The cradle of fluid dynamics

Burgers' lab, as the Laboratory for Aero and Hydrodynamics is affectionately known, recently celebrated its ninetieth birthday. To mark this special occasion, we take a look at some of current research projects, from studying droplets to tickling turbulence.

Tomas van Dijk

If you're stuck in traffic and it's pouring rain outside, take a good look at the water on your windshield before the wiper blade sweeps it away. Those zigzagging tracks down the glass have been puzzling fluid mechanics engineers for decades. According to the accepted laws of fluid mechanics, droplets should not be able to stream down a sheet of glass.

This so-called contact line paradox fascinates Professor Dr Jerry Westerweel, section head at TU Delft's Laboratory for Aero and Hydrodynamics. "The paradox states that drops of water are unable to roll across a smooth surface because the water molecules move faster as they approach the front of the droplet, which results in infinitely greater friction," the fluid dynamics expert explains.

A team of Westerweel's researchers is now focusing on droplets. By investigating at a micro level what occurs inside a droplet, they hope to unravel one of the great mysteries of fluid dynamics. But there is more to it than that. The research also has a real-world application; it is intended to help manufacturers of microchip-making machines speed up their machines.

The droplet example is typical of the research conducted at the laboratory. From studying drops of water and tickling turbulence, to investigating blood flows in chicken embryos, it is a place where fundamental and applied research always go hand in hand.

"It's always been like that," says Westerweel, who believes this is the reason for the success of the laboratory, which was founded in 1918 by fluid dynamics researcher Johannes Martinus Burgers and has since become the cradle of fluid dynamics in the Netherlands.

Westerweel says a major factor contributing to the lab's success is the fact that the lab conducts research on turbulence and complex flows in many different ways, such as, for example, through experimentation, by using modern laser technology, and by means of simulations on large supercomputers. Westerweel supervises the experimental research, while the Dr Bendiks-Jan Boersma leads the simulation-based research.

Over the next few years Westerweel intends to join forces with other fluid dynamics groups within TU Delft that are also investigating flows. "Together with those groups I'd like to set up a single, large laboratory that can be used for large-scale experiments and where we can share our expertise. All together we would probably form the largest fluid dynamics laboratory in Europe."

The droplet paradox

Amid loud sputtering noises caused by trapped bubbles of air, a droplet appears on a rotating glass disc. Caught in a laser, the droplet lights up reddish-orange, as a result of a myriad of fluorescent micrometre-sized globules contained by the water.

The test setup used by two PhD students, Hyoungsoo Kim and Mark Franken, and looks a lot like a microchip-making machine. They received it a few months ago from the microchip-manufacturer, ASML. The machine consists of a rotating glass disc (which replaces what would normally be the chip wafer), a lithography head, a pump that deposits a minute droplet on the glass, a laser beam device, and four cameras that record images of the droplet from below.

ASML wants to gain a better understanding of what happens at a micro level inside moving droplets. The company needs this knowledge to improve their latest generation of microchip machines.

> *ASML wants to gain a better understanding of what happens at a micro level inside moving droplets.*

Franken and Kim are helping the company in a research effort aimed speeding up the microchip manufacturing process by reducing the number of rejected microchips. Inside the machine, which uses so-called immersion technology, a water droplet is sandwiched between the wafer and the lithography head's lens. Because water does not refract in the same way as air, the beam of light is refracted in a different way. As a result, the immersion lens machines are capable of creating smaller lithography ▸▸

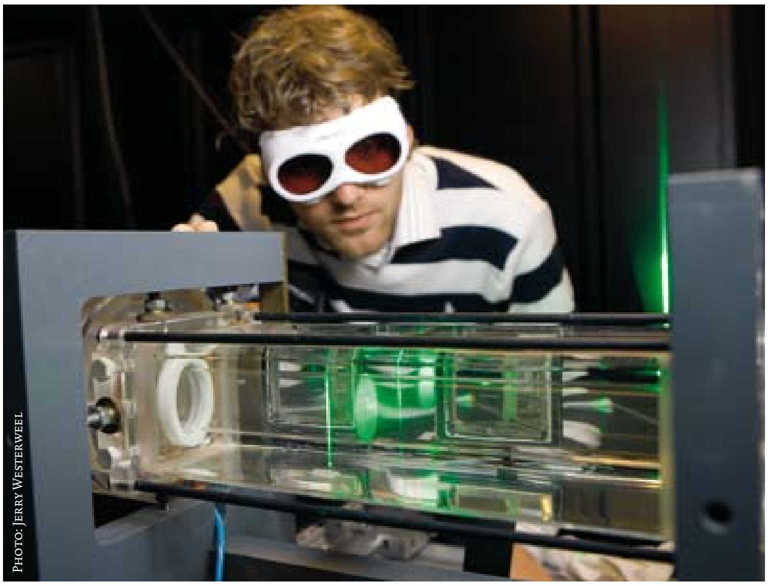

Photo: Jerry Westerweel

Dirk Jan Kuik films how turbulence decays at the halfway point in a 24-metre long tube.

structures, down to as little as 38 nanometres. A few years ago, ASML had to be content with a minimum size of 60 to 65 nanometres.

The drawback of the new technology is that the droplet slows down the lithography process if the wafer is moved too fast as it passes under the lens. "The maximum speed of the wafer during the lithography process is currently half a metre per second," Franken says. "Any faster and the droplet becomes unstable. This could result in air bubbles getting trapped in the water, and possibly even leaving a trail of much smaller droplets behind on the wafer, which is known as pearling. In either case, the lithography results in a malformed microchip."

ASML is now trying to find out whether the droplet will stay in position longer if it is blown upon, if the lithography exerts a little suction on it, or if the wafer is made smoother using special coatings.

Finding the optimum settings for these interventions requires insight into what exactly goes on inside the droplet at the precise moment when things start to go wrong. Franken and Kim are investigating the matter using Particle Image Velocimetry (PIV), a technique in which minute fluorescent plastic globules visualise the flows in liquids. "ASML would like the lithography speed increased to one metre per second," Franken says, as he gradually increases the rotation speed of the glass disc. "It would make their equipment more than twice as fast."

Westerweel hopes the doctoral research project will eventually provide insight into the contact line paradox. "It's one of his hobbyhorses," Franken says, laughing. "Who knows, it might just result in new insights, but it's still very application-driven."

Tickling turbulence

Running right across the Laboratory for Aero and Hydrodynamics is a 24-metre long tube with a diameter of four centimetres, enclosed in a thick layer of insulating material. Halfway down the tube is a pair of cameras, which are to record what has never been recorded before: a decaying packet of turbulence. The ultimate purpose of this experiment conducted by PhD student Dirk Jan Kuik is even more remarkable, as he intends to 'tickle turbulence'.

"On one end of this tube I inject a little extra water to induce turbulence at regular intervals," he explains. "These turbulence packets decay to nothing at various points along the tube. If we understand how that happens, we might just be able to 'tickle' turbulence in such a way that it speeds up the decay, for example by injecting a little extra water into the turbulence, or by vibrating the tube."

That would make the oil industry very happy. Pumping turbulent oil through pipelines consumes a great deal of energy. "Oil companies in Alaska add polymers to the oil to increase its liquidity and thus reduce the flow resistance," Westerweel explains, "but it would be much better if we could simply eradicate the turbulence." Kuik nods in agreement. "But eradicating turbulence is still far off in the future," he adds.

Kuik's research builds on a spectacular discovery Westerweel and his colleagues made and was published in NATURE in 2006, when they demonstrated that eventually turbulence always decays to zero, regardless of how fast a liquid flows. The problem however is that it can take a very long time to stabilise. For example, it would take 10 to the power of 3000 (i.e. 1 followed by three thousand zeroes) years for the water in the mains network of a medium-sized city to stabilise..

Even so, the conclusion that eventually all flows must stabilise was completely at odds with what fluid dynamics had predicted until then. According to Westerweel, this means that theoretically it should be possible to cause turbulence to decay at an increased rate.

Of course, Westerweel and his colleagues didn't conduct their experiment on a city water mains system; instead, they allowed water to flow through a thin, 30-metre long copper tube. It was a bit like a significantly scaled-down version of a water mains system, but with a much lower Reynolds number – a key number in fluid dynamics – to somewhat speed up the stabilising process. Prior to this discovery, the theory was that whenever the Reynolds number of a flow exceeded a certain critical value, as was the case in the experiment, the turbulence would never decay to zero. The researchers injected a little extra water at regular intervals to create turbulence in the flow. At the other end of the tube, the water occasionally stabilised.

For the first time, blood flows were filmed inside a living embryo

Even in Kuik's setup the turbulence decayed to zero. "We measure this by means of the pressure gauges attached to the tube at two-metre intervals," the PhD student explains. What are the chances of a pocket of turbulence decaying exactly at the spot where his cameras are recording the events? Kuik doesn't know. "I haven't done those calculations yet," he says, "but I'm assuming that I'll be able to record the event before I conclude my doctoral research."

"What you see on the recordings looks like a starry sky," Kuik says. "Minute hollow spheres in the water light up when they are picked out by a laser beam."

The recording sessions each last twenty seconds, or about as long as it takes a turbulence pocket to decay to zero. The cameras record a thousand images per second. A special computer program reconstructs the velocity fields in the water by tracking each individual polyester globule.

"Each image takes up one megabyte," Kuik says, "so twenty seconds of recording requires quite a lot of computer memory. A computer analysis of one sequence takes several days, so we only transfer the data to the computer if we think we have actually recorded a decaying turbulence pocket. The pressure gauges will show us. Who knows, we might get a good result. It's a pity about all the building work going on nearby, though. The vibrations interfere with our tests."

Using a plastic coffee stirrer, Ruitao Yang carefully prods a few lugworms lying in a plastic container. "I'm trying to find the most cooperative of the lot," the guest researcher from Bath University in the England says, laughing.

At Bath University, Yang worked on amphibian robots that crawl and swim. He draws his inspiration from what he observes in the animal kingdom. At TU Delft, the researcher is temporarily working on an EU project that aims to develop pumps for 'labs-on-a-chip', minute microchip-mounted laboratories that can perform chemical analyses.

"All the current-generation pumps work at high Reynolds numbers only," Yang says. "Inside a lab-on-a-chip, the Reynolds numbers are very low, so the pumps don't work. By studying this worm I hope to discover a method which will work at microscale."

"Aha!" Yang suddenly exclaims, "Here's a worm that moves a lot." He takes the lugworm and places it on a tray with a thin layer of water. A camera mounted over the tray records the flows that occur all around the worm as it starts to wriggle with the whole length of its body and paddle with its many leg-like parapodia.

"You can see where the strongest flows occur near the parapodia," Yang says. He then laughs, adding: "It's a brilliant motion. For a pump at least, not for swimming."

Chicken embryo

Over the past few years, Dr Christian Poelma and his colleague, Dr Peter Vennemann, peeled hundreds of eggs, preparing them for filming the blood flow inside the embryos.

Together with development biologists from Leiden University, Poelma is trying to determine what effect the flow of blood has on the development of blood vessels.

"One of the processes we're interested in is the development of the heart," Poelma says. "The heart is formed by a blood vessel folding back on itself and then becoming constricted. Biologists think that the forces exerted by the blood flow against the vessel's walls activates genes inside the endothelium cells that form the lining of the blood vessels. This biomechanical stimulus would cause the blood vessel to transform itself into a heart. To prove this concept, we need a clear image of the forces acting on the walls of the blood vessel."

Poelma, together with Vennemann, who last year received his doctorate with honours and now works elsewhere, used an optical flow measuring method called Particle Image Velocimetry, which uses minute globules that light up when they are hit by green laser light. Because the globules had been given a special coating, the body's immune system failed to recognise them as foreign bodies and did not reject them. Their research gave them a first: never before had blood flows been filmed inside a living embryo.

"By focusing the camera on different depths of the blood vessel, and then superimposing the various images, we can create a 3-D reconstruction of the blood flow," says Poelma, who is still busy processing the data.

Poelma also collaborates with researchers at Rotterdam's Erasmus Medical Centre in research on capillaries. He would like to know how capillaries change into larger blood vessels. "If you constrict a blood vessel, the surrounding capillaries create a new blood vessel," Poelma says. "They create a kind of bypass."

To some of the embryos, Poelma has added a hormone, homocysteine, which occurs naturally in the human body. Elevated or reduced levels of this hormone can result in congenital defects in the cardiovascular system. Poelma intends to find out how this process works. The research is a massive undertaking. "Ideally, we want to film a thousand embryos," he says. "Only then would we be able to use the results for statistical analysis."

Microscopic globules in the blood of a chicken embryo become fluorescent and visible in the blood stream when Dr Christian Poelma shines a green laser beam on a peeled egg.