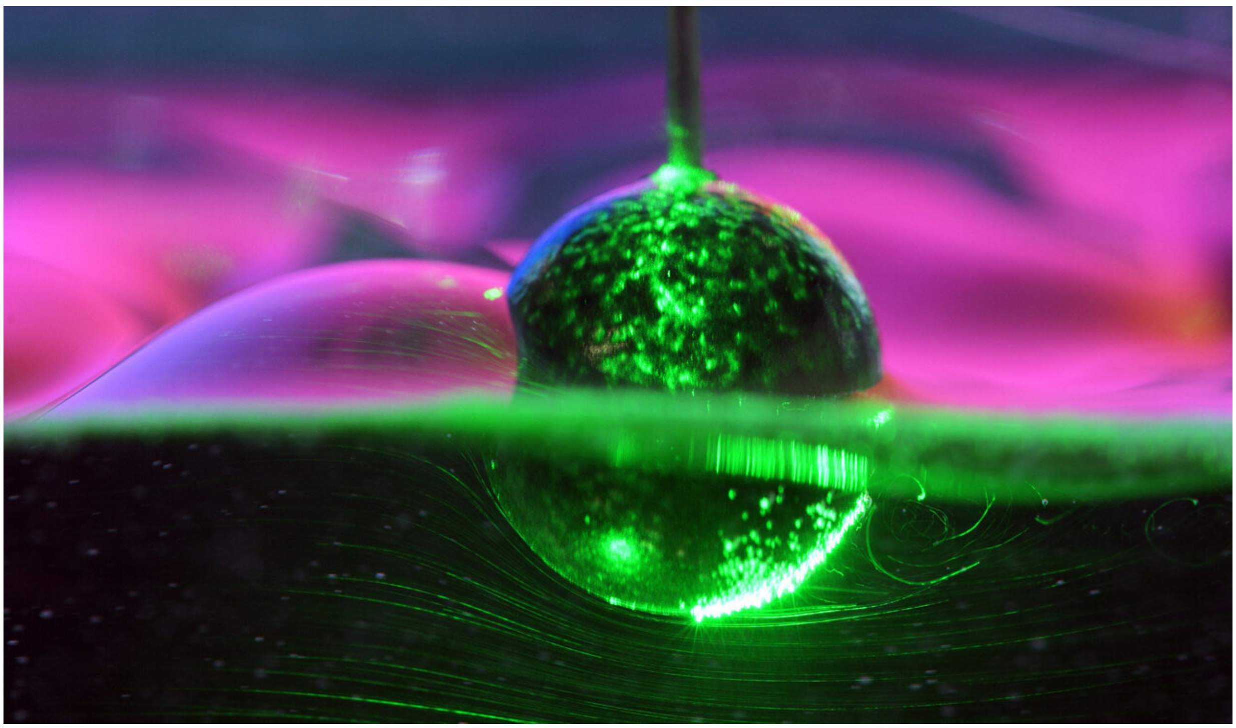

In new study, Brown researchers describe how drag on a partially submerged object may be several times greater than drag on a fully submerged object. Image courtesy of the Harris Lab. Credit: Harris Lab.

One of the most common and practically useful experiments in all of fluid dynamics involves holding an object in air or submerging it fully underwater, exposing it to a steady flow to measure its resistance in the form of drag. Studies on drag resistance have led to technological advances in airplane and vehicle design and even advanced our understanding of environmental processes.

That's much tougher these days. As one of the most thoroughly studied aspects in fluid dynamics, it's become hard to glean or detail new information on the simple physics of drag resistance from these classic experiments. But a team of engineers led by Brown University scientists managed to do so by bringing this problem to the surface—the water surface, that is.

Described in an new paper in *Physical Review Fluids*, the researchers created a small river-like channel in the lab and lowered spheres—made of different water repellent materials—into the stream until they were almost fully submerged by the flowing water.

The results from the experiment illustrate the fundamental—and sometimes counterintuitive—mechanics of how drag on a partially submerged object may be several times greater than drag on a fully submerged object made of the same material.

For instance, the researchers—led by Brown engineers Robert Hunt and Daniel Harris—found that drag on the spheres increased the moment they touched the water, no matter how water repellent the sphere material was. Each time, the drag increased substantially more than what was expected and continued to increase as the spheres were lowered, beginning only to drop when the spheres were fully beneath the water.

"There's this intermediate period where the spheres going into the water are creating the biggest disturbances so that the drag is much stronger than if it were way below the surface," said Harris, an assistant professor in Brown's School of Engineering. "We knew the drag would go up as the spheres were lowered because they are blocking more of the steady flow, but the surprising thing was how much it goes up. Then as you keep pushing the sphere deeper, the drag goes back down."

The study shows drag forces on partially submerged objects can be three or four times greater than on fully submerged objects. The largest drag forces, for instance, were measured just prior to the sphere becoming fully submerged, meaning water is flowing all around it but there's still a small dry spot sticking out at the surface.

"You might expect how much of the sphere is in the water to correspond with how big the drag is," said Hunt, a postdoctoral researcher in Harris' lab and the study's first author. "If so, then you might naively approximate the drag by saying that if the sphere is almost 100% in the water, the drag is going to be almost the same as if it was fully immersed beneath the surface. What we found is the drag can actually can be much larger than that—and not like 50% but more like 300% or 400%."

The researchers also found that the sphere's level of water repellency plays a key role in the drag forces it experiences. This is where things get a bit counterintuitive.

The experiment was done with three spheres that are otherwise identical except one was coated with a superhydrophobic material, making it very repellent to water, while the others were made of materials that are increasingly less water repellent.

Running the experiments, the researchers found that the superhydrophobic coating encountered more drag than the other two spheres. It was a surprise because they expected the opposite.

"Superhydrophobic materials are often proposed to reduce drag, but, in our case, we found that superhydrophobic spheres when almost fully immersed have a much larger drag than the sphere made of any other water repellency," Hunt said. "In trying to decrease the drag, you might actually increase it substantially."

The paper explains simple physics is the likely cause.

"The water wants nothing to do with this superhydrophobic sphere so it does anything that it can to, sort of, get out of the way of the sphere," Harris said. "But what happens is much of it piles up in front of it, so there ends up being a wall of water that the sphere is hitting. Intuitively, you would think the water should slip by more freely. Physics actually conspires against that in this scenario."

The findings from the paper may one day hold implications for designs and structures that operate at an air and water interface, like small autonomous vehicles. For now, the standalone physics of this basic research is interesting enough as studies on partially submerged objects aren't as currently well characterized or understood in the field.

"We were surprised no one had made these measurements," Harris said. "It's such a simple idea but there's just a lot of rich physics here."

The researchers chose spheres as the first three-dimensional objects because of how simple their geometry is. They only have one length scale—the radius. The sphere acts as a starting point to be able to strip the physical mechanics down to its most fundamental principles before moving on to more complicated shapes.

"Starting from the simplest point, we look at what are the physics here and then as a next step we begin to apply our knowledge to more realistic structures, whether it's emulating a biological structure or looking at manmade propulsive structures," Harris said.

Hunt and fellow lab member Eli Silver designed the flume apparatus for creating the water stream experiment and programmed the motorized lift that lowers the spheres into the water channel. The work started as a collaboration with Yuri Bazilevs, a professor at Brown's School of Engineering. It also included researchers from the University of Illinois Urbana-Champagne, who performed computer simulations.

More information: Robert Hunt et al, Drag on a partially immersed sphere at the capillary scale, *Physical Review Fluids* (2023). DOI: 10.1103/PhysRevFluids.8.084003

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