Fighting Turbulence **with Eddies**

Turbulence is omnipresent: it plays an important role during planet formation, mixes fuel and air in the cylinder of an engine, but also increases the energy needed for pumps to push oil through pipelines. **Björn Hof** and his team at the **Max Planck Institute for Dynamics and Self-Organization** in Göttingen investigate the finer points of how it originates and search for tricks to prevent the eddies from forming where they interfere.

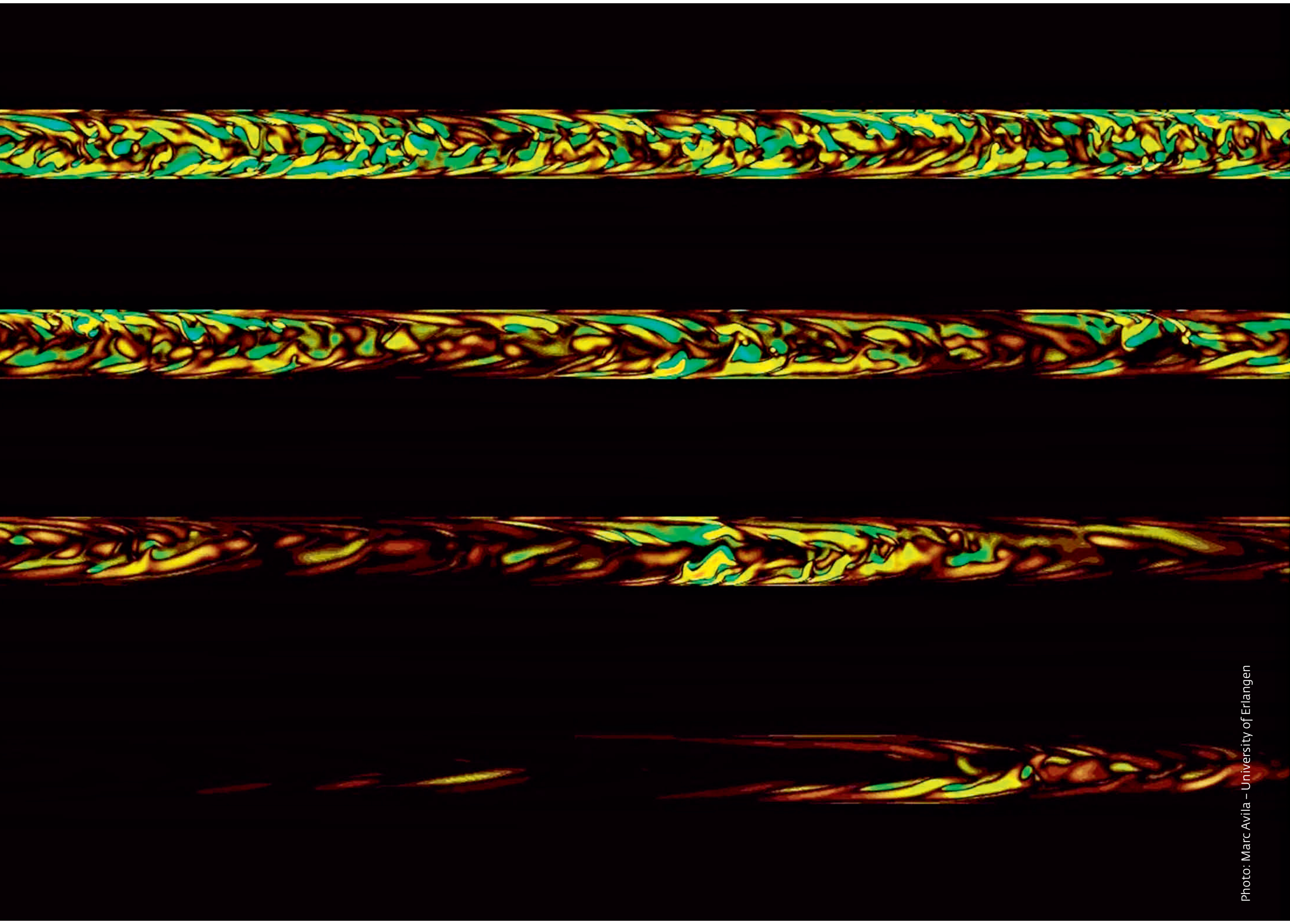


Photo: Marc Avila – University of Erlangen

TEXT **ROLAND WENGENMAYR**

Duo Xu stands in front of a glass tube six meters long but just one centimeter wide. It stands in a lab surrounded by technical equipment. The young Chinese scientist is a postdoc in Björn Hof's research group at the Max Planck Institute for Dynamics and Self-Organization in Göttingen. He starts the measurement program on the control computer. At the end of the tube, a long metal arm starts to move, and the piston sets the long column of water in the tube in motion. "We want to find out how turbulence forms," says Duo Xu: "And this is where we investigate how pulsation affects the flow of blood." The heartbeat forces the blood through the circulatory system in pulses. To imitate this, the pumping metal lever draws the water through the glass tube – sometimes faster and sometimes slower.

At the front of the glass tube, a thin hose is attached to the side. It leads to a rather makeshift-looking water bucket suspended from the ceiling. At the beginning of every stroke, the control computer allows a tiny surge of water to enter the tube through a valve on the hose, shooting into the pipe flow from the side. This causes a small, swirling disturbance in the water column. It now migrates a few meters along the flow until it is in front of a camera. Tiny platelets in the water light up in the laser light, making the eddies easily visible even to the naked eye. Xu explains that the computer analyzes this flow pattern and determines when turbulence forms.

A UNIVERSAL AND FUNDAMENTAL PHENOMENON

In our blood vessels, the steady blood flow also switches time and again to turbulent motion. It occurs particularly in the large blood vessels, such as the aorta, where it can cause vascular diseases. Evolution, otherwise so inventive, may have been unable to prevent these eddies in the blood stream, but it has given rise to the most familiar sound in our life: the double pulse of the heartbeat is the acoustic signature of the turbulence that is being generated at the heart valves.

In Göttingen, we learn that turbulence is both a universal and a fundamental phenomenon of our world. In the disk of dust around infant stars, it ensures that the matter can condense and clump together until a planet is born. Huge vortices also stir in the weather factory of our atmosphere. "Fluid turbulence is probably the most frequent and important example of a spatiotemporal disorder in nature," emphasizes Björn Hof.

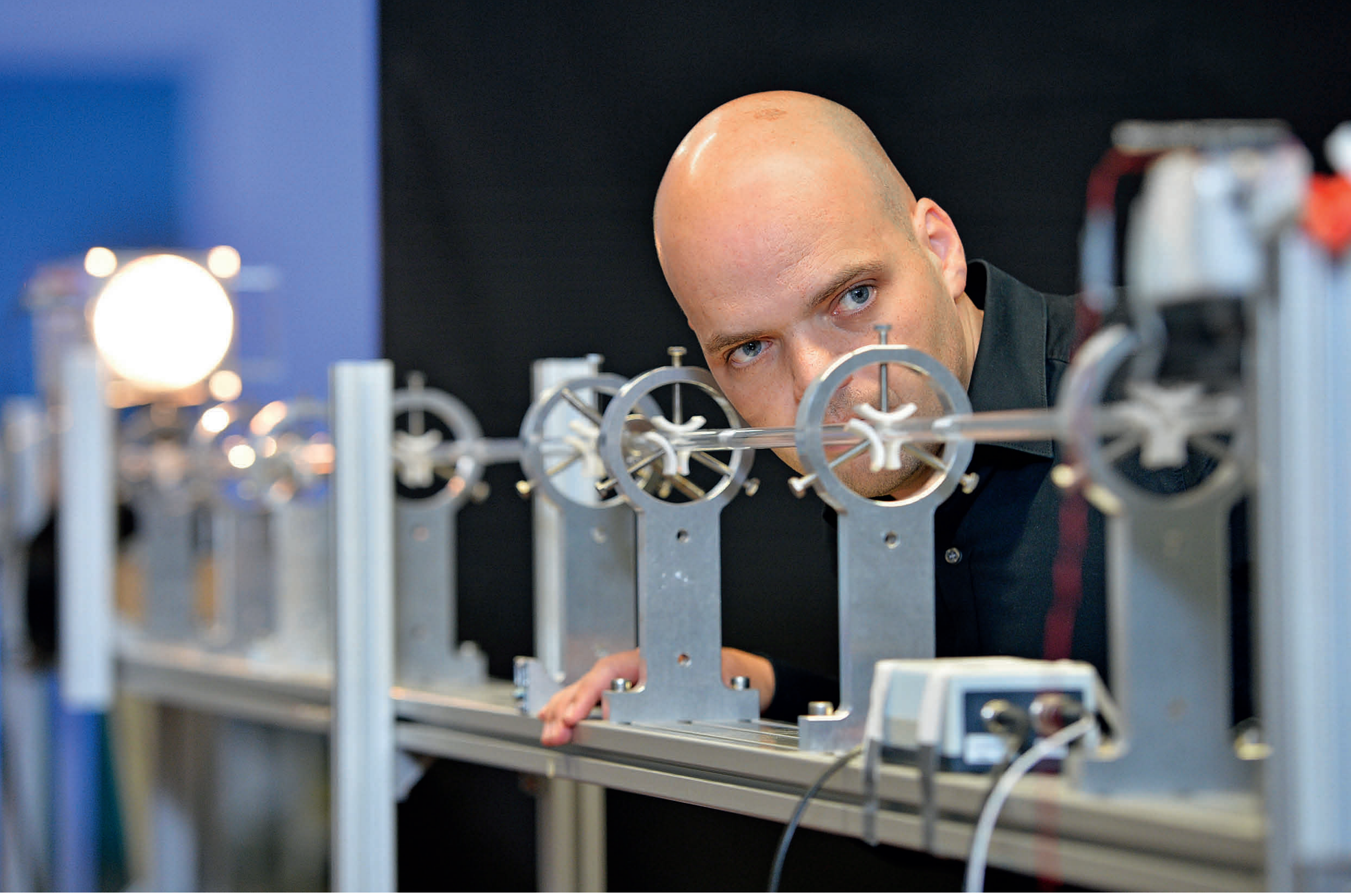
Turbulence also plays an important role in engineering. Combustion engines, for example, would be much less efficient without the thorough turbulent mixing of the injected fuel. And when we stir milk into our coffee, turbulence helps the two to mix. But often it is not quite so welcome. Air turbulence on aircraft wings or car bodies, for example, is feared because it pushes up the fuel consumption. And turbulence can significantly increase the energy consumption in pipe flows, in the huge network of gas and oil pipelines, for instance.

There they are: Tiny platelets and laser light make the water eddies in the glass tube visible.

Turbulence removes valuable kinetic energy from the flow, and the internal friction of the swirling medium converts this into useless heat. "If you pump a fluid through a pipe with constant mass flow," explains Björn Hof, "the energy needed to do this can increase by a factor of one hundred when it transitions to turbulent flow!" >

The trick with the kick: This simulation shows how the researchers are attempting to control turbulence. A fully turbulent flow can be seen in the tube at the top; the color gradients make the turbulence visible. A skillful kick makes the turbulence disappear (from top to bottom).

Photo: Frank Vinken



Eddies in his sights: Björn Hof at one of the experiments with which the Max Planck researchers investigate the formation of turbulence in pipe flows.

The question as to the exact point at which a flow suddenly switches over to turbulence has been motivating Hof for many years. He is particularly interested in fluids flowing through pipes. Experiments with long glass tubes like those in Göttingen can also be found at Hof's new research facility, the Institute of Science and Technology (IST) Austria in Klosterneuburg, near Vienna. The fluid flowing through the tubes is usually water, sometimes containing additives, and its behavior is detected by pressure sensors or, alternatively, by lasers and cameras.

With the help of this arsenal, Hof's team has been able to solve some stubborn puzzles about the transition to turbulence in recent years. This may be astonishing, considering its technical and social relevance, but what exactly happens during this transition has only recently been understood. However, the systematic research into turbulent flows in a pipe started more than a hundred years ago. In 1883, British scientist Osborne Reynolds published his pioneering work. He developed the original experiment, which Björn Hof's team has now perfected in a high-tech form. It essentially consisted of a long, horizontal tube. This was connected to a supply tank and a type of drainpipe into which gravity sucked the water like a pump.

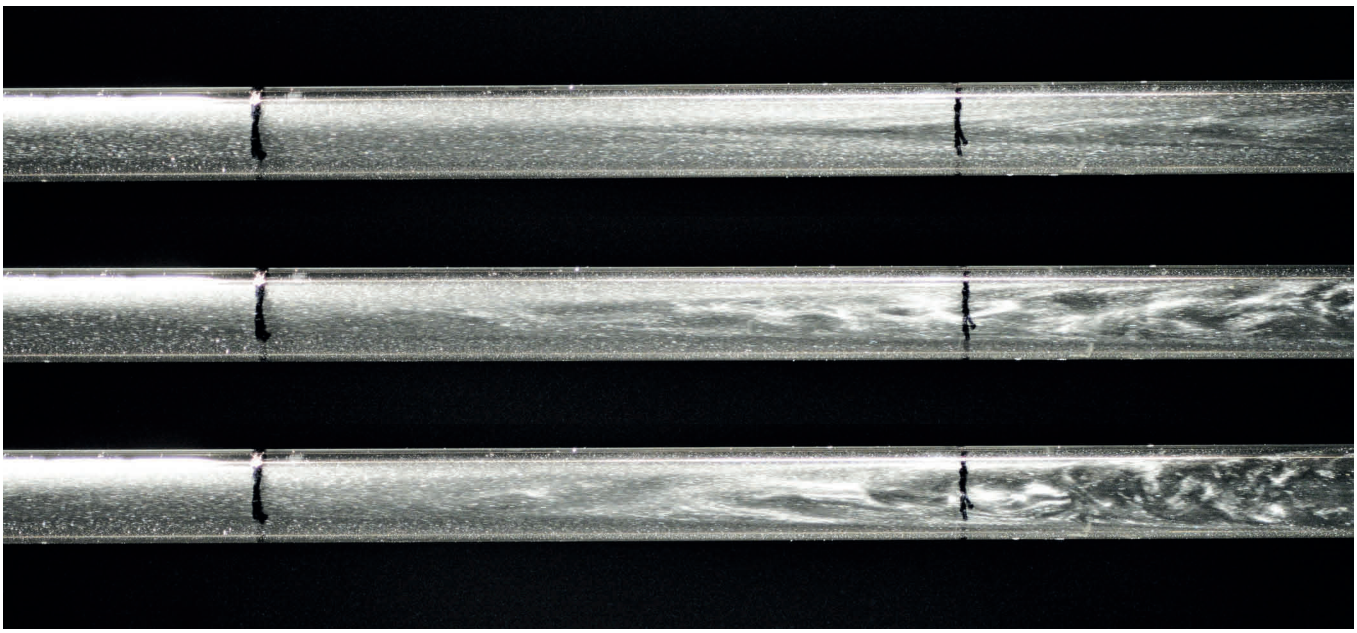
TURBULENT FLOWS CONSUME LARGE AMOUNTS OF ENERGY

The art of turbulence research consists in producing conditions that are as uniform, stable and repeatable as possible. "Since we work mainly with water, even, for example, extremely thin biofilms formed by bacteria and algae are a problem," says Hof. Osborne Reynolds himself put many years of work into the repeatability of his experiments. That was the only way he could obtain informative results about the conditions under which steady, "laminar" flows switch and become turbulent flows.

Hof's modern experiments work according to the same principle. "You inject a perturbation at the beginning of the tube and watch to see whether this small turbulence field survives the journey to the end of the tube," explains the physicist. As soon as the eddies no longer decay, the transition point to turbulence is reached. At least that is how the theory goes.

Reynolds discovered a universal character of flows that would gain enormous technical significance. In general, only three properties influence the point where turbulence can occur for the first time: the flow velocity, the diameter of the pipe and the viscosity of the fluid. That's easy to understand: the faster the fluid flows and the further away the calming and guiding pipe wall is from the center of the flow, the easier it is for eddies to form. And the more viscous a fluid, the more difficult it is for turbulence. A lot of friction in a fluid – this is precisely what high viscosity means – has a greater braking effect on the ed-

Photo: Frank Vinken



Looking into the experiment, which uses specially prepared water to simulate a pulsing blood flow. The pictures show the flow at one point at intervals of a few tenths of a second. A turbulent eddy migrates from the right into the quiet, laminar water flow.

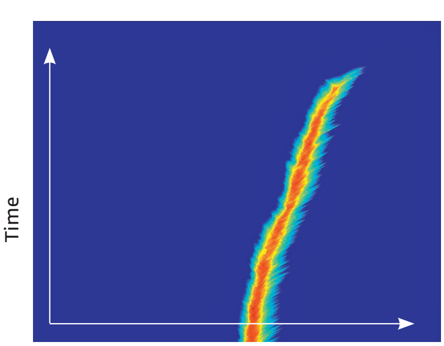
dies. When we stir milk into our coffee, the very runny water means we need much less force to generate mixing turbulence than when we mix two shades of a viscous emulsion paint.

Reynolds combined the three crucial quantities – flow velocity, pipe diameter and viscosity – in a universal number. Fluids with the same Reynolds number generally exhibit the same behavior. This hydrodynamic similarity makes it possible to carry out wind tunnel experiments using scaled-down models of cars, for example, and transfer the aerodynamic properties thus observed directly to the original size. The engineers need only ensure that the Reynolds number of the large cars at traveling speed corresponds to that of the small models in the wind tunnel. According to the same principle, the results of Hof's experiments can be transferred to pipes with much larger diameters – oil pipelines, for example.

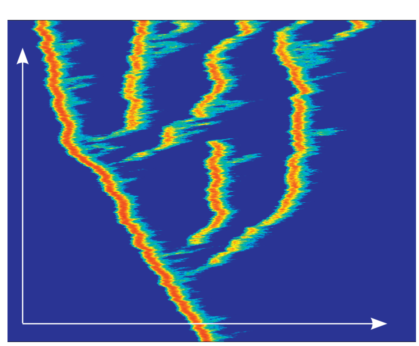
However, Reynolds also observed something very strange. In his experiments, the turbulence that set in occurred only locally at individual spots – and not always at precisely the same flow velocity. And this happened despite his doing everything to keep the conditions as stable as possible. He made sure the water temperature was constant, for example, which is also very important in Hof's experiments.

"For more than a hundred years, the local changeover between turbulent and laminar regions that Reynolds observed remained largely unexplained," says Hof. "Nor could scientists confirm his proposition of a critical velocity above which turbulence is maintained permanently." Only a few years ago, Hof's team was part of an international research cooperation that

Reynolds number: 1,800



Reynolds number: 2,300



Flow patterns: The laminar, eddy-free regions are blue. If the flowing medium has a Reynolds number of 1,800 (left), a turbulent eddy (yellow and red) disintegrates again; at 2,300, the flow is fully turbulent (right).

Photos: Frank Vinken (top), MPI for Dynamics and Self-Organization – Baofang Song

Puzzle in the pipeline: If the flow becomes turbulent in oil pipelines, the additional friction of the viscous liquid consumes up to 80 percent more pumping energy. In the 1940s, engineers accidentally found that polymers dissolved in the oil calmed the flow. Max Planck researchers have now discovered why.

demonstrated that individual turbulent eddies decay time and again. "At first sight this seems to contradict the proposition of a fixed transition point," says the physicist.

THEORETICIANS HAVE BEEN AGONIZING FOR YEARS

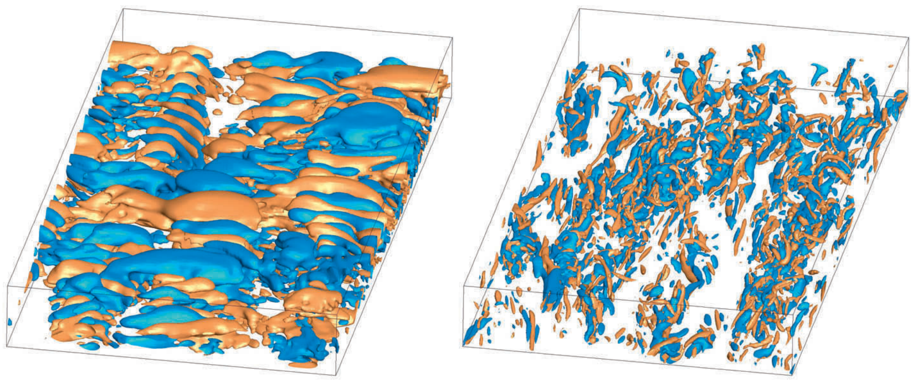
Reynolds had thus discovered an important characteristic, although the means available to him at the time meant he couldn't unravel its deeper meaning. Generations of theoretical physicists then agonized over the correct explanation of the transition to turbulence. When American Nobel laureate in Physics Richard Feynman died in 1988, he left behind a blackboard on which he had written a short list of important unsolved problems in physics. One item on the list was turbulence.

To be fair to the theoretical physicists, it must be said that physics only recently developed the mathematical toolbox required for the solution. Apart from chaos theory, it is modern statistical physics that is of prime importance here. For this reason, Hof's experimental group always works closely with theoretical physicists. The latter generate models based on the new observations and simulate the flow conditions in the pipes on the computer. If the virtual flow patterns match the experimental observation reliably and repeatably, then the scientists can assume that they have gained a deeper understanding of the phenomenon. Hof's cooperations have succeeded in doing this several times in the recent past.

One of the greatest challenges for experimentalists is the statistical nature of the transition to turbulence. "We have to investigate hundreds of thousands and even millions of these processes again and again," says Hof. Reliable conclusions can be drawn only from such a vast quantity of data. Although Hof's team does this "drudgery" with its laboratory computers, which fully automate control of the experiments and record and analyze data, the work still requires enormous patience. In this way, the physicists succeeded in finding the critical point Reynolds proposed.

In the beginning, the eddy perturbations injected into the pipe flow remain localized (so-called turbulent spots) and decay at some point on their journey. It isn't possible to predict when an individual spot of turbulence will decay in this flow regime. "Turbulent spots have no memory – they don't remember the point in time when they formed," explains Hof. In this, they resemble a completely different physical phenomenon, radioactive decay. For an individual unstable atom, a radioactive uranium atom, for example, it is also impossible to predict when it will decay. It is, however, possible to observe a large number of these uranium atoms and derive a precise statistical law from their random decays. This is the half-life, after which it is guaranteed that only half of the atoms present

Photo: iStockphoto



Unexpected discovery: Björn Hof's team found that a new form of turbulence calms the flow through pipelines as soon as a small amount of polymer is dissolved in the liquid. It permeates the flow with "good-natured" eddies perpendicular to the direction of flow (left). In "normal" turbulence, the energy-consuming eddies are longitudinal (right).

at the beginning will still exist. Turbulent spots behave exactly the same way.

The researchers observed that spots can also create new spots, and this process becomes more frequent at higher velocities. This process also takes place on a purely statistical basis, just like radioactive decay. Ultimately, new spots will be created at a faster rate than individual ones decay. Between the spots, the flow continues in a nice and calm, laminar way.

LIKE A DISEASE THAT SPREADS THROUGH A COMMUNITY

The multiplication of turbulent spots reminds the researchers of a different phenomenon, one that afflicts us especially in winter. "This is similar to how a disease spreads through a community," explains Hof. Just like a sick person, one turbulent spot alone can infect the laminar flow in its immediate environment. "This isn't possible twenty meters away in the flow," says the physicist, "just as someone with influenza can't infect someone with whom they don't come into contact."

If the spread of turbulence triumphs over the decay, the flow passes the first transition point. This is to be found at a flow velocity that corresponds to a Reynolds number of slightly above 2,000: the turbulence becomes permanent. Now individual patches of eddies are distributed across the laminar flow like holes in Swiss cheese. However, there is a second transition point: it marks the velocity at which the flow becomes fully turbulent. The holes in the cheese combine, so to speak. The characteristic properties of these two transitions form the focus of Hof's research.

From a technical point of view, a fully turbulent flow is full of useless kinetic energy that isn't available for the forward thrust through the pipe. For many technical applications, it would thus be highly interesting to be able to specifically switch off turbulence. There is one astounding finding, in particular, from the research work carried out at Göttingen that is raising hopes here. If we imagine the physically possible states of a pipe flow as a function of the Reynolds number as a map, then there are two kingdoms on this map fighting for supremacy: the land of laminar flow and the kingdom of turbulence. Above a Reynolds number of 2,000, the kingdom of turbulence usually seizes power over the pipe world.

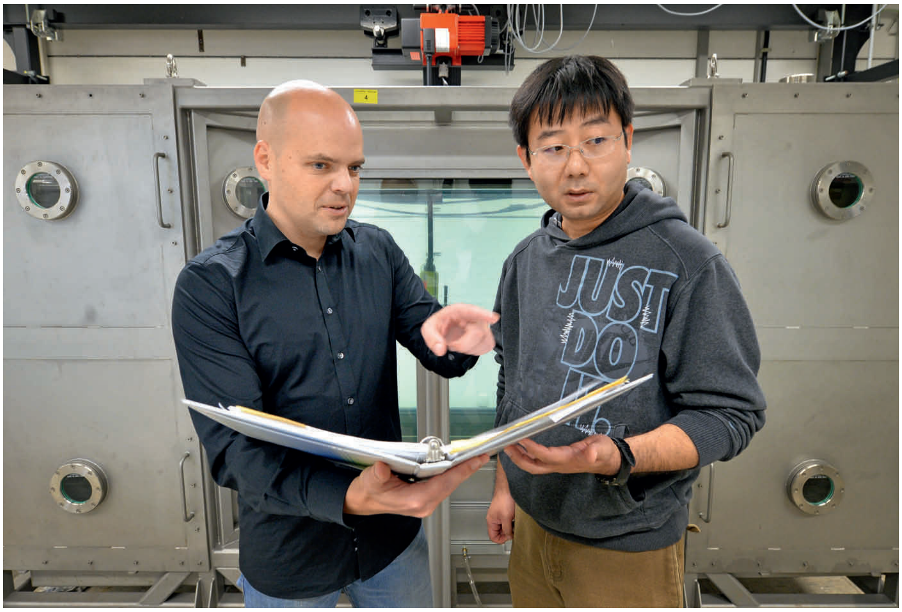
Their many years of research work have enabled Hof's cooperations to show that the laminar land is not actually wiped off the map at all. It merely disappears beyond a horizon where the flow world is normally unable to reach it. "The laminar state is fundamentally always stable, even at high Reynolds numbers," explains Hof. So it is still possible for a current to flow steadily. If the flow state could be shown a way into the domain of laminar flow at high Reynolds numbers, then victory over the energy-guzzling turbulence would be possible.

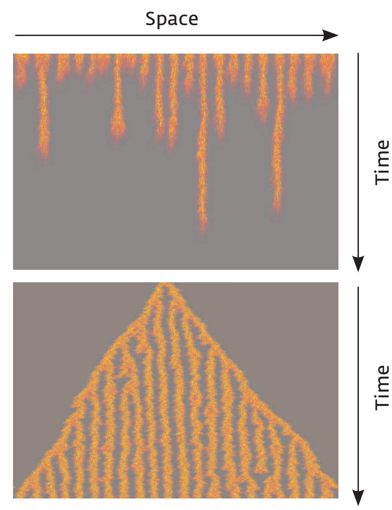
ONE EDDY CHOKES THE NEXT

Hof's team has been working on realizing this idea for years. In 2010, they succeeded in achieving a breakthrough for flows that contain individual turbulent eddies. The trick is surprisingly simple. Turbulent spots are particularly sensitive at their tail, viewed in the direction of motion. "The creation of turbulent eddies here depends on the thrust of the laminar flow behind it," says Hof. The researchers therefore came up with the idea of generating further eddies right behind the first patch of eddies. This "strangles" the leading patch from behind, because it cuts it off from its thrust. Though this extinguishing process works only with individual turbulent patches, "it gives us insight into the conditions that turbulence needs to survive even at much higher velocities," says Hof.

Today, his group is working on driving fully turbulent flows back into the land of laminar flows with the aid of an intelligent kick of this kind. But he is also interested in the tricks of clever engineers, in the oil industry, for example. They had to struggle with the problem of turbulence in the oil pipelines making it dramatically more

Photos: University of Vermont – Yves Dubief (2)





Briefing: Björn Hof and Duo Xu in front of an experiment to investigate how turbulence forms in a film of water between two sheets moving against each other. Right: The space-time patterns show how the turbulence decays (top) or propagates (bottom) in this process.

difficult to pump the black gold through them. In the 1940s, clever engineers discovered a trick by simple trial and error: they mixed a small dose of long-chain polymer molecules into the crude oil.

LONG MOLECULES CALM THINGS DOWN

These long molecules calmed the turbulence so efficiently that the oil could be pushed through the pipeline with 80 percent less energy loss in the ideal scenario. "Various theories were circulating on what causes this maximum achievable reduction in friction," explains Hof. But in 2012, it was his team that discovered that, at maximum friction, reduction of the flow is dominated by an entirely different type of disordered motion.

This new type of turbulence that forms in oil enriched with the polymer was completely unknown until then. This "elasto-inertial" turbulence, to give it its scientifically correct name, can even form at much lower flow velocities than the conventional "Newtonian" turbulence. But it is much more good-natured, because it increases the internal friction of the oil to a much lesser extent. And even more significantly, it suppresses Newtonian turbulence. So a further powerful kingdom that seizes power has turned up on the map of flow states. And it is a welcome sight for engineers.

What Björn Hof and his colleagues are doing is basic research, but their discoveries have the potential to improve many technical applications. And there's every probability that they will hit on further surprises with far-reaching implications. ◂

TO THE POINT

- **Turbulence plays an important role in engineering, a role that is sometimes useful, sometimes harmful: in engines, it causes a thorough mixing of fuel and air; in pipelines, it increases the energy required to pump the oil.**
- **The precise conditions under which turbulence forms have been the subject of research since the end of the 19th century, but it is only now that they are slowly becoming clearer.**
- **There are two transition points, which depend on the pipe diameter, the flow velocity and the viscosity of a fluid at the transition from laminar to turbulent flow. At the first one, eddies don't decay. As the flow velocity increases further, they even produce new eddies. The flow becomes fully turbulent at the second transition point.**
- **Eddies generated in a flowing fluid in a specific way can destroy other eddies.**

GLOSSARY

Laminar flow: Steady flow that loses much less forward thrust energy to internal friction than turbulent flow. A fluid under laminar flow can therefore be pumped with much less energy.

Reynolds number: The flow behavior of a fluid can be characterized by the Reynolds number. It increases with flow velocity and pipe diameter and decreases with increasing viscosity. Flows with the same Reynolds number behave in the same way as far as the onset of turbulence is concerned.

Viscosity: A measure of the internal friction in a fluid or, descriptively speaking, of its viscous flow. The more viscous a fluid, the greater the internal friction, and the more viscous its flow.

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