As diverse as their work may be, technologists around the world have one thing in common: their endless dedication to the development of novel technologies, such as next-generation electronics and medical applications, which make our lives healthier, easier, more enjoyable and more sustainable. The technologists at the Delft University of Technology (TU Delft) are no exception. They labour tirelessly to develop the knowledge, models and designs needed to improve industrial processes.

Curiosity, dreams and dedication to design practical solutions: these are common themes in the stories you are about to read. But these stories tell you more than just this. They also tell you that in their search for innovation, these technologists are contributing to a fundamental understanding of the world’s physical and chemical mysteries.

I welcome you to share their innovation dreams and to marvel at their creative inventions!
Beer, wine, bread, cheese... Some of our most common foods and beverages are products of industrial fermentation. Vital steps in their production process are performed by micro-organisms, such as yeast or bacteria. “Fermentation also plays an essential role in the production of many other products,” says PDEng Maria Cuellar, PhD student at the Department of Biotechnology, “not only in the food industry, but also in the pharmaceutical industry.”

The challenge in these industrial processes is to recover the product, in other words, to separate the product from the medium. “This is not as simple as it seems,” says Cuellar. “First of all, in addition to the product and the micro-organisms themselves, the medium contains various dissolved nutrients. Secondly, micro-organisms usually release their product in a complex mixture. They produce the desired compound in combination with a wide range of related compounds. Recovering the right compound is a challenge in its own.”

Recovering the product of an industrial fermentation process often requires many different steps, each causing an efficiency loss. Scientists at the Biotechnology Department are integrating different technologies to develop a more efficient process: crystallisation outside of the fermenter, but in a continuous loop.

“One way to address this problem is to aim for higher product concentrations during the fermentation,” Cuellar continues. “Genetic modification is a tool to achieve this: micro-organisms can be modified in a way that increases their level of production.”

The bottleneck, however, is the fact that many products are toxic to the micro-organisms when present in higher concentrations. In natural situations, a feedback mechanism ensures that micro-organisms stop producing a compound as soon as its concentration reaches a certain level. “To avoid that, we need to take the compound out of the fermentation process as soon as it is produced,” Cuellar explains. “This means that we’re fooling the micro-organisms. We take away the cue that would tell them that they’ve produced enough.”

Several technologies are available for product recovery, such as adsorption, extraction and membrane technologies. Products that are solids, however, including many pharmaceuticals, require a different technology: crystallisation. “Many industrial processes make use of a purifying step followed by crystallisation. Our approach is: why not recover the product directly after fermentation, in a crystallised form. This reduces the amount of steps in the chain of downstream processing. It is simpler, cheaper, and requires fewer auxiliary materials such as organic solvents.”

The secret of Cuellar’s work is the integration of several existing technologies into one continuous, closed-loop production process. The loop is centred around the fermenter, which contains the micro-organisms in a nutrient-rich medium. Liquid containing the fermentation product is continuously removed from the fermenter through a membrane, which ensures that the micro-organisms remain in the fermenter. Crystallisation then takes place in a separate container, either by cooling or by concentration.
One way to tackle this challenge is to perform the crystallisation at a temperature higher than 37°C. The monohydrate crystallises first, but eventually transforms into the anhydrate. However, this two-step process is tricky, and very difficult to control. Fortunately Cuellar has some other tricks up her sleeve, like adding small amounts of anhydrate crystals to the liquid before the spontaneous crystallisation of the monohydrate takes place. These crystals, also called seeds, then trigger the formation of other anhydrate crystals. “This works out really well if the conditions are right. In a way the seed crystals act as crystallisation nuclei for the right crystal form. The mechanisms behind the selective crystallisation of the anhydrate crystals are still a bit of a mystery. Luckily, there are other research groups focusing on the fundamentals of this type of crystallisation. The important thing is that the seeding trick proves to be effective.”

One of the strategies Cuellar uses is phenylalanine. This built-in water turns the product into a viscous gel that is useless for industrial purposes. Apart from that, we cannot separate it from the medium by filtration. The problem is that this undesired monohydrate is usually the first form to crystallise. Making sure that we only get the anhydrate form is an extra challenge.

Phenylalanine can crystallise in two different forms: an anhydrate form and a monohydrate form. The anhydrate (left) is the desired crystal form. The monohydrate (right) is too viscous.

The monohydrate contains one extra water molecule for each molecule of phenylalanine. This built-in water turns the product into a viscous gel that is useless for industrial purposes.

One of these is the fact that the genetically modified micro-organisms used in these systems, like the strain of E. coli bacteria that Cuellar uses, are often more sensitive to infections than their natural conspecifics. “This makes it harder to cultivate them, especially in a continuous loop. You need to work under extremely sterile conditions. The rate of infection determines the maximum duration of the production process.”

Being able to put more and more of these puzzle pieces together is Cuellar’s professional ambition. This will not only place a high demand on her lab skills and knowledge of biotechnology, but also requires an aptitude for model development. Computer modelling, as Cuellar underlines, plays an increasingly important role in biotechnology. “Trying to answer all of our questions on the basis of trial and error in the laboratory is simply impossible. Using computer models is much less time-consuming and expensive. Even after elaboration of the ultimate, all-encompassing model, industrial-scale application might still be far away. In order to scale up the lab experiments and make them economically viable, some additional practical challenges need to be overcome. One of these is the fact that the genetically modified micro-organisms used in these systems, like the strain of E. coli bacteria
Many industrial processes, such as the combustion of coal, make use of fluidized bed technology. A fluidized bed is a collection of solid particles that are suspended in an upward gas stream. The particles in a fluidized bed behave like a liquid. The gas, if injected at a certain speed, forms bubbles. These conditions ensure optimal mixing of materials and heat, which benefits the combustion.

The mixing, however, is gradually hindered by undesired processes. Not only do the particles react with the gas, they also interact with each other. As a result, the particles may stick together and form clusters, or agglomerates, that decrease the efficiency of the process and may even damage the reactor. “The combustion of coal is relatively easy,” says Dr. Ir. Ruud van Ommen at the Department of Chemical Technology (DelftChemTech), “and agglomeration is not a big issue. However, the combustion of biomass, such as wood chips, is much more prone to these problems. The ash of biomass is typically stickier than that of coal. The ash particles stick together with the sand particles that we use as heat carriers to stabilise the system. The result is the formation of large ‘rocks’ inside the reactor.” Van Ommen shows an impressive, fist-size example of an agglomerate. “This is only a small one,” he clarifies. “Agglomerates that form in other types of fluidized beds, for instance during polymerisation of ethylene, are sometimes over a meter high.”

**EARLY WARNING**

These agglomerates are a nightmare for reactor operators. Not only do they decrease the reaction efficiency, they also force operators to shut down their reactors periodically and empty out their contents. This may cost days of valuable running time, not to mention the waste of materials. In large factories, such clean-ups may cost a few hundred thousand euros.

“It’s not surprising that the industry can’t wait for a solution,” Van Ommen points out. “This problem is widespread in fluidized bed applications, not just combustion and polymerisation. It happens in the food and pharmaceutical industry, which use fluidized beds to dry particles. It happens in synthesis reactions of many chemicals. Solving the agglomeration problem, in other words, is high on everyone’s agenda.”

Avoiding agglomerates requires adjustment of the reaction during the process. In biomass combustion, one way would be to replace the reactor’s sand more often and run the reactor temporarily at a lower level. “You wouldn’t want to do this any more than is strictly necessary,” Van Ommen underlines, “not just because of the cost aspect, but also because replacing the materials more often results in more chemical waste. This is a problem of sustainability.”

In light of this, scientists are looking for ways to determine the optimum level of intervention. This calls for a close monitoring of...
The mean value is abnormal. "What you would want is a system that shows you in one glance if the conditions are changing, even when the average pressure is still unchanged," Van Ommen summarises. Using a methodology that originated from chaos theory, the technologists at DelftChemTech have managed to design such a system. Chaos theory aims to identify patterns in chaos and uses a so-called attractor to do that. An attractor is a visual representation of a fluctuating pattern, but it is different from a regular graph that plots a parameter, for instance pressure, against time. An attractor takes various points from the signal and represents them in a new graph: one that plots the pressure at a certain time against the pressure one time interval later. If this is done for many different points in time, the result is a graph that looks like a ball of yarn. In practice, a multi-dimensional attractor is used, that cannot be visualised but still can be used for statistical analysis.

The starting point is the attractor that represents a reference time interval: a period during which the reactor is running under optimal conditions. After a certain time, a second attractor is made, which represents the conditions at the second point in time. This is done repeatedly during the industrial process. Van Ommen: "We developed software that calculates a so-called similarity index: a value that indicates how much a given attractor resembles the reference attractor. Based on practical experience, operators can then establish at which similarity index they should start adjusting the reaction process."

**BRAIN AND SEISMIC WAVES**

Van Ommen stresses that it is not just fluidized bed technology that will profit from this development. "Many other types of reactors also experience constant change," he says, including bubble-column fermenters used in biotechnology. Another example are processes in which agglomerates are not a nuisance, but the desired end state, for instance in the pharmaceutical industry. In that case you wouldn't use the reference attractor at the beginning of the reaction, like in biomass combustion, but at the end, when the right grain size has been reached.

The scientists in Delft are currently testing their technology in industrial situations. "Cooperation with people in the field is incredibly important," says Van Ommen. "For every process and every reactor, reference conditions will be different. They also depend on the preference of the operator. Especially in continuous processes that produce a sequence of different products, it is a challenge to manage the conditions during the different transition phases."

The next step will be to develop a practical tool for operators, making sure it addresses the industries' specific needs while still being user-friendly. "The final challenge will be to convince the various industries that this is the technology they need," Van Ommen notes. "We have to show them the added value. People in industry usually possess a healthy sense of scepticism, and rightly so: implementing our technology might call for a substantial investment. However, given the potential savings of hundreds of thousands of euros, they will find this a worthwhile investment."

Van Ommen and his colleagues are not only dreaming of seeing their technology applied in industry. They also speculate about applications in other areas. For instance, epileptic patients could benefit from a system that warns them – on the basis of the pattern of their brain waves – that an attack is on its way. Similarly, the system might help seismologists estimate the likelihood of earthquakes based on seismic patterns. Wouldn't stock holders be interested as well, hoping to find out when to buy or sell? "Unfortunately not," laughs Van Ommen, "since people actually influence these fluctuations by the way they react to them. It is a psychological feedback mechanism that probably can't be captured by a method like this. But you'll be surprised to see how many processes in daily life and in science are actually reflected in hidden patterns. Who knows which applications might arise in the future."

**A fluidized bed is a collection of solid particles that are suspended in an upward gas stream. The gas, if injected at a certain speed, forms bubbles.**

**An attractor (right) visualises the changes that take place over time in a two-dimensional graph (left). The attractor plots the pressure at a certain time against the pressure one time interval later.**

**Reconstructed attractor in m-dimensional state space**

**An operator can establish at which similarity index fluctuations occur.**
It is difficult to imagine a world without lenses. Optical design is all around us: in eyeglasses, photo cameras, telescopes, microscopes, and even in satellite systems. In our modern world, lenses also play a vital role in the process of making chips for computers and for other electronic devices that change people’s everyday lives. As electronic devices are becoming smaller and smaller, as well as more sophisticated, so do the chips that make them work.

Dr. Florian Bociort at the Department of Imaging Science & Technology (IST) has taken on the challenge of designing optical systems needed for microchip production. “Designing lenses for photo cameras or binoculars is relatively easy,” he says, “because the demands placed on these systems are quite straightforward. Modern-day computer chip production, however, requires objectives with a nearly impossible combination of characteristics.”

A TON OF GLASS

To illustrate his point, Bociort explains how a typical computer chip is made. The basic technology is called photolithography: a technique by which light is used to sculpture really small structures. The light, in this case ultraviolet light, triggers a photochemical reaction in a thin film deposited on the target material, usually a thin polished slice of silicon. The light pattern is determined by a pre-fabricated mask, which contains the relevant information. An objective projects the light pattern onto the silicon slice.

While the objective of a slide projector enlarges the slide image, the lithographic objective that produces a computer chip is designed to miniaturise the image. “The information is projected onto a surface of a few hundred square millimeters,” says Bociort, “where it sculptures countless structures at the size of seventy nanometers, not just in one layer but in multiple layers on top of each other. The key to producing cheap, powerful computer chips is transferring this high-resolution information very rapidly. The optical system has to transfer all the information very accurately, at a speed comparable to burning three hundred DVDs per second.”

Every optical system, explains Bociort, has imperfections. The rays of light that pass the lenses always deviate slightly from the desired path, which causes the image to be slightly blurred and slightly at the wrong position. “Our aim is to design lens systems that not only produce sharp images, but also reduce this lateral deviation to less than one nanometer. In other words, the precision should approach the atomic scale.” To control the path of many light rays with that degree of precision, these optical systems need to be extremely complex. They consist of as many as twenty lenses, which together account to the size of a person.
Bociort explains, “it is relatively simple to find the so-called distance between surfaces. “If you look at only one parameter,” number of lenses, the curvature of each lens surface and the a function of the parameters of the system – for instance, the specified task. Designers consider the errors in image quality as a system that has precisely the right characteristics to perform a task. It is relatively easy, he continues, to calculate the qualities of an optical system based on certain optical parameters, but the inverse is endlessly more complicated: to design an optical system based on certain optical parameters, but the inverse is endlessly more complicated: to design an optical system to be designed is of a well-known type and has only a modest complexity,” says Bociort, “then traditional methodology may be satisfactory. However, for highly complex systems, the traditional techniques are not only too slow, but they may also miss new and interesting design possibilities.”

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In this context, it is important to understand the role of the so-called valleys and mountain passes. In a multi-dimensional landscape, looking at local minima is not enough. There might be minima that are even better, but further away. But which route leads to them? “This is where your intuition is no longer useful,” laughs Bociort. “When there are many solutions, it is very easy to overlook some of them.”

Bociort and his colleagues apply a revolutionary new way of looking at this complex mathematical problem. “Try to understand it at the level of a regular, three-dimensional mountain landscape. Imagine that you are in a valley – a local minimum. If you want to visit the next valley, you will seek out a route via a mountain pass. The mountain pass is what we call a saddle point. It is the highest point on the easiest path that connects two local minima.”

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In other words, adding extra parameters to an optical system by inserting an extra lens increases the number of solutions to the problem of creating the perfect image. “But given the cost of each single lens, the challenge is to achieve the required quality with the smallest number of components. However when using our method, called saddle point construction, inserting a lens gives you two distinct shapes of the system rather than one, and for further design you can choose the better one.” By adding and removing lenses with this method, one can improve the design productivity considerably. One of the designs of Bociort’s colleague Oana Marinescu, for instance, achieves the same image quality as a state-of-the-art design made by top-class experts, but with three lenses less.

Bociort suspects that the concept of saddle points in a multi-dimensional error landscape can be fruitful outside of the optics field as well. “There’s nothing in optics that makes it fundamentally different from other sciences. Eventually it comes down to finding efficient solutions to complex problems. I’d be surprised if the same principles didn’t hold true for instance in biology or economics. There might be more parallels than you’d think, and they might not be based on coincidence.” Expressing hope that the Deft findings might stimulate research in other fields, Bociort emphasises that only a modest start has been made and large-scale application may not follow immediately. “Many questions still need to be answered, but the few things that we now understand about the design landscape are already helping us to design better systems. As far as I see it, we’re now at the verge of an entirely new approach to design.”

**Networks**

The breakthrough in Deft came when the scientists discovered a hidden order in their multi-dimensional landscapes: an underlying reason why some optical systems work better than others. “In short, we have discovered that saddle points are essential in the multi-dimensional landscape. The local minima form a network in which all nodes are connected by paths that contain saddle points. One valley may have several different saddle points that lead to it. In other words, there are different paths that lead to the same solution.”

Naturally it is not the saddle points that the designers are interested in, but the valleys: the points where the error is smallest. “But,” as Bociort points out, “by looking at the design landscapes from our network perspective, we have discovered something new. If you’re already in a minimum, you can insert an extra component into your system in such a way that your original minimum becomes a saddle point, which has two new minima, one on each side of it. You suddenly have two solutions instead of just one. This is how saddle points split the evolution paths of the system.” Considering, when we contaminate a system with two lenses easily has over a hundred relevant parameters. The design space then has the same number of dimensions.”

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Recovering oil from a reservoir at three kilometers’ depth is a technological challenge. It is economically interesting when the pressure inside the reservoir is sufficient to force the oil to the surface. Over time, as production continues, the pressure decreases and eventually fails to expel any more oil – even if the reservoir still holds seventy percent of its oil.

“Fortunately there are ways to increase the productivity of a reservoir,” says Prof. Dr. René Oliemans at the Department of Multi-Scale Physics (MSP). “One trick, so-called gas lift, is well over a hundred years old. It makes use of double-walled oil pipes in which the oil flows upward in the inner space. In the space between the inner and the outer wall, which we call the annulus, gas is pumped downward. It is injected into the inner tube at the bottom of the pipe. The bubbles decrease the effective density of the oil, which enables the existing pressure to force the oil out of the reservoir.”

INVERSION POINT

Oil companies enjoy significant benefits from this technology, but they aren’t fully satisfied yet. Gas lift, as they experience, results in a highly unpredictable flow regime, with flow rates fluctuating strongly. The system is even more unstable when the mixture contains not just oil and gas, but also water. This is a realistic situation, as water is pumped into oil reservoirs at different locations to enhance the flow of oil through the porous reservoir. Some of this water inevitably enters the oil pipes.

“Apparently there is something about this mixture of gas and two different liquids that makes the system unstable,” says Oliemans. “Our challenge was to find out why this three-phase system behaves the way it does, and to see if we could develop ways to improve the system’s stability.”

The first step in this process was to study the behaviour of a two-phase system consisting of oil and gas flowing through a vertical pipe. This system easily becomes unstable if gas is injected through only a few holes at the bottom of the pipe. The bubbles tend to merge. They form larger bubbles that push liquid upwards as ‘slugs’ and cause the flow to be variable. “A solution to this problem is to inject the gas through a porous ring in the bottom of the pipe,” Oliemans points out. “This creates a more homogeneous flow of small bubbles, ensuring a faster and more stable flow of oil at the same level of gas injection. This relatively simple adjustment has the potential to increase the productivity of an oil well by roughly thirty percent. We are currently looking into the practicalities of this option – so far it is not widely applied yet.”

During their experiments, the MSP scientists discovered an interesting phenomenon: bubbles of different sizes are not evenly distributed throughout the column. Turbulence causes smaller bubbles to move to the outside, while larger bubbles stay

Water generally flows through pipes in a rather straightforward way. However, a mixture of water, oil and gas – a reality in the oil industry – behaves much less predictably. The Department of Multi-Scale Physics is studying such three-phase systems. Tricks to enhance oil productivity are discovered along the way.
in the centre. Smaller bubbles are more efficient at creating a gas lift effect than large ones and lead to a more uniform liquid flow rate. “This is the case for water as well as oil,” notes Oliemans, “but the critical bubble size is different for each substance. Bubble behaviour strongly depends on the liquid used.”

The situation becomes even more complicated when water and oil are mixed. Their relative concentrations prove to be of significance. At high water fractions, the mixture consists of oil dispersed in water, while at low water fractions, water is dispersed in oil. An important feature of the mixture is the inversion point: the critical fraction of water at which a water-in-oil dispersion switches to an oil-in-water dispersion, and vice versa. This inversion generally occurs at a water fraction of thirty to sixty percent, depending on the exact composition of the oil. The inversion process is associated with a dramatic increase in both viscosity and bubble size. As a result, at the inversion point the gas lift is no longer functional: its effect is offset by an increased friction between the mixture and the wall of the pipe, as well as by the instability caused by the larger bubbles. “It is this phenomenon that explains why oil companies sometimes experience sudden instabilities in the flow regime. These happen when the composition of the mixture changes, and reaches the inversion point.”

Oliemans and his colleagues discovered that small bubbles not only enhance the gas lift near the wall of a pipe, but also affect the friction between liquid and wall. “We were first to be able to observe this phenomenon,” notes Oliemans, “making use of specially designed equipment to measure bubble behaviour close to the wall.” It turns out that the fraction of oil droplets in a water-dominated mixture determines to what extent small bubbles can have a positive effect on gas lift. The MSP scientists do not yet fully understand all of the underlying physical processes. They suspect that turbulence plays a role, but teasing apart the different parameters remains a challenge. Computer models now allow them to search for the conditions at which it is still possible — despite the complicated interactions between the three phases — to effectuate a constant degree of gas lift. “Modelling helps us to understand phenomena that experiments cannot capture,” says Oliemans, “particularly in relation to the specific processes taking place at the scale of real oil-producing sites.”

Powerful computers can make three-dimensional simulations of the forces that influence single particles in a multi-phase system. The next step is to use the newly acquired insights to increase reservoir productivity. “Unfortunately there is not much you can do to change the conditions underground,” Oliemans underlines. “Oil and water enter a pipe at varying fractions, and this is a situation that oil companies have to accept. Nevertheless it is important to understand how a system reacts to different parameters. Some of them, such as the regime of gas injection, can be adjusted relatively easily.”

BRIDGING THE GAP

It is the combination of computer simulations and lab experiments that makes the Delft research unique. Oliemans: “We are very lucky to have extremely sophisticated lab facilities and supporting technical staff. Another bonus here in Delft is the possibility to work closely together with other faculties, including Civil Engineering and Geosciences. Together with these colleagues next door we are now looking into flow systems that include a solid phase, for instance sand. What happens when sand enters a oil pipe? This knowledge is also extremely useful for sand mining and dredging technology.” In addition, MSP recently entered into cooperation with Shell and the Netherlands Organization for Applied Scientific Research (TNO). The aim is to develop new models and applications in relation to multi-phase industrial flows. “This is an ideal combination of fundamental and applied research,” spines Oliemans, “where TNO is bridging the gap between our academic work and Shell’s applied work.”

Oliemans, having worked for Shell for many years himself, is very content with his role at the interface of science and technology: “The industry is interested in solving problems. Academics are interested in in-depth exploration of the underlying science, thereby dividing the problem into sub-problems. My personal satisfaction lies in identifying which discoveries might have a useful application, and then finding the right people to share them with. The most exciting moments in our work occur when we eventually, via interesting side-tracks and sub-problems, find a solution to the original problem. That is science at its best.”

A homogeneous flow of small bubbles (right) is more efficient at creating gas lift than a flow of bubbles with varying sizes (left).
Dr. Ir. Martin Rohde has a straightforward message: “The global reserves of fossil fuels will be exhausted within the next century. Renewable fuels will not be able to satisfy the world’s demand for energy. Sooner or later, we’ll have to face the fact that nuclear power might be the only viable solution.”

Rohde, physicist at the Department of Radiation, Radionuclides & Reactors (R3), acknowledges the negative stigma associated with nuclear power. However, he firmly believes that a new generation of nuclear reactors will guarantee increased safety and reduced amounts of nuclear waste. In fact, his own R3 department is contributing to the ‘greening’ of the nuclear reactor industry by taking a closer look at the physical processes taking place inside nuclear reactors. The resulting knowledge may prove vital for sustainable nuclear energy development.

**FEEDBACK MECHANISMS**

The type of reactor studied in Delft is a boiling water reactor (BWR). The BWR is unique in the fact that it uses a single loop of fluid to conduct heat away from the nuclear fuel and drive the steam turbines that generate electricity. In the more generally used pressurised water reactor (PWR), there are two separate loops which are connected through a heat exchanger. “The water in the BWR,” explains Rohde, “runs past the fuel rods in the core, and picks up the heat that results from the nuclear reaction. The heat causes the water to boil, after which it rises through an upward-leading pipe as a mixture of steam and liquid. The steam is used to drive the turbines, after which it is condensed and led back into the system, together with the surplus of liquid water.”

The beauty of this particular system, as Rohde points out, lies in the fact that nature itself causes the water to flow through the system. Due to the density difference between the heated channels, which contain steam as well as water, and the so-called down-comer, which is filled with recirculated liquid water, the water starts to circulate by itself in an endless loop. This eliminates the need for pumps, making the system safer: pumps, if they break, can cause serious problems. The system operates under high pressure and temperature; if the circulation is halted the core may become overheated, with all associated safety problems.

“This brings us to the main advantage of a BWR with natural circulation,” enthuses Rohde: “This is a system that regulates itself. As soon as the fuel rods become too hot, an excess of bubbles is formed. This increases the natural circulation flow, resulting in a better cooling of the fuel rods. Nature does the job and will never malfunction.”

This is a very efficient feedback mechanism, as Rohde points out. He is currently studying how it responds to different conditions.
parameters. The problem is that this mechanism interacts with other feedback processes, and the net result may be a positive feedback: a mechanism that enhances itself and causes the reactor to become unstable. This means that under extreme operational conditions, fuel rods might become hotter due to the fission process even though more bubbles are produced in the nuclear core. Rohde: “Natural circulation BWRs aren’t ready yet for commercial applications. First we need to know how all the nuclear core. Rohde: “Natural circulation BWRs aren’t ready yet for commercial applications. First we need to know how all feedback mechanisms interact.”

VALID MODEL
Testing systems under field conditions, however, is not easy in the world of nuclear reactors. If scientists wish to study the dynamics of such systems, they will need to build them in a laboratory. “In Delft we were the first to build a down-scaled model of an existing commercial BWR, one that was developed by General Electric,” notes Rohde. “They commissioned us to test their system and look into its stability.” The lab-scale model is slightly different from its larger brother. It measures a mere ten meters in height, as opposed to the twenty meters of a real BWR – but even so, it required the roof of the R3 lab to be drastically reconstructed. Instead of water, the model uses freon as the circulating substance. Freon shows the desired behaviour at a much lower temperature and pressure than water: 45°C and 11 atmosphere are sufficient, versus 300°C and 71 atmosphere in the case of water. These conditions, although not commercially attractive due to freon’s high cost and low heat capacity, are far more convenient for lab experiments. In the core of a real nuclear reactor, the neutrons have to be slowed down in order to enhance the fission process. This so-called moderation process is induced by the water itself. The more water molecules neutrons meet, the more they slow down and the more heat is produced. This, in turn, results in more bubbles being formed, decreasing the moderation and decreasing the heat production. In the R3 facility, the moderation process is mimicked by a fast electronic heating system, in which the heat production. In the R3 facility, the moderation process is mimicked by a fast electronic heating system, in which the amount of freon bubbles is measured and translated to a specific power sent to the heating rods. “The freon system allows us to study different system parameters,” says Rohde, “such as the gas-liquid flow characteristics and the dynamics of the system. Scaling down the system, like we did with the BWR, is a difficult task; all the physics present in the reactor should be scaled properly. The challenge is to find an optimum testing arrangement that realistically reflects the real BWR.”

Even though freon causes more friction than water, and its thermal properties are completely different, the dynamics of the scaled-down model appeared to imitate the real-scale conditions remarkably well. “This was in fact quite a coincidence,” Rohde smiles. “We’d never thought we’d get it right the first time.” The physicists found that their results were remarkably similar to the calculated estimates of General Electric. “This was an important finding,” says Rohde, “because such a good similarity between a real BWR and an experimental facility had never been shown before.”

This success allows the R3 scientists to measure the stability of the system – its capacity to moderate oscillations – under different operating regimes. “It also allows us to look at what happens when you vary different parameters in the system design. What can we do to make the system even more stable? Perhaps we can decrease the distance between the feedwater sparger and the inlet of the core. Or we can experiment with different core designs. Our model allows us to play with different set-ups and see what we can learn about the reactor dynamics.”

Another aspect of nuclear reactor physics high on Rohde’s agenda is the start-up phase of a BWR. Within the chimney section, for instance, there is the risk of sudden appearance of large amounts of vapour, the so-called flashing phenomenon, which causes very large fluctuations in the reactor. Rohde: “Our group showed, for the first time, that the start-up process of a natural circulation BWR may undergo a range of stages: from in-phase to chaotic to out-of-phase and finally to a stable situation. Such stages need to be investigated, because the oscillations of the flow in a real reactor may show amplitudes of 12,000 kg per second.” The excellent results with the freon facility provide good hope that even the more complicated reactor processes might be imitated at lab scale.

“In a world based on numerical models there is a strong need for validation,” Rohde concludes. “Some processes are so complicated that they tend to give us headaches. But we are making significant progress. In the end, our work is crucial in the development of any new type of nuclear reactor. That makes this research fascinating and worth while.”
In a sense, Prof. Dr. Ir. Herre van der Zant and his colleagues at the Kavli Institute of Nanoscience are mechanical engineers. They build suspended bridges and study their mechanical motion as well as the forces that deform them. The difference with the work of their colleagues at Mechanical Engineering is the scale at which they work. The bridges built by Van der Zant are one micrometer long and two nanometers in diameter.

As their building material, the nanoscientists are using carbon nanotubes: tiny hollow tubes consisting only of carbon atoms. When connecting two electrodes, a nanotube can conduct an electric current. This makes it an interesting structure in the context of nanoelectronics – the science that aims to miniaturise the functional components of electronic devices.

“The electrostatic forces acting on the nanotube can be significant,” says Van der Zant. “In larger-scale electronic devices these are relatively insignificant, but in devices at nanoscale they actually result in mechanical deformation of the device. This in turn influences the way the device functions.”

If they are to optimise the functionality of nanoscale devices, scientists need to identify and understand these forces. In fact, not all of them are necessarily undesired. They may be an essential feature in the functionality of certain devices. To better clarify his point, Van der Zant first describes the set-up used in Delft to study nanotube deformation: “We use a carbon nanotube that is freely suspended between two electrodes, and that is conducting a current. Underneath this ‘bridge’ lies a layer of conducting silicon, which we call the ‘gate’. When applying a static as well as a small oscillating voltage to the gate, electrostatic forces cause the nanotube to vibrate. In fact, it behaves like a miniature piano string. You can even tune it by adjusting the static, non-oscillating voltage on the gate, which pulls the wire down by a few nanometers.”

At an earlier stage, calculations had shown the possibility of this phenomenon, but the Delft researchers were the first to prove this in a laboratory. The ‘tuning’ of nanowires, as Van der Zant highlights, allows for entirely new ways of device operation. After all, many present-day electronic devices, such as mobile phones, make use of high-frequency resonators. Nanotube technology could, in theory, increase their resonance frequency dramatically. This would help to make this type of electronics smaller and much more energy-efficient.

“Another field where this would be helpful is medical technology,” notes Van der Zant: “Patients with pace makers, for instance, currently need to have an operation every few years because the battery of their pace maker needs to be replaced. Although this is still very speculative, I can imagine a future device that uses less energy, eliminating the need for frequent replacements.”
nanostructures. An example he gives is graphene: a carbon membrane with a thickness of only one atom. “I can imagine a lightweight, very sensitive construction of vibrating graphene – a nanodrum! – that could perhaps be useful in membrane technology.”

Van der Zant is also dreaming of exploring the full scope of chemistry to identify other molecules with a potential for future electromechanical applications. “Many single molecules, when you study them closely, have a varying three-dimensional conformation. One part of the molecule may rotate relative to another. In addition, if current can flow through the molecules, countless possibilities arise for electromechanics. A single molecule, for instance, could be the smallest switch imaginable, and cheaper and more flexible than the traditional silicon switch.”

To be able to elaborate on these “wild ideas”, as Van der Zant describes them, the nanoscientists intend to increase their cooperation with chemical engineers. “By searching for the right materials to ensure the desired qualities, we operate on the limit of what we know and of what is physically possible. Sometimes we know where to look, but usually we don’t. Fascinating new discoveries may present themselves at any moment.”

QUANTUM THEORY

The Delft researchers have developed a model that can predict the vibrations of the suspended nanotubes. This enables a different kind of potential applications. To name an example, nanotubes may function as highly sensitive mass sensors. “Nanotubes are extremely lightweight,” explains Van der Zant. “If you attach something to the tube that is also extremely lightweight, like a protein or any other molecule, then the change in mass is reflected in a different vibration frequency. From this, you can determine the size of the extra mass.” A variation on this theme allows this nanoscale construction to function as a molecule detector. “If you fit the nanowire with a receptor molecule – a molecule that, like a puzzle piece, will only bind with a particular kind of molecule – a change in the vibration frequency will tell you when the molecule in question has been ‘captured’ by its receptor.” This too is still very speculative,” Van der Zant underlines.

Another potential application is an electromechanical switch. A flexible nanowire that is attached to an electrode on only one side may make contact with another electrode – and thus enable an electric current to flow – only once its position is altered by means of electrostatic forces. Such a switch would be much smaller, and again less energy-consuming, than traditional electronic switches.

As an added bonus, this applied research allows the nanoscientists to look into the fundamental principles of quantum mechanics: the science that, for instance, describes the structure and behaviour of atoms and molecules. “Regardless of the electric currents running through them, nanotubes vibrate as a result of thermal influences,” says Van der Zant. “At low temperatures, about 273°C below zero, these fluctuations freeze out. Quantum mechanics however tells us that particles always keep on vibrating, albeit with a small amplitude, even at zero temperature. Our nanotubes are so lightweight that they allow us to study this ‘zero point motion’.”

By combining their nanotube research with quantum-electrodynamics, the nanoscientists, as Van der Zant phrases it, are in fact “putting mechanics back into quantum mechanics”, which has until now mainly been studied in single atoms and molecules. However, the question remains whether the carbon nanotube bridge, which consists of a few hundred thousand atoms, still behaves quantum-mechanically. Van der Zant: “This is in fact a theoretically profound and even philosophical question, which touches upon phenomena that are not easy to measure. It is an incredibly complicated matter. Yet we need to look into it, because the principles of quantum mechanics pose an ultimate limit to the sensitivity of nanoscale electromechanic devices.”

WILD IDEAS

Van der Zant’s research group at the Kavli Institute of Nanoscience is relatively new, and considers itself to be in a build-up phase. Its research is mainly explorative. “We find ourselves in an ideal position,” laughs Van der Zant, “because we are allowed to fantasise about a wide range of research questions that might be interesting.” One of the items on the researcher’s wish list is studying the electromechanical properties of other
The Faculty of Applied Sciences is the largest faculty within TU Delft. Research at the faculty is fundamental and application-oriented in nature and spread over six departments. The faculty offers research-oriented education at both undergraduate (BSc) and postgraduate (MSc, PDEng, PhD) levels. The domains of science the faculty targets through its education and research are life and health science & technology, nanoscience & technology, chemical engineering, radiation science & technology and applied physics.

**FACTS & FIGURES 2006**

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