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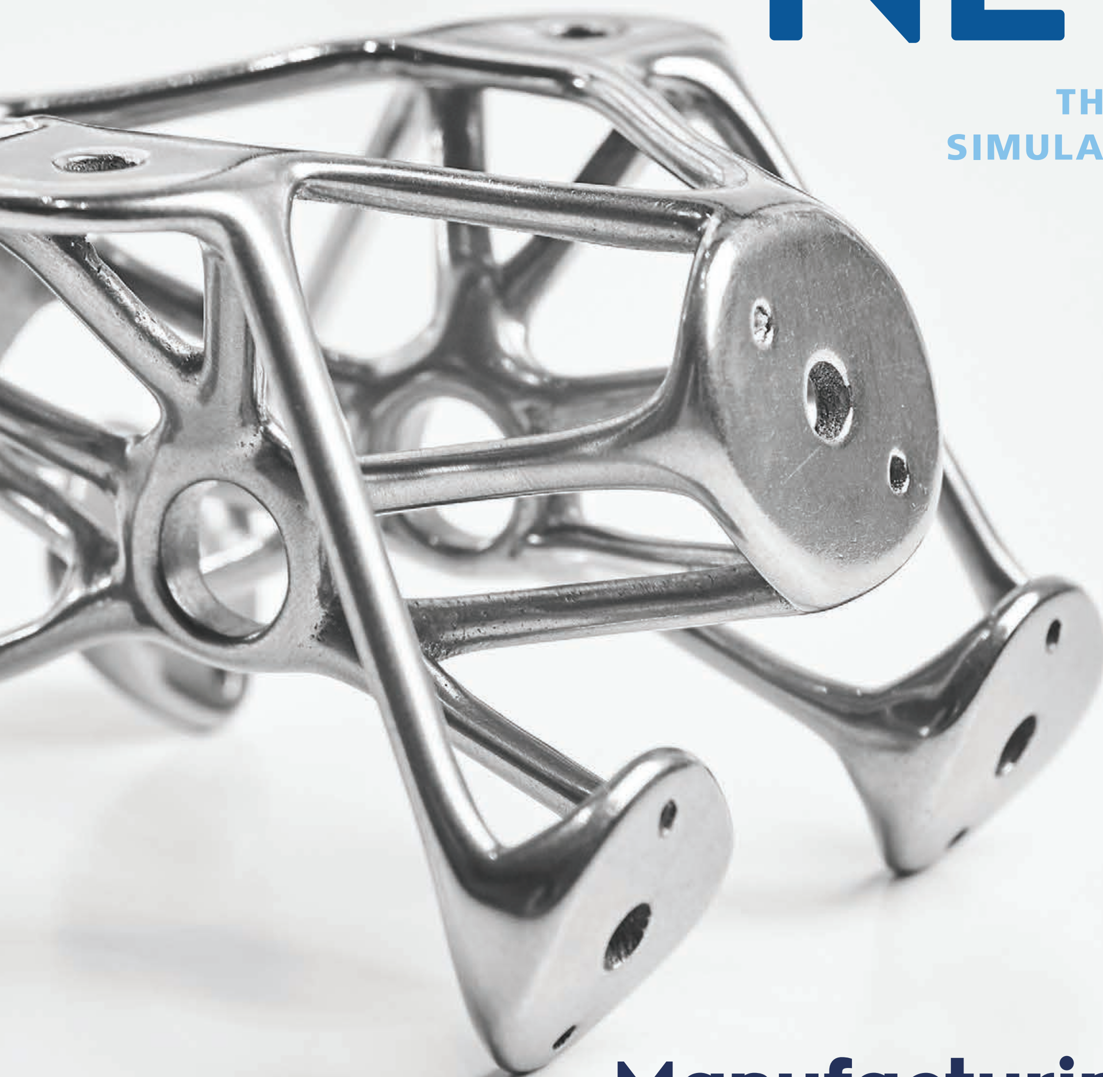
COMSOL NEWS

THE MULTIPHYSICS SIMULATION MAGAZINE



Additive Manufacturing Meets Predictive Modeling

Simulation App Enables Real-Time Management of Factory Conditions

PAGE 8

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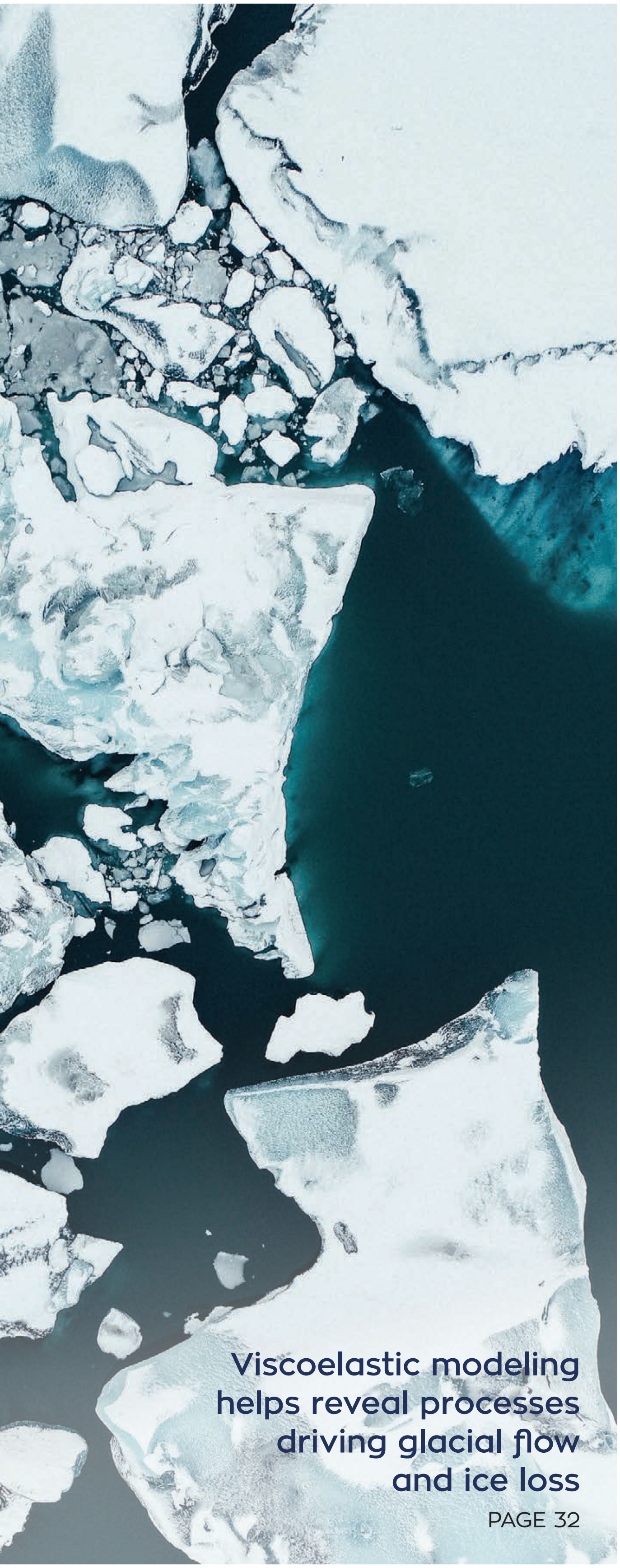

As Global Challenges Intensify, Innovators Step Up

What defines a decade? The 2020s have hardly begun, yet we have already witnessed dramatic changes. The long-predicted effects of climate change are reshaping lives worldwide, even as we also confront unexpected crises like the global pandemic.

But is an era defined only by its difficulties? History suggests that how we *respond* to difficulties may be just as important. In this year's COMSOL News, we present nine stories of people who are stepping up to meet the challenges of our time — with help from multiphysics simulation.

Some of them are directly researching the effects of climate change, such as Angelika Humbert of the Alfred Wegener Institute, whose team is modeling the viscoelastic forces that are reshaping Greenland's glaciers. Others, including teams at companies like Exicom and Bosch, are developing electric vehicle technology to help reduce dependence on fossil fuels. There are also startups like Polar Night Energy of Finland, whose ingenious system stores solar-generated heat inside a "battery" made from sand. Other innovators are tackling perpetual challenges, such as health care and communications, with promising new technologies.

All of these R&D stars are striving to craft a brighter future — and they're doing it with help from the COMSOL Multiphysics® software. Even those who are new to simulation are putting its power to work; on page 8, learn how England's Manufacturing Technology Centre has empowered factory workers with an app that can serve as a prototype "digital twin" of their facility.

Perhaps if we can take inspiration from innovators like these, we will remember this era not for its setbacks, but for the steps being taken to help build a better world.

Alan Petrillo
COMSOL, Inc.

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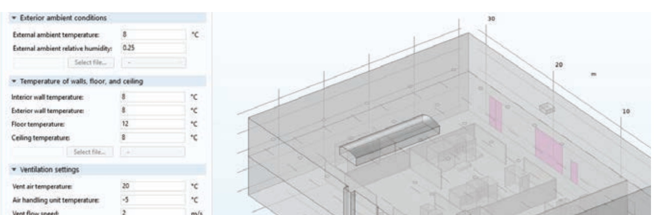

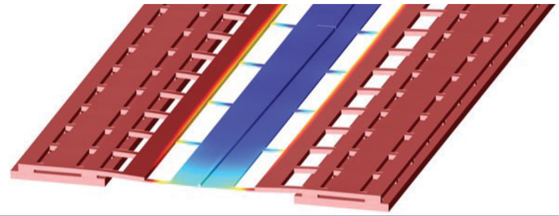

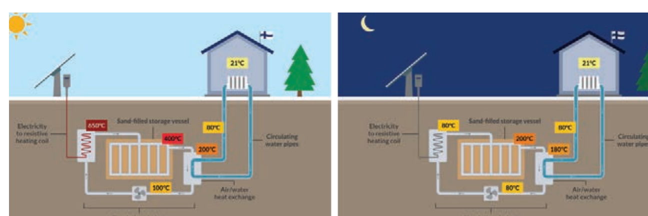

Bosch, Germany

BOSCH POWERS THE AUTOMOTIVE SECTOR TOWARD AN ELECTRIFIED FUTURE

The global transition toward electric cars is getting a boost from industry suppliers like Robert Bosch, which provides electrical components and systems to car manufacturers. The Bosch team optimizes three-phase inverters and DC link capacitors with a simulation-powered design process, which enables them to identify potentially destructive "hot spots" early in the development cycle.

by **ALAN PETRILLO**

Just as tourists in Paris are drawn to the Louvre, visitors to Stuttgart, Germany, also flock to museums displaying the great works of the city. Stuttgart may not boast of Degas or Monet, but its prominent names are perhaps even more famous than Paris' painters: Mercedes–Benz and Porsche. Each of these iconic automakers maintains a museum in the southwestern German city they call home. Their gleaming galleries feature many historic and influential cars, almost all of them powered by petroleum-fueled internal combustion (IC) engines. Looking ahead, Stuttgart will likely continue to be the heart of the German auto industry, but how long will the IC engine remain the heart of the automobile?

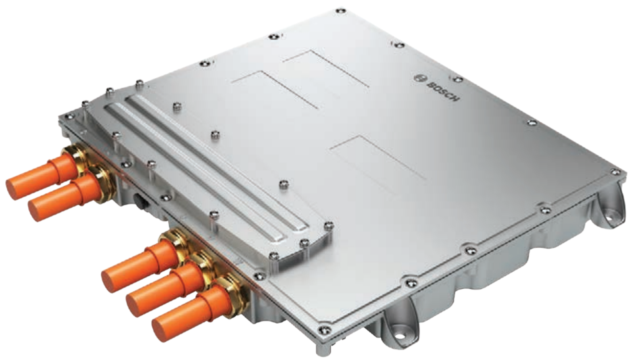

FIGURE 1 A Bosch three-phase inverter for automotive drivetrains.

Even the most successful manufacturers must adapt to changing conditions. The German automotive sector, along with its global counterparts, is doing so by developing *elektrische autos*. Electric cars are an important focus of Robert Bosch — another leading automotive company founded in Stuttgart. Today, Bosch supplies electric powertrains, systems, and components to automakers worldwide.

As the automotive industry races toward an electrified future, Bosch is accelerating its R&D into the essential building blocks of electric drivetrains. One of these components is the inverter, which changes direct current (DC) from the car's batteries into alternating current (AC) to power its drive motor (Figure 1). The inverter's ability to provide a smooth flow of current depends on its integral DC link capacitor (Figure 2). "The capacitor is one of the most expensive components of the inverter. Its performance has a direct impact on the performance and reliability of the inverter, which is fundamental to the operation of the drivetrain," explains Martin Kessler, Bosch senior expert for automotive electronics.

For the global automotive sector to meet its ambitious electrification goals, inverters and their capacitors must undergo continuous improvement and optimization. Martin Kessler and his team rely on multiphysics simulation to test and refine Bosch's DC link capacitors. Their simulation-enabled predictive analysis complements and optimizes the live

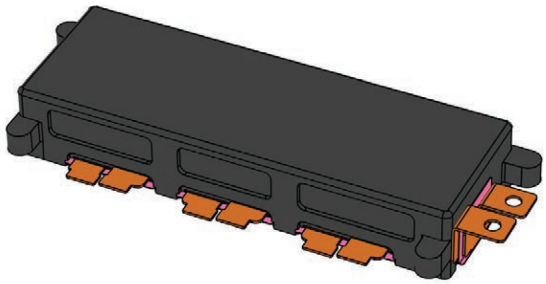

FIGURE 2 A typical DC link capacitor, with a battery interface on the right and transistor connectors on the front.

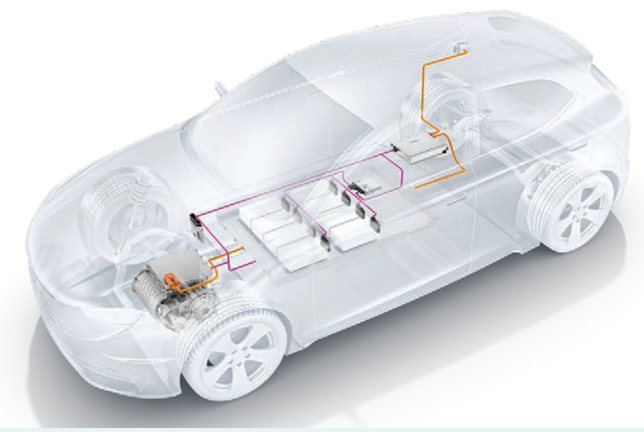

FIGURE 3 The path of current through a generic electric drivetrain. The path flows from a charger-converter, at right, to the battery shown at the center of the car. The battery provides DC to a three-phase inverter mounted above the drive motor assembly. The inverter converts DC into three-phase AC to power the car's drive motor.

prototyping of new designs. "It is simply not possible to predict potential problems with testing alone; we need both simulation and prototyping working hand in hand," says Kessler.

» THE EMERGING ERA OF THE ELECTRIC AUTOMOBILE

"Drivers, start your engines!" As if heeding the call to begin a worldwide race, people everywhere begin their days by firing up a rumbling IC engine. But this familiar sound can seem ominous, especially as the environmental impact of vehicle emissions grows more apparent. To lessen these emissions and their contribution to global climate change, the automobile industry is ramping up the production of electric-powered cars and trucks. Many of the electric vehicles available today have familiar brand names, but under the hood, these cars often rely on the technology and expertise of outside suppliers.

It is worth noting just how significant a shift this is for a major global industry. Leading automakers are some of the world's largest employers, and a vast share of their workers, R&D, and production capacity is dedicated to producing IC engines. The centrality of internal combustion to these companies can be found in their names, from General Motors to Bayerische Motoren Werke (better known as BMW). Why would companies known for their engines turn to outsiders to make their cars go? Perhaps it is because, in a sense, electrification is forcing the industry to learn how to produce an entirely different type of machine.

» ANATOMY OF AN ELECTRIC DRIVETRAIN

To make a fully electric car, it is not enough to replace the engine with an electric motor and the gas tank with a battery. Such familiar devices are only parts of a larger system, which helps deliver smooth, reliable performance by adjusting to the constantly varying conditions under which every vehicle must operate (Figure 3).

» INDISPENSABLE INVERTER, CRUCIAL CAPACITOR

The role of the inverter in an automotive drivetrain is simple in concept, but complex in practice (Figure 4). The inverter must satisfy the AC demands of the motor with the DC provided by the battery, but it must also adjust to ongoing fluctuations in load, charge, temperature, and other factors that can affect the behavior of each part of the system. All of this must occur within tight cost and spatial constraints, and the component must sustain this performance for years to come.

To understand the inverter's function, consider what a three-phase AC motor needs in order to operate. If connected to DC, the motor simply will not rotate. Instead, it must be provided with alternating current with three distinct but complementary waveforms, enabling the motor's three-part field coil to magnetically attract the segments of its rotor in a sequential pattern. "To control the activity of the motor, we must control the amplitude and frequency of the inverter's current output," explains Kessler. "The speed of the motor is proportional to frequency, while amplitude helps determine its torque."

"The desired current waveform through the transistors has a relatively steep gradient. The only way to achieve switch-mode current with this high gradient is to have very low inductance in the source path," Kessler says. Inductance is the particular force opposing changes in current flow. Every slight change in current will be limited by an induced counteracting voltage, which will disrupt the desired waveform — and the smooth rotation of the motor.

To reduce the inductance in the source path of the transistors, a capacitor is placed in parallel across the input lead from the battery, which is called the DC link. The DC link capacitor (Figure 5) is placed in direct proximity to the transistors and provides the desired current waveforms through the transistors. The low impedance of the capacitor minimizes any remaining ripple voltage on the battery side.

A typical capacitor consists of two electrodes separated by an insulating gap, which may simply be airspace or some kind of material. In this application, Bosch uses capacitors made with metallized polypropylene film. A thin coating of metal (forming the electrodes) is sprayed on each side of the film, which provides the necessary dielectric gap. The metallized film is then wound tightly into a canister shape. As with the inverter itself, the capacitor's conceptual simplicity conceals a multifaceted engineering design problem.

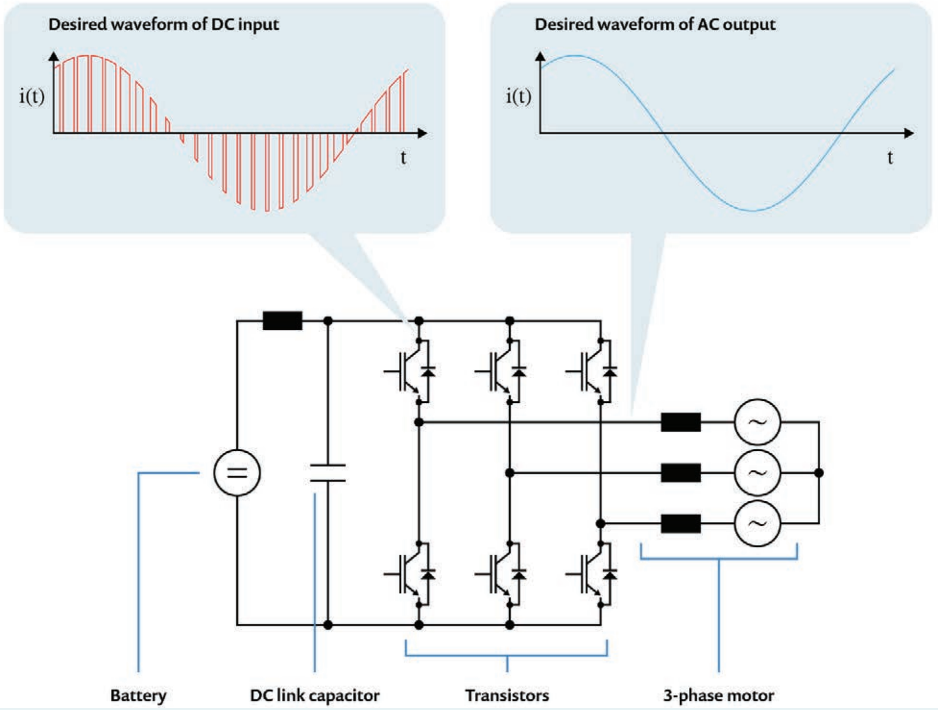

FIGURE 4 Inside a three-phase inverter, DC from the battery is converted to three-phase AC by three sets of transistors. By switching on and off in sequence, the transistors produce AC in three distinct phases, causing the car's drive motor to rotate. The DC link capacitor helps manage the input current.

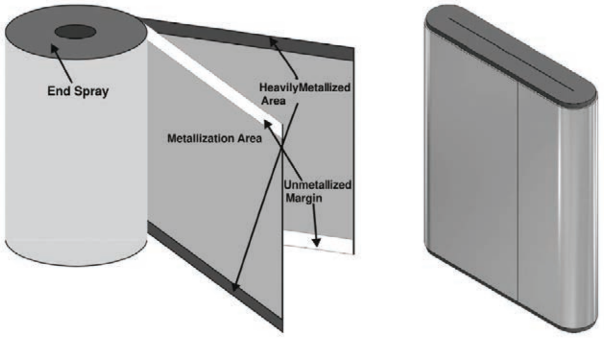

FIGURE 5 DC link capacitors are made from metallized polypropylene film, which is wound into an elongated canister shape.

» CHALLENGES OF DC LINK CAPACITOR DESIGN FOR VEHICLE INVERTERS

Capacitors are widely available components that are installed in countless electronic devices. For the past seven years, Martin Kessler has been responsible for DC link capacitor design at Bosch. He has been with the company since 1989 and has worked on electric car technology since 2010. That such an experienced engineer is dedicated to this one component shows its importance — and its complexity.

"Why can we not just pick up a capacitor from the marketplace?" asks Kessler, rhetorically. "There are multiple interdependent factors at work. First, we have high demands for performance and reliability. Second, there are very tight spatial requirements. Third, we face difficult thermal constraints, as the polypropylene film in a capacitor can only withstand temperatures up to around 105°C. This issue is compounded by the interaction of electromagnetic and thermal activity throughout the inverter. And finally, the capacitor is relatively expensive," Kessler explains.

» SIMULATION (NOT LUCK) HELPS SOLVE THE BLACK BOX PROBLEM

To meet the design challenges of a DC link capacitor, Kessler developed a process that combines experimental testing with multiphysics simulation. As an example of why simulation-based analysis is a necessary part of his work, he cites the difficulty of finding and measuring potential hot spots, where high heat and coupled effects can cause failures. "We try to locate hot spots by placing a lot of thermocouples inside prototypes and measuring temperatures at various load points," Kessler says. "But my mantra is that you will never find a hot spot like this without a lot of luck! You will need to be lucky to place the thermocouple in the right position," he laughs.

"A simple 2D model of a capacitor is also insufficient," Kessler continues. "The inverter is a distributed system with internal resonances and a complex loss distribution. Our coupled EM and thermal analysis must account for skin effects and proximity effects. We cannot calculate an absolute value for peak temperatures without a 3D finite element approach, which also enables us to model the spatial distribution of coupled EM and thermal effects. This is an ideal task for the COMSOL Multiphysics® software," Kessler says (Figures 6–7).

Kessler's design process validates simulation models against measured results, where possible, and then uses the validated models to pinpoint potential problems (Figure 8). "By helping us locate hot spots in the model, the simulation helps us avoid issues that would have appeared late in the development process, or even after production had started," says Kessler. "Instead, we can get specific results and make adjustments early in the process."

"We perform EM modeling and validation of every new design. We compare the calculated equivalent series resistance (ESR) curve with the ESR curve as measured

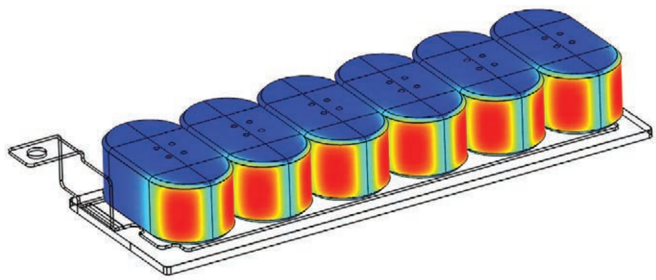

FIGURE 6 3D model image showing simulation of EM effects inside a DC link capacitor design.

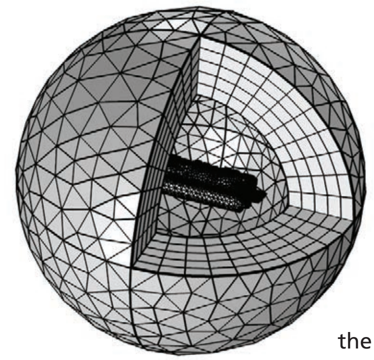

FIGURE 7 A model of the electromagnetic field generated by the capacitor, which aids the calculation of loss distribution in the unit.

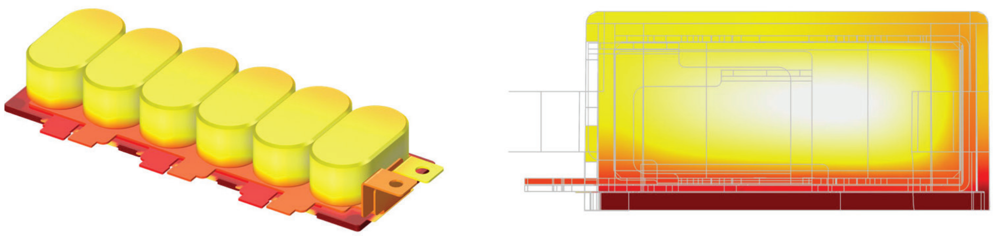

FIGURE 8 A 3D model showing simulation of thermal effects inside a DC link capacitor design, and a cutaway view showing the hotspot location in the capacitor.

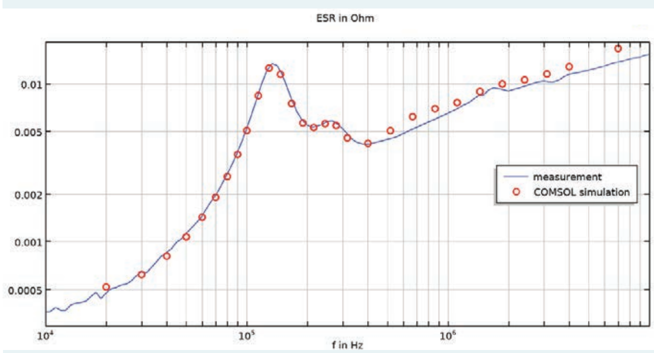

FIGURE 9 A plot of the ESR curve, as calculated in the simulation, compared with ESR values derived from measurement of a live prototype. Alignment of these curves helps validate the model for further analysis.

from a prototype (Figure 9). If these curves are aligned, we can set up boundary conditions for stationary and transient heat calculations," says Kessler. "We can compare the temperature curves from our thermocouples with the results of probes in the COMSOL Multiphysics model. If they match, we can then simulate all the critical points where we must keep temperatures within limits." The curve data is put into the COMSOL Multiphysics software via the LiveLink™ *for* MATLAB® interfacing product.

"Before we can do this, we have to think about which factors should be incorporated into the model," says Kessler. "Some of the variables we receive from the OEM, such as maximum DC link voltage, are not very relevant to our simulation," he continues. "But the current, switching frequency, e-machine values, and modulation schemes all help define a current spectrum. We need to calculate the current spectrum for all three phases of our output in order to establish power losses. Once we have this, we can do the harmonic analysis with COMSOL Multiphysics for the frequencies of the current spectrum. Then we sum up our losses for every harmonic," Kessler explains.

Other important values include the boundary conditions, which help Kessler and his team determine coupled effects. "We calculate parasitic inductance of the capacitor with the AC/DC Module," Kessler says. "We also find the complete AC loss distribution through the capacitor windings or internal busbar. Then we can couple the results and determine a temperature-dependent resistivity of the cover parts with the Heat Transfer Module," he says. "This enables us to establish the maximum element hot spot temperature resulting from the EM activity."

Findings from their analyses can then lead to design changes. Kessler explains that each new capacitor design typically undergoes three rounds of testing. "With simulation, the improvement curve gradient is much steeper from one phase to the next. Our knowledge grows quickly, and this is reflected in the final product." The latest generation of Bosch inverters promises 6% greater range and a 200% jump in power density compared to previous designs.

» ELECTRIFICATION SHIFTS INTO HIGH GEAR

As automakers convert more of their product lines to electric propulsion, Martin Kessler believes that the need for rapid, cost-conscious R&D will also increase. "Electric mobility is growing up now," he says. "We expect that the OEMs will come to us with more varied needs, for inverters in different power classes and that meet tighter spatial constraints," says Kessler. "I do think that the number of products that require new capacitor designs will keep expanding. With our simulation-driven development methods, we are confident that we can keep up with this growth."

In the years to come, perhaps visitors to Stuttgart's car museums will stop to admire the historic motors and inverters that powered the industry into a new electric age. ◎

Manufacturing Technology Centre, United Kingdom

FINE-TUNING THE FACTORY: A SIMULATION APP HELPS OPTIMIZE AN ADDITIVE MANUFACTURING FACILITY

Additive manufacturing (AM) processes, such as metal powder bed fusion, can provide rapid and customizable production of high-quality components. Britain's Manufacturing Technology Centre, along with partners in the aerospace sector, has built an on-site powder bed fusion facility — and also developed a simulation model and app to help factory staff make informed decisions about its operation.

by **ALAN PETRILLO**

History teaches that the Industrial Revolution began in England in the mid-18th century. While that era of sooty foundries and mills is long past, manufacturing remains essential — and challenging. One promising way to meet modern industrial challenges is by using additive manufacturing (AM) processes, such as powder bed fusion and other emerging techniques. To fulfill its promise of rapid, precise, and customizable production, AM demands more than just a retooling of factory equipment; it also calls for new approaches to factory operation and management.

That is why Britain's Manufacturing Technology Centre (MTC) has enhanced its in-house metal powder bed fusion AM facility with a simulation model and app to help factory staff make informed decisions about its operation. The app, built using the Application Builder in the COMSOL Multiphysics® software, shows the potential for pairing a full-scale AM factory with a so-called "digital twin" of itself.

"The model helps predict how heat and humidity inside a powder bed fusion factory may affect product quality and worker safety," says Adam Holloway, a technology manager within the MTC's modeling team. "When combined with data feeds from our facility, the app helps us integrate predictive modeling into day-to-day decision-making." The MTC project demonstrates the benefits of placing simulation directly into the hands of today's industrial workforce and shows how simulation could help shape the future of manufacturing.

» ADDITIVE MANUFACTURING FOR AEROSPACE WITH DRAMA

To help modern British factories keep pace with the world, the MTC promotes high-value manufacturing throughout the United Kingdom. The MTC is based in the historic English industrial city of Coventry (Figure 1), but its focus is solely on the future. That is why the team has committed significant human and technical resources to its National Centre for Additive Manufacturing (NCAM).

"Adopting AM is not just about installing new equipment. Our clients are also seeking help with implementing the digital infrastructure that supports AM factory operations," says Holloway. "Along with enterprise software and data connectivity, we're exploring how to embed simulation within their systems as well."

The NCAM's Digital Reconfigurable Additive Manufacturing for Aerospace (DRAMA) project provides a valuable venue for this exploration. Developed in concert with numerous manufacturers, the DRAMA initiative includes the new powder bed fusion AM facility mentioned previously. With that mini factory as DRAMA's stage, Holloway and his fellow simulation specialists play important roles in making its production of AM aerospace components a success.

FIGURE 1 The headquarters of the Manufacturing Technology Centre in Coventry, England.

FIGURE 2 An example of a part produced through the metal powder bed fusion process.

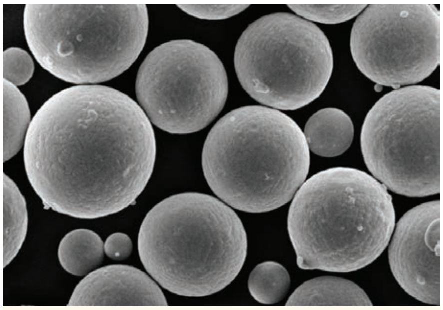

FIGURE 3 A microscopic close-up of powdered metal grains, as used for powder bed fusion.

» MAKING SOFT MATERIAL ADD UP TO SOLID OBJECTS

What makes a manufacturing process "additive", and why are so many industries exploring AM methods? In the broadest sense, an additive process is one where objects are created by adding material layer by layer, rather than removing it or molding it. A reductive or subtractive process for producing a part may, for example, begin with a solid block of metal that is then cut, drilled, and ground into shape. An additive method for making the same part, by contrast, begins with empty space! Loose or soft material is then added to that space (under carefully controlled conditions) until it forms the desired shape. That pliable material must then be solidified into a durable finished part.

Different materials demand different methods for generating and solidifying additive forms. For example, common 3D printers sold to consumers produce objects by unspooling warm, plastic filament, which bonds to itself and becomes harder as it cools. By contrast, the metal powder bed fusion process begins with, as its name suggests, a powdered metal which is then melted by applied heat and re-solidified when it cools. A part produced via the metal powder bed fusion process can be seen in Figure 2.

» HOW HEAT AND HUMIDITY AFFECT METAL POWDER BED FUSION

"The market opportunities for AM methods have been understood for a long time, but there have been many obstacles to large-scale adoption," Holloway says. "Some of these obstacles can be overcome during the design phase of products and AM facilities. Other issues, such as the impact of environmental conditions on AM production, must be addressed while the facility is operating."

For instance, maintaining careful control of heat and humidity is an essential task for the DRAMA team. "The metal powder used for the powder bed fusion process (Figure 3) is highly sensitive to external conditions," says Holloway. "This means it can begin to oxidize and pick up ambient moisture even while it sits in storage, and those processes will continue as it moves through the facility. Exposure to heat and moisture will change how it flows, how it melts, how it picks up an electric charge, and how it solidifies," he says. "All of these factors can affect the resulting quality of the parts you're producing."

Careless handling of powdered metal is not just a threat to product quality. It can threaten the health and safety of workers as well. "The metal powder used for AM processes is flammable and toxic, and as it dries out, it becomes even more flammable," Holloway says. "We need to continuously measure and manage humidity levels, as well as how loose powder propagates throughout the facility."

To maintain proper atmospheric conditions, a manufacturer could augment its factory's ventilation with a full climate control system, but that could be prohibitively expensive. The NCAM estimated that it would cost nearly half a million English pounds to add climate control to its relatively modest facility. But what if they could adequately manage heat and humidity without adding such a complicated system?

> "We're trying to present the findings of some very complex calculations in a simple-to-understand way. By creating an app from our model, we can empower staff to run predictive simulations on laptops during their daily shifts."
> — ADAM HOLLOWAY, MTC TECHNOLOGY MANAGER

» RESPONSIVE PROCESS MANAGEMENT WITH MULTIPHYSICS MODELING

Perhaps using multiphysics simulation for careful process management could provide a cost-effective alternative. "As part of the DRAMA program, we created a model of our facility using the computational fluid dynamics (CFD) capabilities of the COMSOL® software. Our model (Figure 4) uses the finite element method to solve partial differential equations describing heat transfer and fluid flow across the air domain in our facility," says Holloway. "This enabled us to study how environmental conditions would be affected by multiple variables, from

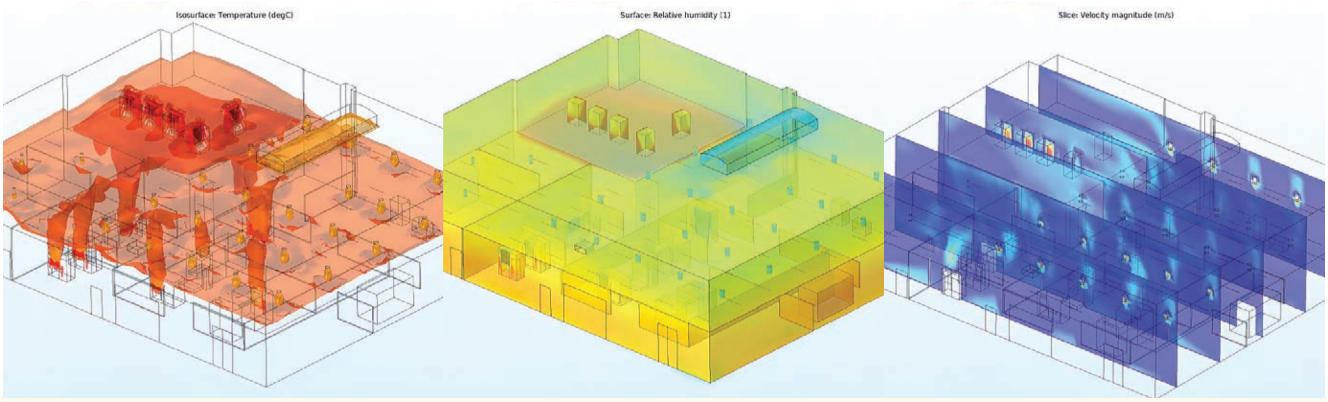

FIGURE 4 Three simulation images of the DRAMA facility with seven machines operating. At left is an isosurface plot showing temperature variations. The center image shows the distribution of humidity variations, and the image at right is a slice plot showing airflow velocity throughout the space.

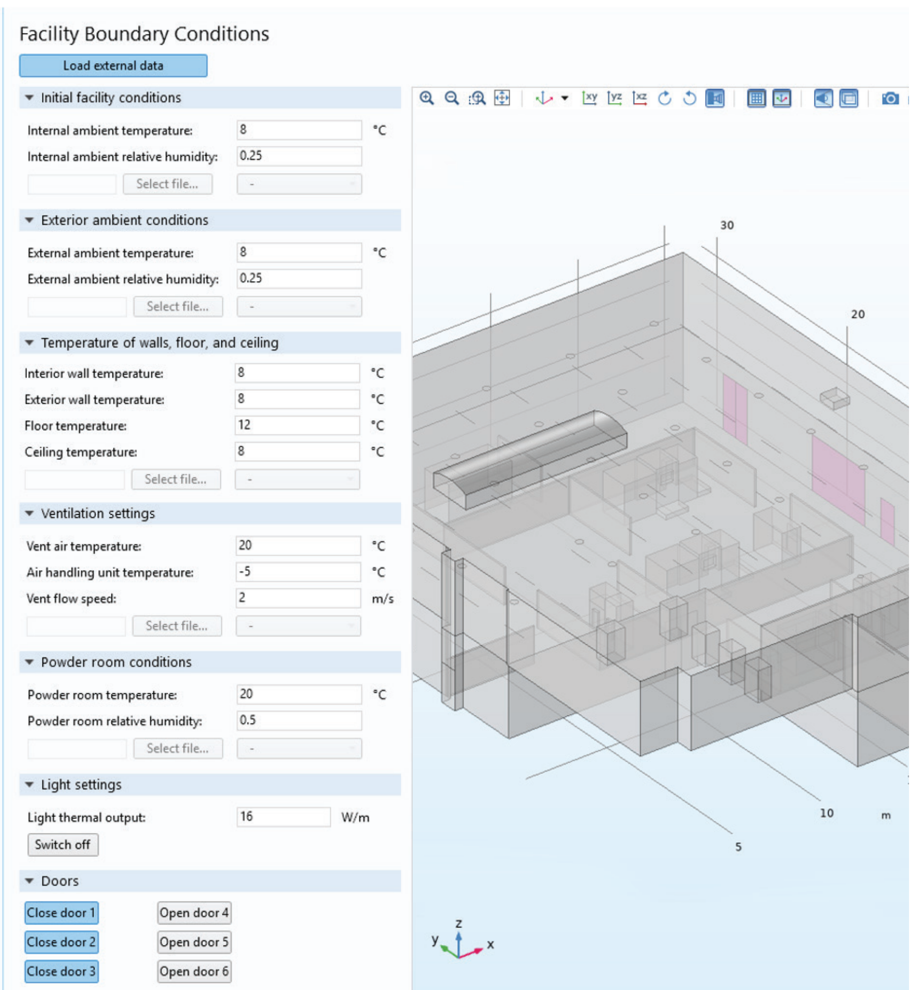

FIGURE 5 A simulation app of the DRAMA powder bed fusion facility, showing the machines it contains and the locations of the air vents. Users can specify the initial temperature and humidity throughout the space, along with settings for the air handling system, lights, and metal powder storage room. In this case, some doors (highlighted in pink) have been left open.

the weather outside, to the number of machines operating, to the way machines were positioned inside the shop. A model that accounts for those variables helps factory staff adjust ventilation and production schedules to optimize conditions," he explains.

» A SIMULATION APP THAT EMPOWERS FACTORY STAFF

The DRAMA team made their model more accessible by building a simulation app of it with the Application Builder in COMSOL Multiphysics (Figure 5). "We're trying to present the findings of some very complex calculations in a simple-to-understand way," Holloway explains. "By creating an app from our model, we can empower staff to run predictive simulations on laptops during their daily shifts."

The app user can define relevant boundary conditions for the beginning of a factory shift and then make ongoing adjustments. Over the course of a shift, heat and humidity levels will inevitably fluctuate. Perhaps factory staff should alter the production schedule to maintain part quality, or maybe they just need to open doors and windows to improve ventilation. Users can change settings in the app to test the possible effects of actions like these. For example, Figure 6 presents isothermal surface plots that show the effect that opening the AM machines' build chambers has on air temperature,

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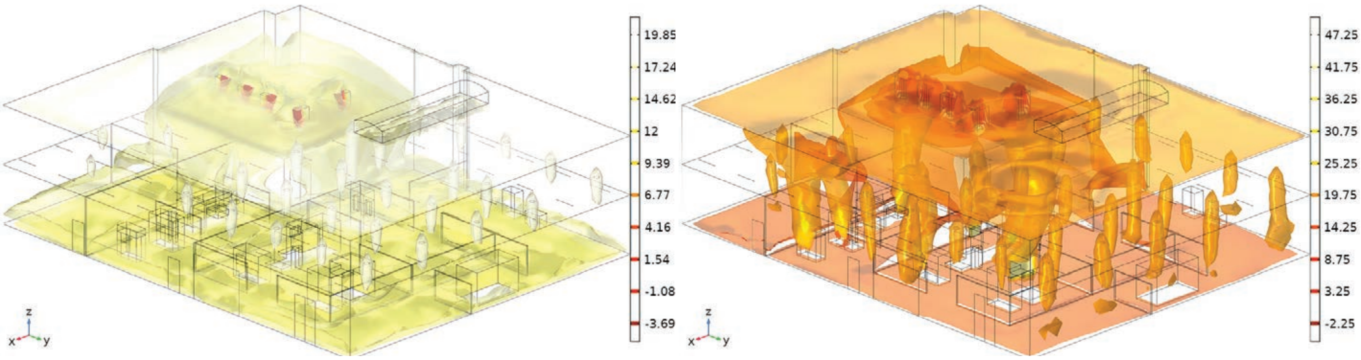


FIGURE 6 The simulation can capture variations in the thermal and fluid output of the machines over time. These isothermal surface plots show changes in temperature at 30 seconds (left) and 60 seconds (right) after opening the build chambers of every AM machine in the facility.

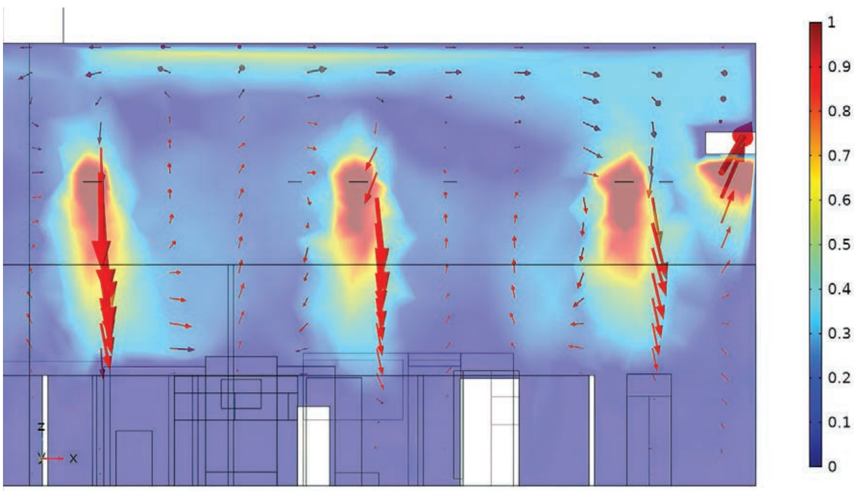


FIGURE 7 A slice plot showing the effect that opening a door has on airflow. Air velocity toward an outlet duct is significantly weakened when the door directly beneath it is opened.

while Figure 7 shows how airflow is affected by opening the facility doors.

» A STEP TOWARD A "FACTORY-LEVEL DIGITAL TWIN"

While the current app is an important step forward, it does still require workers to manually input relevant data. Looking ahead, the DRAMA team envisions something more integral, and therefore, more powerful: a "digital twin" for its AM facility. A digital twin, as described by Ed Fontes in a 2019 post on the COMSOL Blog, is "a dynamic, continuously updated representation of a real physical product, device, or process." It is important to note that even the most detailed model of a system is not necessarily its digital twin.

"To make our factory environment model a digital twin, we'd first provide it with ongoing live data from the actual factory," Holloway explains. "Once our factory model was running in the background, it could adjust its forecasts in response to its data feeds and suggesting specific actions based on those forecasts."

"We want to integrate our predictive model into a feedback loop that includes the actual factory and its staff. The goal is to have a holistic system that responds to current factory conditions, uses simulation to make predictions about future conditions, and seamlessly makes self-optimizing adjustments based on those predictions," Holloway says. "Then we could truly say we've built a digital twin for our factory."

» SIMULATION AT WORK ON THE FACTORY FLOOR

As an intermediate step toward building a full factory-level digital twin, the DRAMA simulation app has already proven its worth. "Our manufacturing partners may already see how modeling can help with planning an AM facility but not really understand how it can help with operation," Holloway says. "We're showing the value of enabling a line worker to open up the app, enter in a few readings or import sensor data, and then quickly get a meaningful forecast of how a batch of powder will behave that day."

Beyond its practical insights for manufacturers, the overall project may offer a broader lesson as well: By pairing its production line with a dynamic simulation model, the DRAMA project has made the entire operation safer, more productive, and more efficient. The DRAMA team has achieved this by deploying the model where it can do the most good — into the hands of the people working on the factory floor. ◎

Workers inside the NCAM metal powder bed facility at MTC.

Exicom Tele-Systems, India

REFINING AUTOMOTIVE BATTERY MANAGEMENT SYSTEMS WITH LUMPED-APPROACH THERMAL MODELING

For India's transportation sector to meet its ambitious electrification goals, manufacturers must accelerate the development of essential components, such as battery management systems (BMS). Exicom optimizes BMS performance by using multiphysics simulation to understand the thermal behavior of different battery cell and pack designs.

by **NEENA PICARDO**

India is a fast-growing market for electric vehicles (EVs), with one study predicting that over 30% of the vehicles sold in India will be electric by 2030. The battery packs that power EVs are one of the main drivers of the electric mobility revolution in India. In order to monitor and manage battery pack performance and safety, packs are usually equipped with a battery management system (BMS). A BMS is an electronic system that monitors a battery's voltage, temperature, coolant flow, and health and predicts a number of other performance parameters, such as current variation and heat generation, helping to extract optimum performance from a battery pack.

» THE ROLE OF SIMULATION IN DEVELOPING ACCURATE BMS

Exicom Tele-Systems Pvt. Ltd. designs, develops, and deploys energy solutions, including the latest Li-ion battery technologies. To date, it has deployed Li-ion battery solutions totaling more than 1.8 GWh — among the highest in the world by a single company. Exicom also offers charging solutions and BMS for electric two-wheelers and light electric vehicles, which are driving the growth of electric mobility in India. Exicom's innovative BMS solutions are prized for their performance and life.

At Exicom's R&D center in Gurugram, India, the technology team led by Dr. Parmender Singh has developed a BMS that can be used to precisely monitor and manage Li-ion batteries in applications across a broad voltage range (up to 1000 V). This BMS is also chemistry agnostic; it can be used with Li-ion batteries of a range of chemistries such as lithium ferrophosphate, or lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA).

The precision of the BMS depends on the quality and accuracy of the inputs used for programming or calibrating the system. For example, the BMS includes a number of thermal sensors distributed across the battery pack. In order to accurately monitor a battery pack's temperature distribution and predict corresponding performance, it is imperative that the sensors be placed at the right locations. This requires a detailed understanding of the heat profile of each battery cell as well as how heat varies throughout the pack. This is where COMSOL Multiphysics® plays an integral part, by allowing for accurate computation and collation of the inputs, like heat profile information, that are required to develop a BMS with surgical precision.

» PREDICTING AND PREVENTING POTENTIAL THERMAL RUNAWAY

Dr. Singh's team at Exicom used COMSOL Multiphysics to perform a number of analyses on the thermal behavior of battery cells. They also used simulation to analyze potential external short circuits, which could cause thermal runaway — an uncontrolled self-heating process that can damage equipment or even cause fires. The Exicom team began by analyzing the heat generated in cylindrical cells with different form factors and further extended this model to the pack level using the heat profile generated for the cells. "We were especially interested in improving the temperature gradient across the pack for air-cooled battery packs," said Dr. Singh.

The results for thermal modeling at the cell level for cylindrical cells during a 1C discharging are shown in Figure 1. The visualization on the left in Figure 1 shows the temperature distribution, where the maximum temperature is observed in the middle of the cell. The visualization on the right shows the contour distribution of temperature, where the maximum temperature is located in the active material of the cell.

The simulation results, when validated with experimental findings, were observed to be within the error limits of ±5% at the standard charge–discharge profile. The model was then further extended for 2C discharge at 100% state of charge (SOC) according to Standard UL1642, which is defined for external short-circuit testing.

The positive and negative terminals of the cell were shorted via an 80 ±20 mΩ resistance. The COMSOL® software's lumped approach-based thermal model was validated against experimental data for charge–discharge profiles of the cell. They also developed:

- Cyclic and calendric capacity-fade models for cylindrical cells based on the optimization features available in COMSOL®
- A high-fidelity pseudo two-dimensional (P2D) model for cylindrical cells using extracted electrochemical parameters

They found that the lumped approach enabled them to construct models using a minimal number of parameters — such as cell geometry, electrode thickness, thermal conductivity, heat capacity, drive cycle, and open-circuit voltage (OCV)-SOC table — that are readily available from battery pack manufacturers.

Extracting these parameters experimentally is not only a time-consuming process but also prone to errors due to variable experimental conditions. For example, ambient temperature fluctuates, so extracting an accurate heat profile of a cell requires performing an extensive series of tests at different ambient temperatures. Using simulation, however, Dr. Singh and the team were able to perform these experiments with great ease. They were able to efficiently study charge and discharge profiles, thermal behavior at different charge and discharge rates, and thermal runaway (Figure 2) due to external or internal short circuits for

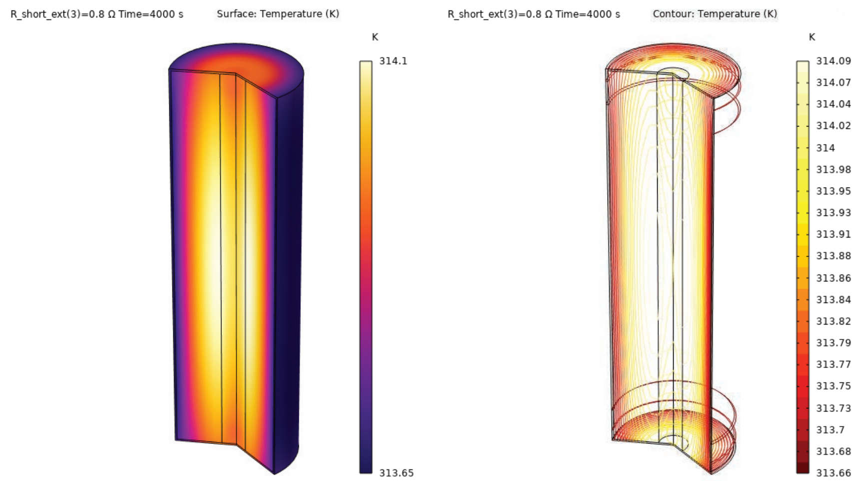


FIGURE 1 The temperature distribution in a cylindrical cell at 1C discharge (left) and the contour distribution of temperature (right).

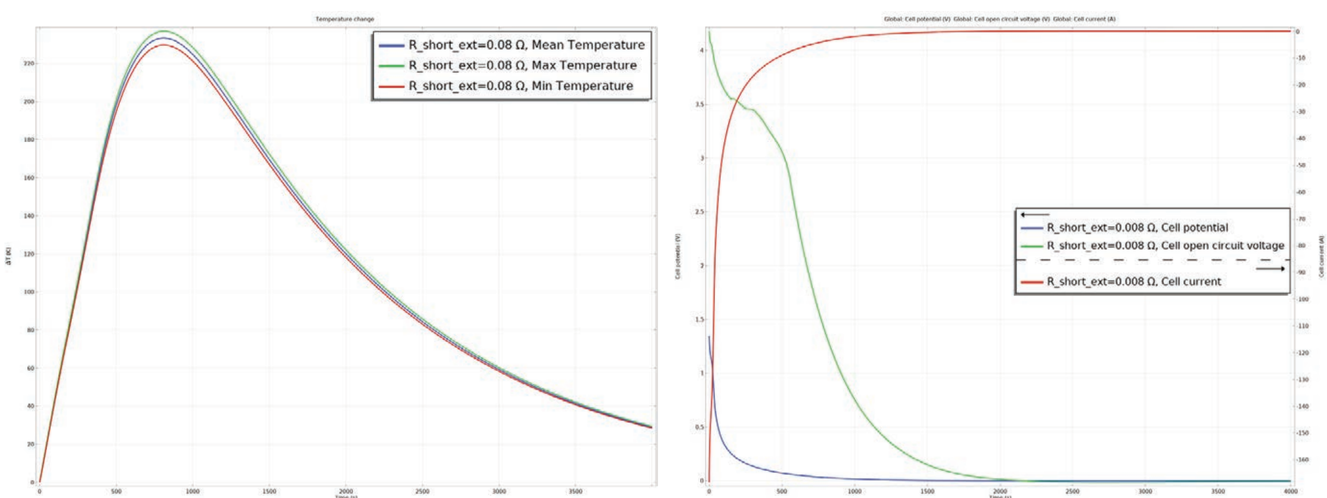


FIGURE 2 The temperature profile in a cell after thermal runaway (left) and the electrochemical profile in a cell after thermal runaway (right).

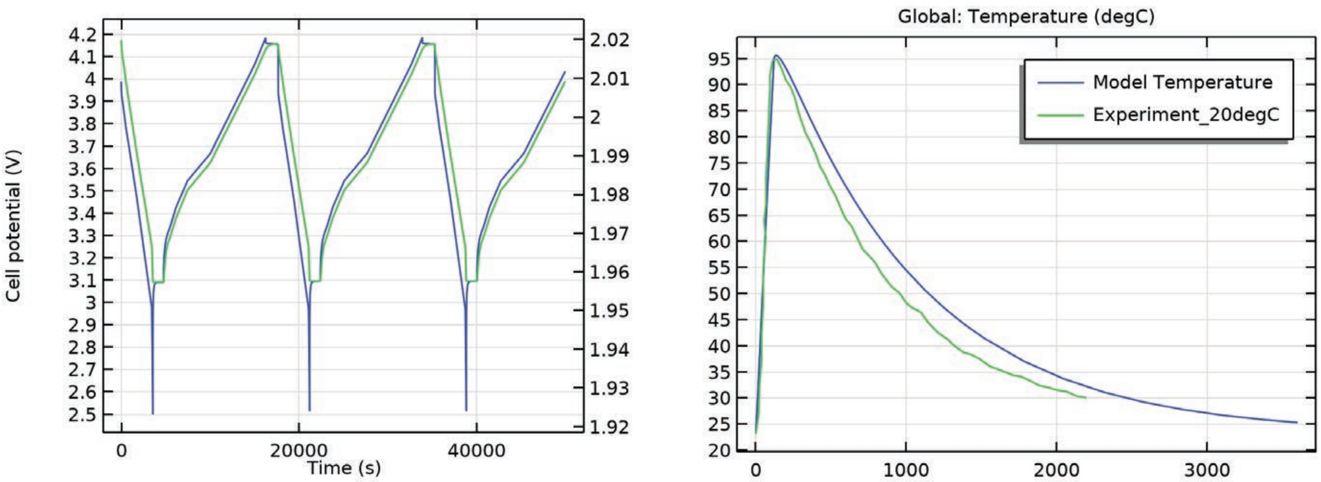


FIGURE 3 Simulated and experimental data during external short-circuit testing.

different cell chemistries (Figure 3). They were also able to identify the hotspots in the battery pack and determine the cell grading based on capacity fade analysis with high accuracy. These results had direct applications in reducing the development cycle time of the BMS, as the hotspots indicated the best positions for deploying the thermal sensors within the BMS in order to function most efficiently. According to Dr. Singh, "COMSOL® is an easy-to-learn and adaptable finite element tool for battery design and thermal modeling."

» FUTURE SCOPE: EXTENDING BATTERY SIMULATIONS TO PREDICT AGING

In addition to the thermal simulations, Dr. Singh has expanded the use of simulations to investigate another important phenomenon: battery aging. During the lifetime of a battery, its state of health (SOH) progressively deteriorates due to irreversible physical and chemical changes, such as the growth of a solid electrolyte interphase (SEI) layer, which can lead to loss of porosity in a battery cell, which in turn can lead to an increase in polarization and internal resistance. Magnetic field probing (MFP) is a noninvasive method for monitoring a battery's SOH. With the aim of demonstrating the potential of the MFP method, Dr. Singh developed a multiphysics model in COMSOL® to evaluate the magnetic field response, battery polarization, and internal resistance of the Li-ion response (Figure 4). The team observed that variation in electrode porosity has a significant influence on the magnetic field response. Though this research is currently in its preliminary stages, the potential applications are far reaching. "We expect that further investigation into this phenomenon will allow for developing and deploying monitoring features for battery aging as well as better protection mechanisms against it in the BMS itself," said Dr. Singh.

The Exicom team is currently working on electrochemical P2D modeling for thermal and capacity-fading analysis at the cell level. It intends to further extend the model with additional thermal exothermic equations at the electrodes and SEI layer for better accuracy during thermal runaway. They also plan to use the lumped capacity fade model for cyclic and calendric predictive analysis. In the future, they also plan to implement a reduced-order model for SOC and SOH and export the model to MATLAB® for code generation up to the ASIC level.

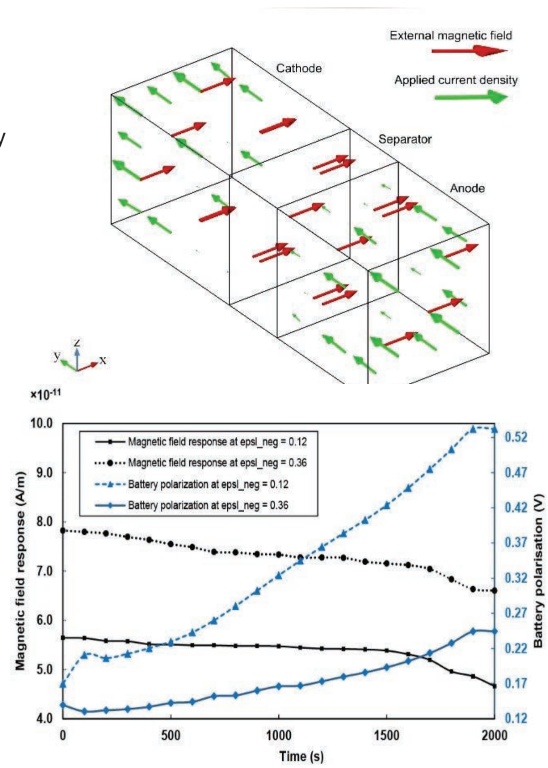


FIGURE 4 3D-designed cell geometry (top). Variation of magnetic field response and polarization behavior during discharging at 0.12 and 0.36 anode porosity values (bottom).

With the accelerating transition to electric mobility in India and worldwide, research on battery technology is expected to increase significantly in the coming years. Simulation software like COMSOL® offers a crucial head start to companies in the electric mobility space that want to provide more effective solutions and improve the time to market for their products. ◎

Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland

DESIGNING A SILICON PHOTONIC MEMS PHASE SHIFTER WITH SIMULATION

by **ALAN PETRILLO**

Optical fiber networks, which make up the backbone of the internet, rely on many electrical signal processing devices. Nanoscale silicon photonic network components, such as phase shifters, could boost optical network speed, capacity, and reliability. To design these small but powerful devices, a team at the Swiss Federal Institute of Technology Lausanne (EPFL) uses simulation to optimize both optical and electromechanical performance.

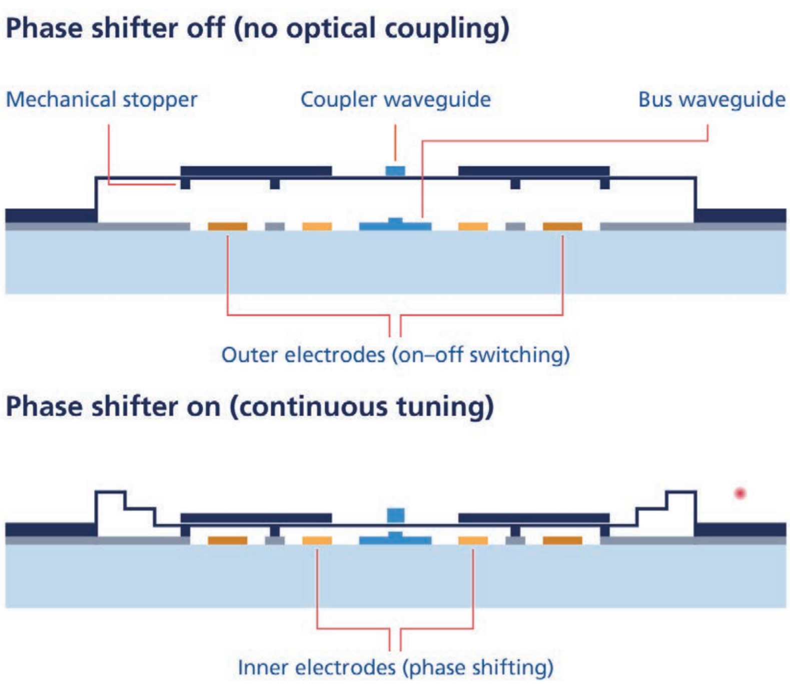


FIGURE 1 Two stages of motion for the MEMS mechanism in the phase shifter.

The modern internet-connected world is often described as *wired*, but most core network data traffic is actually carried by optical fiber — not electric wires. Despite this, existing infrastructure still relies on many electrical signal processing components embedded inside fiber optic networks. Replacing these components with photonic devices could boost network speed, capacity, and reliability. To help realize the potential of this emerging technology, a multinational team at the Swiss Federal Institute of Technology Lausanne (EPFL) has developed a prototype of a silicon photonic phase shifter, a device that could become an essential building block for the next generation of optical fiber data networks.

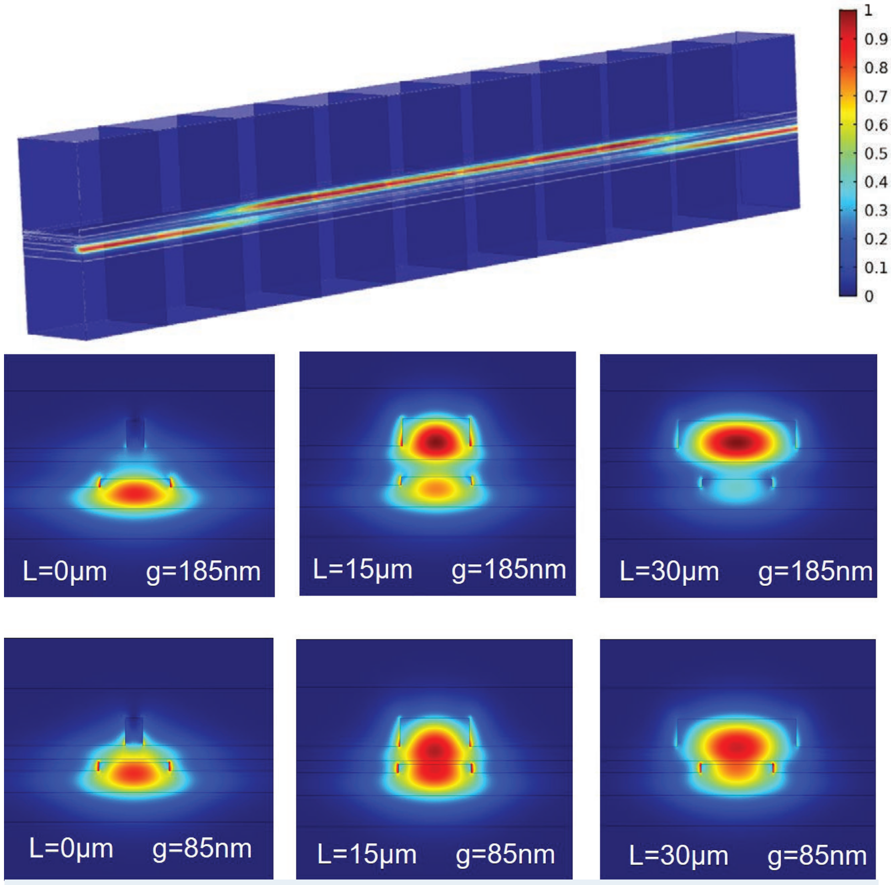


FIGURE 2 Top: Light passes from left to right through a path composed of an optical bus and a coupled movable waveguide. Bottom: six cross-sectional slices of a simulated light waveform as it passes through the coupled device. By adjusting the distance between the two optical elements in their simulation, the EPFL team could determine how that distance affected the speed, or phase, of the optical signal. Images courtesy EPFL and licensed under CC BY 4.0.

» LIGHTING A PATH TOWARD ALL-OPTICAL NETWORKS

Using photonic devices to process photonic signals seems logical, so why is this approach not already the norm? "A very good question, but actually a tricky one to answer!" says Hamed Sattari, an engineer currently at the Swiss Center for Electronics and Microtechnology (CSEM) specializing in photonic integrated circuits (PIC) with a focus on microelectromechanical system (MEMS) technology. Sattari was a key member of the EPFL photonics team that developed the silicon photonic phase shifter. In pursuing a MEMS-based approach to optical signal processing, Sattari and his colleagues are taking advantage of new and emerging fabrication technology. "Even ten years ago, we were not able to reliably produce integrated movable structures for use in these devices," Sattari says. "Now, silicon photonics and MEMS are becoming more achievable with the current manufacturing capabilities of the microelectronics industry. Our goal is to demonstrate how these capabilities can be used to transform optical fiber network infrastructure."

The phase shifter design project is part of EPFL's broader efforts to develop programmable photonic components for fiber optic data networks and space applications. These devices include switches; chip-to-fiber grating couplers; variable optical attenuators (VOAs); and phase shifters, which modulate optical signals. "Existing optical phase shifters for this application tend to be bulky, or they suffer from signal loss," Sattari says. "Our priority is to create a smaller phase shifter with lower loss, and to make it scalable for use in many network applications. MEMS actuation of movable waveguides could modulate an optical signal with low power consumption in a small footprint," he explains.

» HOW A MOVABLE WAVEGUIDE HELPS MODULATE OPTICAL SIGNALS

The MEMS phase shifter is a sophisticated mechanism with a deceptively simple-sounding purpose: It adjusts the speed of light. To shift the phase of light is to slow it down. When light is carrying a data signal, a change in its speed causes a change in the signal. Rapid and precise shifts in phase will thereby modulate the signal, supporting data transmission with minimal loss throughout the network. To change the phase of light traveling through an optical fiber conductor, or *bus waveguide*, the MEMS mechanism moves a piece of translucent silicon called a *coupler* into close proximity with the bus.

The design of the MEMS mechanism in the phase shifter provides two stages of motion (Figure 1). The first stage provides a simple on–off movement of the coupler waveguide, thereby engaging or disengaging the coupler to the bus. When the coupler is engaged, a finer range of motion is then provided by the second stage. This enables tuning of the gap between the coupler and bus, which provides precise modulation of phase change in the optical signal. "Moving the coupler toward the bus is what changes the phase of the signal,"

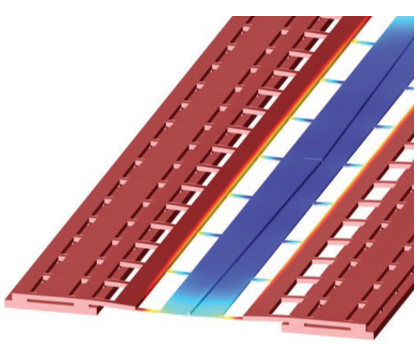


FIGURE 3 Simulation showing deformation of the movable waveguide support structure. The thin elements that suspend the movable waveguide will flex in response to an applied voltage. Image courtesy EPFL and licensed under CC BY 4.0.

explains Sattari. "The coupler is made from silicon with a high refractive index. When the two components are coupled, a light wave moving through the bus will also pass through the coupler, and the wave will slow down." If the optical coupling of the coupler and bus is not carefully controlled, the light's waveform can be distorted, potentially losing the signal — and the data.

» DESIGNING AT NANOSCALE WITH OPTICAL AND ELECTROMECHANICAL SIMULATION

The challenge for Sattari and his team was to design a nanoscale mechanism to control the coupling process as precisely and reliably as possible. As their phase shifter would use electric current to physically move an optical element, Sattari and the EPFL team took a two-track approach to the device's design. Their goal was to determine how much voltage had to be applied to the MEMS mechanism to induce a desired shift in the photonic signal. Simulation was an essential tool for determining the multiple values that would establish the voltage versus phase relationship. "Voltage vs. phase is a complex multiphysics question. The COMSOL Multiphysics® software gave us many options for breaking this large problem into smaller tasks," Sattari says. "We conducted our simulation in two parallel arcs, using the RF Module for optical modeling and the Structural Mechanics Module for electromechanical simulation."

The optical modeling (Figure 2) included a mode analysis, which determined the effective refractive index of the coupled waveguide elements, followed by a study of the signal propagation. "Our goal is for light to enter and exit our device with only the desired change in its phase," Sattari says. "To help achieve this, we can determine the eigenmode of our system in COMSOL®."

Along with determining the physical forms of the waveguide and actuation mechanism, simulation also enabled Sattari to study stress effects, such as unwanted deformation or displacement caused by repeated operation. "Every decision about the design is based on what the simulation showed us," he says.

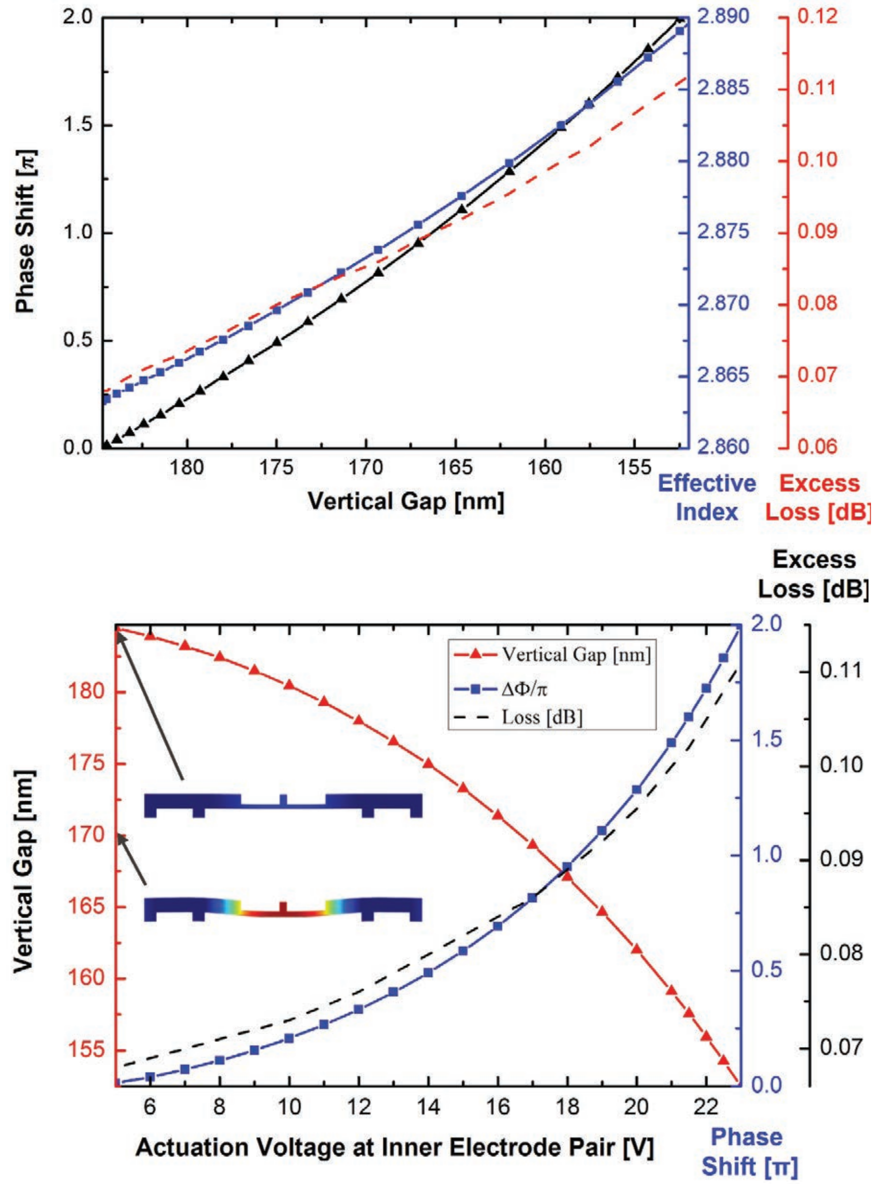


FIGURE 4 Optical simulation (top) established the vertical distance between the coupler and waveguide that would result in a desired phase shift in the optical signal. Electromechanical simulation (bottom) determined the voltage that, when applied to the MEMS mechanism, would move the coupler waveguide to the desired distance away from the bus. Images courtesy EPFL and licensed under CC BY 4.0.

» ADDING TO THE FOUNDATION OF FUTURE PHOTONIC NETWORKS

The goal of this project was to demonstrate how MEMS phase shifters could be produced with existing fabrication capabilities. The result is a robust and reliable design that is achievable with existing surface micromachined manufacturing processes, and occupies a total footprint of just 60 µm × 44 µm. Now that they have an established proof of concept, Sattari and his colleagues look forward to seeing their designs integrated into the world's optical data networks. "We are creating building blocks for the future, and it will be rewarding to see their potential become a reality," says Sattari.

Polar Night Energy, Finland

HEATING BUILDINGS WITH SOLAR ENERGY STORED IN SAND

by **ALAN PETRILLO**

Polar Night Energy, a startup in Finland, has developed technology for warming up buildings with solar-generated heat stored in sand. The team uses thermal modeling to optimize the design of their heat storage and distribution systems, which are helping Finnish cities reduce their consumption of nonrenewable heating fuels.

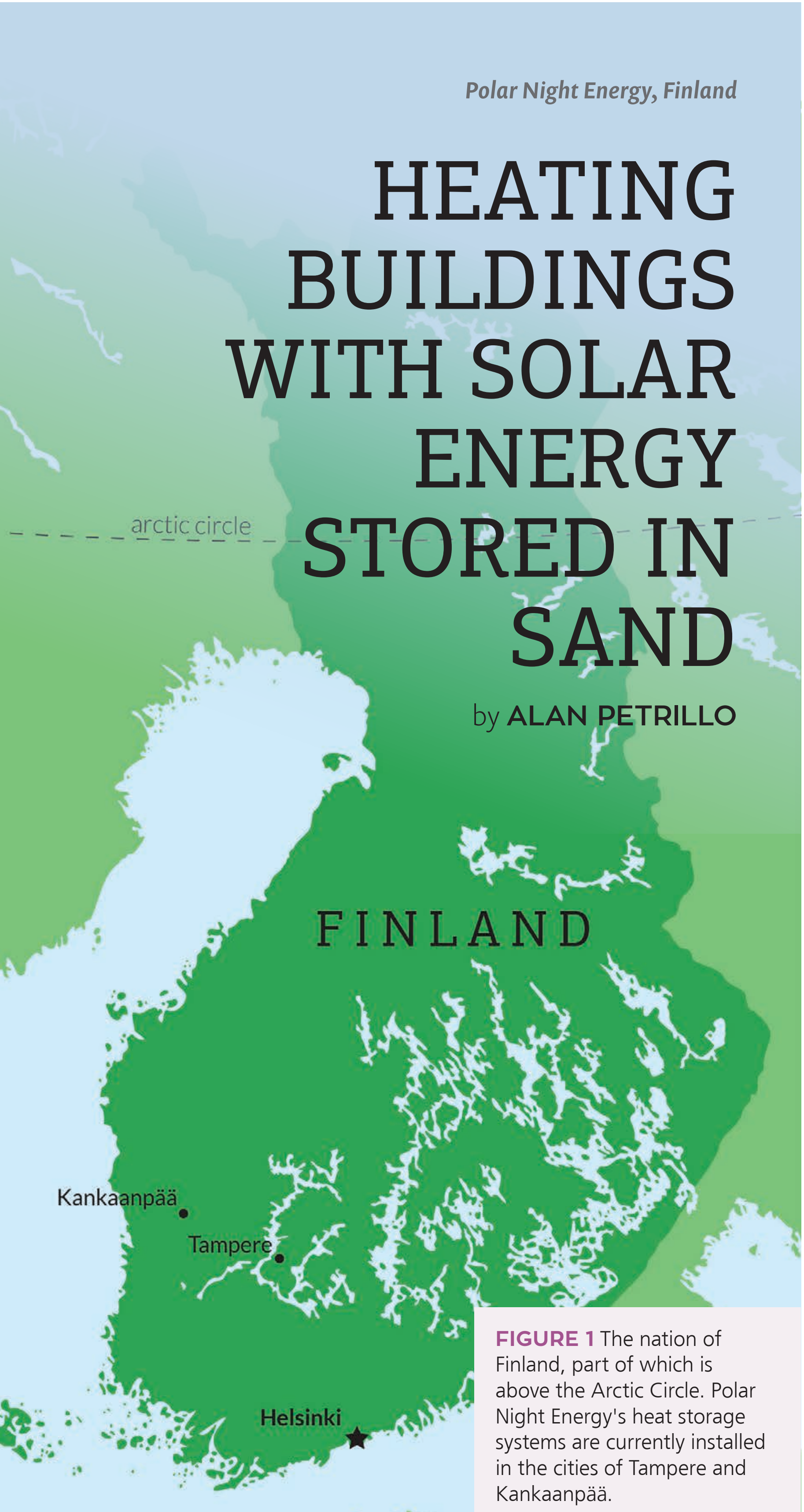


FIGURE 1 The nation of Finland, part of which is above the Arctic Circle. Polar Night Energy's heat storage systems are currently installed in the cities of Tampere and Kankaanpää.

As we try to objectively study nature, we are often reminded of how natural forces affect us personally. We can sit at a desk and consider heat in its various forms, but we might be distracted if our toes are cold! When we turn up the heat in our homes and workplaces, we must balance our personal need for warmth with the global impact of burning fossil fuels like oil, gas, coal, and biomass. Anthropogenic climate change confronts humanity with a challenge: How can we keep warm now as we try to prevent our world from overheating in the future?

It is a daunting question that a startup called Polar Night Energy, in the small and chilly nation of Finland (Figure 1), is attempting to answer. In a region known for long, dark winter nights, Polar Night Energy is building a system in the city of Tampere that can heat buildings with stored solar energy — all day, all night, and all winter long. The apparent

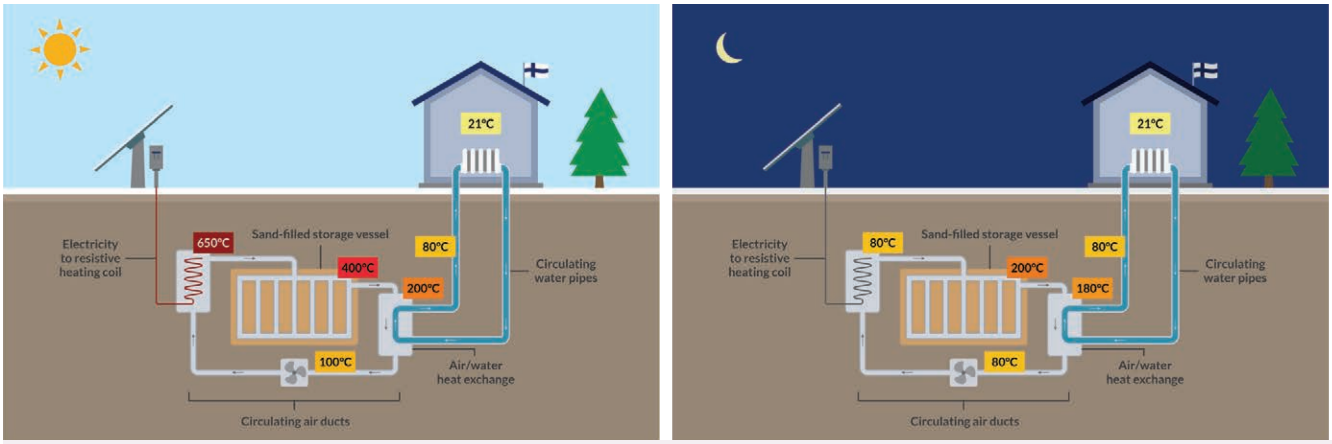


FIGURE 2 A schematic of the components and operating cycle of the Polar Night Energy system.

FIGURE 3 Markku Ylönen with a representative sample of Polar Night Energy's dirt-cheap heat storage medium.

FIGURE 4 Tommi Eronen (foreground) and Ylönen inspecting the ductwork of a Polar Night Energy heat storage vessel.

contradictions do not end there. In an era of complex cleantech solutions, often made from rare and expensive materials, Polar Night Energy's heat storage and distribution system consists of simple ducts, pumps, valves, and sand. The novel system shows potential for tackling global problems in a patient, thoughtful, and human-scaled way.

» A SMALL COUNTRY WITH LARGE HEATING NEEDS

Big problems demand big solutions, and there is perhaps no bigger 21st-century problem than climate change. To meet this challenge, many governments and organizations are investing in new technology to help lessen the use of fossil fuels. These initiatives have largely focused on renewable electric power generation, distribution, and storage.

"When you ask people about cleaner energy, they think of electricity," says Tommi Eronen, CEO of Polar Night Energy. "But we also have to cut emissions from heating." Out of Finland's energy-related emissions, 82% come from heating domestic buildings. "We want to replace all of that if we are to have any hope of meeting our global climate goals," Eronen says.

» THINK GLOBALLY, HEAT LOCALLY

The spirit of "Think Globally, Act Locally", a mantra associated with the 1960s, lives on with Polar Night Energy's team of innovators. Their journey began with a question posed by its founders, Tommi Eronen and Markku Ylönen, when they were university classmates: "Is it possible to build an energy-self-sufficient and cost-effective hippie commune for engineers using only solar power?" After graduation, the project they codenamed "Hippie Commune" became Polar Night Energy, with Eronen as CEO and Ylönen as CTO.

What began as a lighthearted (but serious) student project led to a 3 MWh/100 kW pilot plant in the Finnish city of Tampere, which began operation during the winter of 2020–2021. The system uses electricity to heat air, which is then circulated through an exchanger that heats water and distributes it to multiple buildings in the city's Hiedanranta district (Figure 2).

Inside the system, electrically powered resistive heating elements heat air to more than 600°C. The hot air is circulated through a network of pipes inside a sand-filled heat storage vessel. The hot air then flows

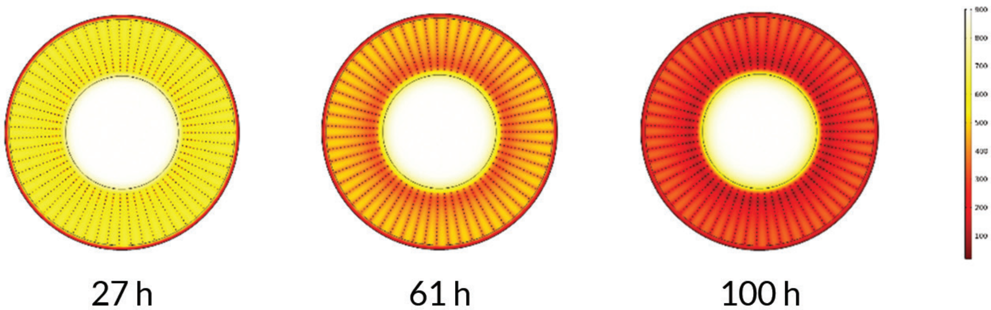


FIGURE 5 Simulation images showing temperature changes inside a proposed sand–air heat storage vessel design over a 100-hour period.

back out of the vessel into a heat exchanger, where it heats water that is then circulated through building heating systems. The sand's heat storage capacity ensures that even when the resistive elements are cool, the circulating air is still hot enough to keep the water (and buildings) warm.

"We only have pipes, valves, a fan, and an electric heating element. There is nothing special here!" Eronen says, laughing.

» A BATTERY FOR HEAT MADE FROM SAND

Noted chemical engineer Donald Sadoway is quoted as saying: "If you want to make a dirt-cheap battery, you have to make it out of dirt." Polar Night Energy's system faces the same core challenges as any other energy infrastructure. It must deliver power to people when they need it, where they need it, and at a manageable price. This means that storing and distributing energy is as important as its generation.

Existing infrastructure meets these challenges in familiar ways. For combustion-based heating, fuels like oil and gas are stored and moved to where they can be burned. The electrical grid also supports the efficient distribution of power and makes use of energy generated through renewable means like wind and solar. The intermittent nature of daylight and strong winds, however, is a stubborn problem. Energy storage is needed to maintain steady power output throughout the peaks and valleys of renewable inputs. But even with recent advances in battery technology, storing electric power remains relatively expensive, especially at the scale required for heating buildings. What if, rather than storing electricity, a "battery" could store heat instead?

Many conventional heating systems already store and distribute heat by retaining and circulating warm water. Eronen and Ylönen recognized the benefits of water-based heat storage as well as its limitations. "There is only so much heat you can add to water before it becomes steam," says Eronen. "Steam can efficiently distribute heat, but it is not really cost-effective for large-scale storage."

To avoid the drawbacks of storing heat in water, they instead turned to sand — 42 metric tons of it! (Figure 3) After the Sun goes down, the sand's stored heat is gradually released back into the circulating airflow. This keeps the air hot enough to maintain steady temperatures in the water that flows through customers' radiators. In this way, sand enables solar power to keep people warm, even during the darkest and coldest Finnish nights. "Sand provides four times the energy storage capacity of water," Eronen says. "Sand is efficient, nontoxic, portable, and cheap!"

> "We need predictive modeling to answer as many questions as possible, before we commit to assembling all this equipment — and all this sand!"
>
> — TOMMI ERONEN, CEO OF POLAR NIGHT ENERGY

» THE SOPHISTICATED ANALYSIS BEHIND A SIMPLE SOLUTION

Cost efficiency is the foundation of Polar Night Energy's value proposition. "As soon as we decided to pursue this idea, we were trying to figure out how the finances looked," says Eronen. In their quest to do more with less, Polar Night Energy has long depended on numerical simulation tools. Eronen and Ylönen began using the COMSOL Multiphysics® software as students, and it remains integral to their design process.

For example, Eronen mentions the specifications of an expanded heat storage system that would serve more buildings in Tampere. The team calculated that supplying heat to a district of 35,000 people would require a sand-filled storage cylinder that is 25 meters tall and 40 meters in diameter. How did they arrive at these dimensions? "The rough quantity of material needed is actually easy to calculate, because we know how much heat we can store in a cubic meter of sand," Eronen explains. "We also had to determine the space required for efficient heat transfer between the sand and our air circulating system (Figure 4). That is much more difficult to do! We used COMSOL® to model and evaluate different design options."

Multiphysics simulation software helped shape Polar Night Energy's heat exchanger design (Figures 5–6). Eronen says, "We built a particular model to explore a design idea: What if we created a super hot core of sand surrounded by heating ducts around the perimeter?" By modeling fluid flow and heat transfer effects in the COMSOL Multiphysics software, the Polar Night Energy team could quantify its design's comparative advantages and drawbacks. "The simulation confirmed that the 'hot core' design was good at storing heat for very long periods of time," says Eronen. "But for our intended operational cycle, it makes more sense to evenly distribute hot air ducts throughout the sand storage vessel," he explains.

The sheer scale of Polar Night Energy's sand-based heat storage system makes simulation software indispensable. "We cannot possibly build full-size

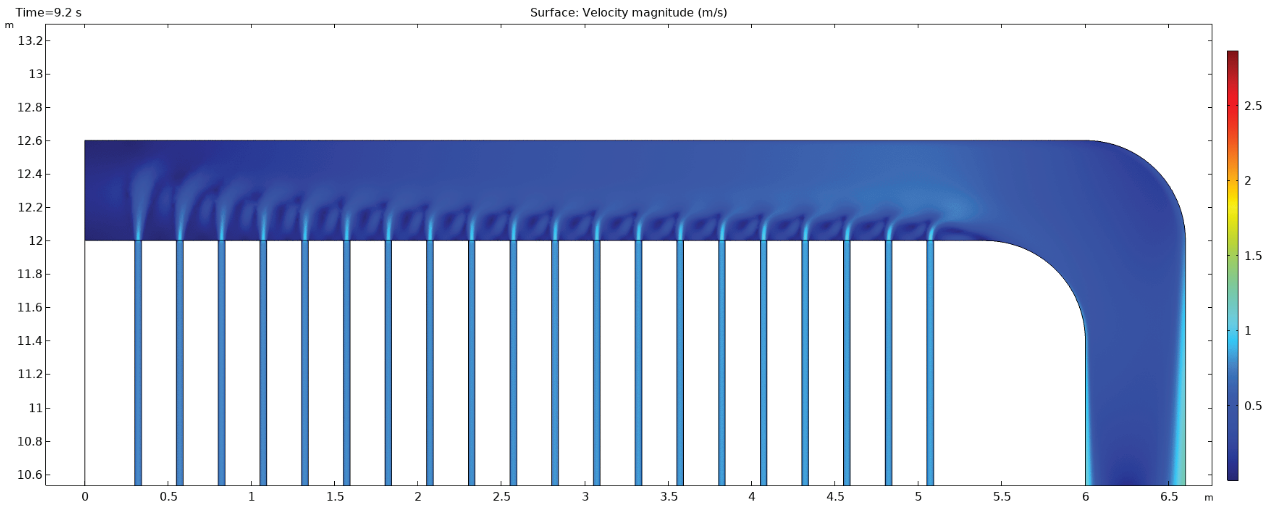


FIGURE 6 Simulation image of natural convection effects through ductwork inside the sand storage vessel.

FIGURE 7 Part of the heat transfer system installed by Polar Night Energy in Tampere, Finland. The vertical pipes at left are part of the heat exchanger, while the resistive heater elements are wrapped in white insulation at right. Between these components is the air-circulating radial blower.

prototypes to test all of our ideas. We need predictive modeling to answer as many questions as possible, before we commit to assembling all this equipment — and all this sand!" Eronen says. "It is essential for us to use these immensely powerful tools."

» ADAPTING NEW IDEAS TO EXISTING INFRASTRUCTURE

By separating the task of heat storage from heat generation and distribution, Polar Night Energy has made its system more efficient and adaptable. There is great potential for retrofitting their sand-filled heat storage and transfer systems into existing infrastructure (Figure 7).

Tampere, an inland Finnish industrial city of nearly 250,000 people, is an ideal testing ground for this new technology. "Tampere, like many European cities, already has a district heating system that circulates water across entire neighborhoods," says Eronen. "That enables us to switch many buildings to a renewable heat source quickly," he says. Polar Night Energy's pilot plant in Tampere can also tap into power from the existing electrical grid, along with electricity generated by new solar panels. Reliable thermal storage enables the city to generate or purchase power when it is most affordable and then distribute heat when it is needed most.

» TODAY: FINLAND; TOMORROW: THE WORLD

Since the Tampere system began operation during the winter of 2020–2021, the Polar Night Energy team has been gathering data to compare to their models.

"Our simulations have proven to be very accurate, which is encouraging," Eronen says. And as the Polar Night Energy team continues to develop their ideas locally, they are aiming to act globally as well.

The same technology that warms Finland's long, chilly nights can also provide better energy management options to the rest of the world. Affordable thermal storage could help industries and cities capture heat that is currently wasted, as well as balance the inconsistencies in wind and solar power output. But while Polar Night Energy is eager to work directly with potential customers, they realize that the challenges ahead are too big for them to tackle alone.

"We want to license this technology. If you operate a power plant, please contact us," Eronen says with a laugh. On a more serious note, he adds, "We have to get away from all kinds of combustion, even biomass. We need to protect and restore forests so they can keep removing carbon from the air. Because climate change is happening so fast, we want our ideas to spread as quickly as possible." ◎

MED Institute, Indiana, USA

RADIOFREQUENCY-INDUCED HEATING OF MEDICAL DEVICES IN MRI SYSTEMS

Implanted medical devices in patients should be designed to be safe in and compatible with a magnetic resonance imaging (MRI) environment. MED Institute, a medical device contract research organization, is using computational modeling and simulation to analyze RF-heating of devices in MRI systems.

by **DIXITA PATEL**

Over 80 million magnetic resonance imaging (MRI) scans are conducted worldwide every year. MRI systems come in many different shapes and sizes, and are identified by their magnetic field strength. These scanners can range from below 0.55 tesla (T) to 3 T and beyond, where tesla is the unit for the static magnetic field strength. For patients with implanted metallic medical devices, the strong magnetic fields generated by MRI systems can pose several safety concerns.

For instance, high-powered magnets generate forces and torques that can cause the implant to migrate and potentially harm the patient. In addition, the gradient coils in MRI systems, used for spatial localization, can cause gradient-induced heating, vibrations, stimulation of the tissue, and device malfunction. Lastly, the large radiofrequency (RF) coil in MRI systems can cause the electrically conductive implant to electromagnetically resonate (called the "antenna effect"), resulting in RF-induced heating that can potentially burn the patient.

MED Institute, a full-service contract research organization (CRO) for the medical device industry, is using multiphysics simulation to better understand the effects of RF-induced heating of medically implanted devices for patients that need MRI scans.

» STANDARDIZED TEST METHODS FOR MEDICAL DEVICES

MED Institute provides support throughout the entire product development cycle. Its MRI Safety team helps manufacturers evaluate and perform physical testing of their medical devices for safety and compliance in the MRI environment (Figure 1). The team works closely with the Food and Drug Administration (FDA), which oversees the development of medical products to ensure safe and effective use. Furthermore, the team complies with the standards of the American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO). Specifically, it follows the ASTM F2182 standard to measure RF-induced heating of a medical implant within a gel phantom (Figure 2) and follows ISO/TS 10974 to evaluate electrically active implantable medical devices (AIMD) during MRI.

The gel phantom used for testing is a rectangular acrylic container filled with a conductive gel that approximates the thermal and electrical properties of average human tissue. The phantom is placed on the patient table inside the RF coil of an MRI scanner and fiber optic temperature probes (1 mm in diameter) are attached to the device before submerging it into the gel. The probes measure the temperature changes experienced by the device during the MRI scan. This type of physical experiment is used often, but it poses some potential problems. For instance, movement within the phantom can introduce uncertainty into the experiment, and inaccurate probe placement can lead to invalid results. In addition, depending on the materials of construction and their magnetic susceptibility, magnetic force could also be an issue.

To help address these issues, the team at MED Institute uses computational modeling and simulation as an alternative to physical testing. David Gross, PhD, PE, Director of MRI Safety

FIGURE 1 Engineers at MED Institute Inc. performing physical MRI testing to evaluate the safety of medical devices in the MRI environment.

Evaluations and Engineering Simulations, leads a team of analysts that use simulation to gain a better understanding of physics-based problems. He says, "The simulation provides us with 3D temperature contours anywhere within a volume of interest; we are not limited to discrete point-probe measurements, and we do not have to worry about the inaccuracies of the equipment or uncertainty of probe placement from the experiment."

The team has experience conducting these simulations for closed-bore MRI systems, in which a patient is contained in a compact tube. The team is now using simulation to perform these same analyses for open-bore systems (Figure 3), which have wider physical access, making them beneficial for "imaging pediatric, bariatric, geriatric and claustrophobic patients", as is explained on the MED Institute website.

» MULTIPHYSICS SIMULATION FOR RF-INDUCED HEATING

With COMSOL Multiphysics®, MED Institute is able to evaluate the RF-induced temperature rise of implants and compare the results of various sizes and constructs of a device within a product family to determine a worst-case configuration. The analysts at MED can import a CAD file of a client's device using the CAD Import Module, an add-on to COMSOL Multiphysics. In terms of RF-induced heating, the team uses the RF Module and Heat Transfer Module add-on products to combine the physics of electromagnetics with transient heat transfer. For analyzing electromagnetics,

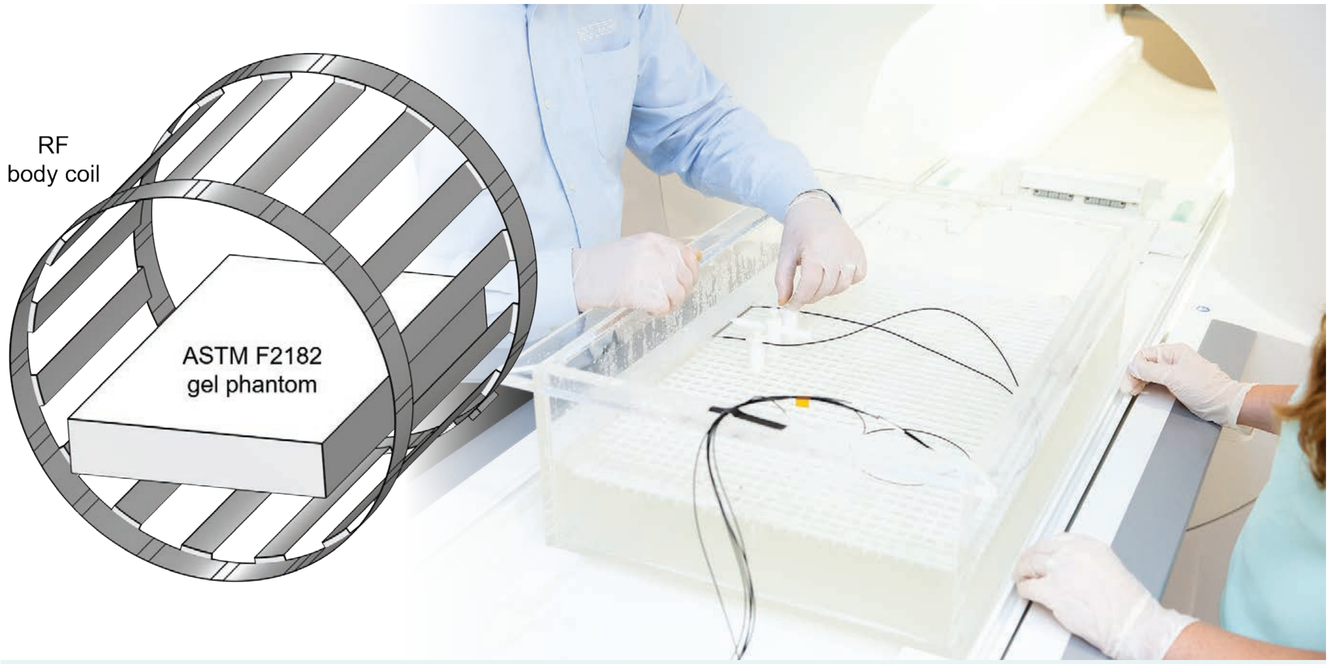


FIGURE 2 The ASTM F2182 standard used under virtual testing (left) and during physical testing under an MRI (right).

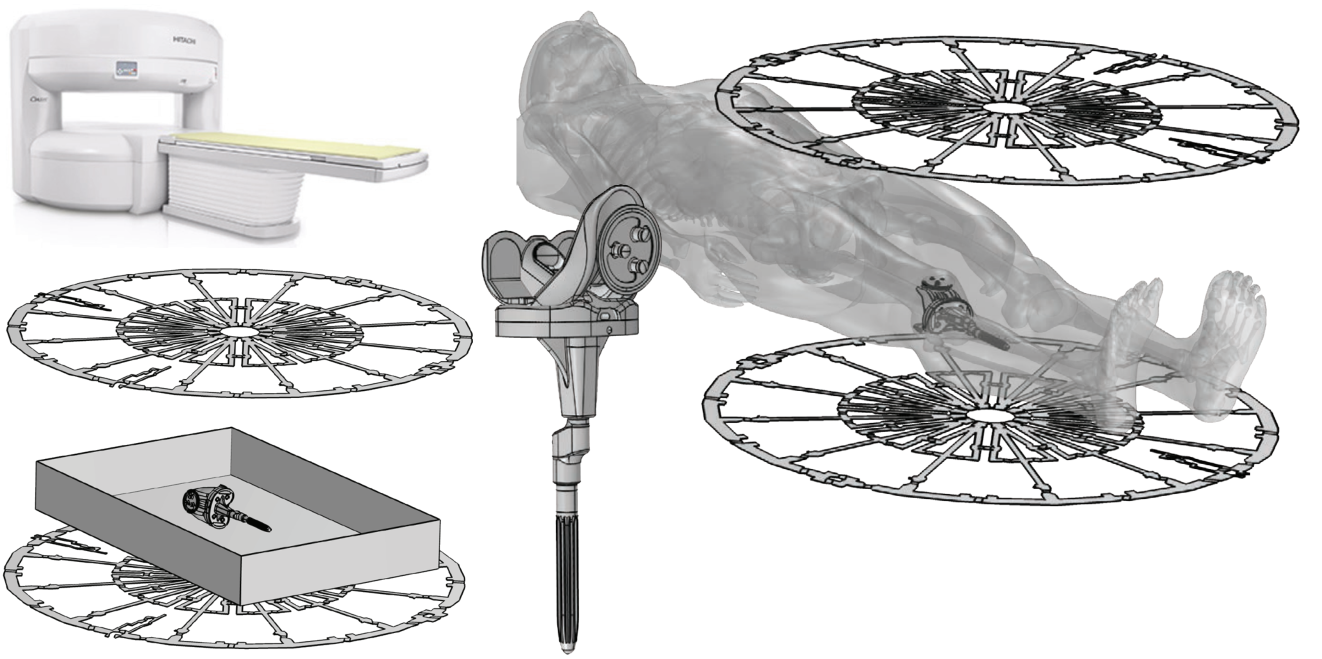


FIGURE 3 An open-bore MRI system (top left), an RF body coil with the IT'IS Foundation's Duke virtual human model (top right), an RF body coil of a knee implant in an ASTM gel phantom (bottom left), and CAD model of a knee implant (bottom center).

the RF Module enables the use of Maxwell's equations to solve for the wave equation at every point within the model that is impacted by electromagnetic fields. This is done in a steady-state frequency domain, which is then sequentially coupled with the transient heat transfer. With the Heat Transfer Module, the team is also able to solve heat conduction equations.

In the example below, MED Institute imported a CAD file of a knee implant into the COMSOL Multiphysics software. The geometry of the implant included a stem extension, tibial tray, femoral tray, and other components. All of these components can have various sizes and can be assembled in various ways, and patients with the implant can be scanned in various MRI systems that create different electromagnetic fields. With the overwhelming amount of permutations that these variables can produce, it is often not clear which configuration would result in the worst-case RF-induced heating.

"This is where the use of simulation comes in; you focus your efforts on the primary factors that can change the resonance of a particular implant," Gross says. By using the COMSOL® software, the organization is able to better understand the relative bounds of where it would expect to see resonance and how the device behaves under different electromagnetic fields. This helps with performing sensitivity analyses, where the team can test what causes the change in resonance, such as modifying the diameter of the stem or other components of the implant. For this particular case, the team ran hundreds of simulations to determine the worst-case device size and worst-case RF frequency.

Using worst-case analysis is crucial in the verification process because it allows manufacturers to test different factors for a wide range of devices — such as determining which size brings the most complications — rather than conducting physical testing for every variant of one product. "Performing multiple physical experiments becomes very expensive and time-consuming, especially when you account for the hourly cost of using a physical MRI scanner," says Gross.

As shown in Figure 4, the electric field in the gel phantom of a 1.2 T open-bore system (upper left) is very different from a 1.5 T closed-bore system (upper right). The knee implant was simulated in both systems, where the results show a different resonance and maximum temperature rise at the end of the stem (lower images).

Using COMSOL® allowed the team to better understand how a device behaves under electromagnetic fields. With these results, the team was then able to determine where the temperature probes should be placed while physically testing the device in an actual MRI system to obtain temperature rise results.

» FDA QUALIFICATION OF MED INSTITUTE'S VIRTUAL MRI SAFETY EVALUATIONS

MED Institute's experience with using simulation to test RF-induced heating of medical devices has inspired development of a promising new simulation tool that accelerates the product development cycle. The MED Institute team submitted this simulation tool to the FDA's Medical Device Development Tool (MDDT) program, which allows the FDA to evaluate new tools with the purpose of furthering medical products and studies. As stated on the FDA website, "The MDDT program is a way for the FDA to qualify tools that medical device sponsors can choose to use in the development and evaluation of medical devices." Once qualified, the FDA recognizes the tool as an official MDDT.

In November 2021, MED Institute was granted FDA

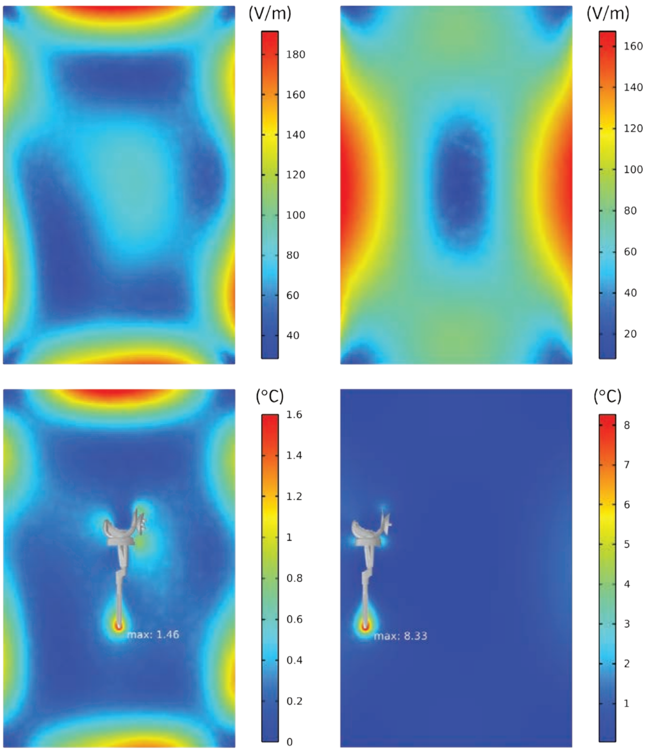


FIGURE 4 A knee implant in a gel phantom comparing the simulation results of an open-bore (left) and closed-bore (right) system.

qualification of its MDDT, "Virtual MRI Safety Evaluations of Medical Devices”. This is an evaluation process that involves using multiphysics modeling and simulation to test the interactions of medical devices in an MRI environment. The tool is used for modeling an RF coil of an MRI system, ASTM gel phantom, and a medical device placed within the gel. Simulation is then used to analyze the electromagnetics and the heat that generates around the device.

After testing is complete, the labeling of the device is described by ASTM 2503 or, if it is an electrically active implant, by the ISO 10974 test. The labeling is placed on the device packaging and inside the instructions for use (IFU) so that an MRI technologist or radiologist can see the relevant information for a patient with an implanted device.

"With our MDDT, we can not only augment physical testing but even replace it with simulation in some cases," says Gross.

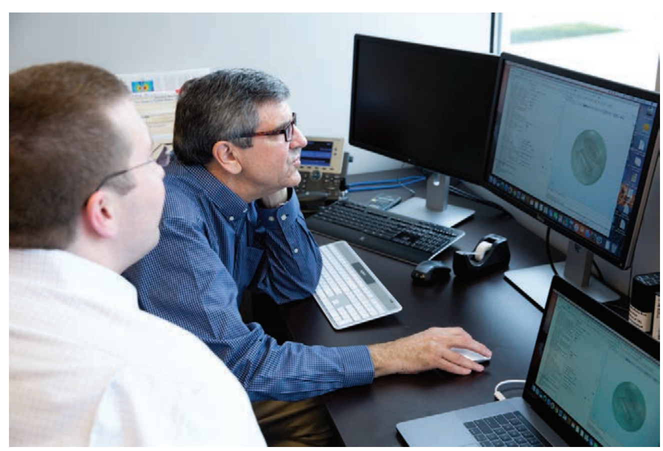
» MODELING AND SIMULATION SUPPORT FROM THE FDA

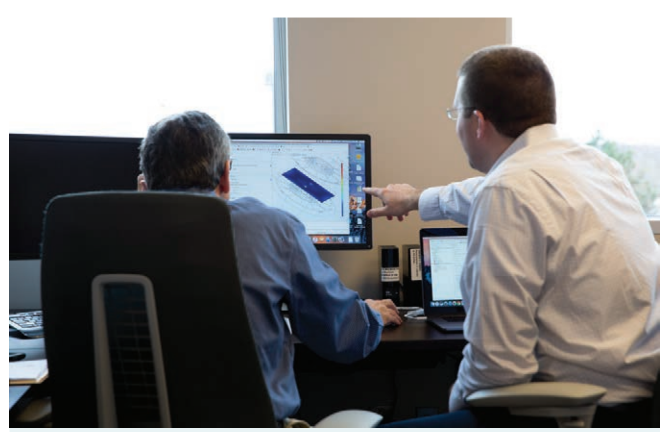
Over the years, MED Institute has evaluated many medical devices for MRI safety with COMSOL Multiphysics simulations. It has found that COMSOL® is a powerful and efficient platform for solving complex multiphysics problems. "The immediate, positive results are that our clients are able to have their products evaluated quicker and at less cost because we are able to rely on the simulation. It does not require them to send us the actual product to test for RF-induced heating," says Gross.

The FDA has been supportive of computational modeling and is willing to evaluate and accept data from simulation in lieu of physical testing. "It is important for medical device sponsors to know that they have the encouragement and support of the FDA," Gross says. MED Institute has had the privilege of working alongside the FDA for many years for the benefit of patients. "It goes to show that they are invested and believe in the power of modeling and simulation," Gross adds. ◎

"With our Medical Device Development Tool (MDDT), we can not only augment physical testing but even replace it with simulation in some cases. The immediate, positive results are that our clients are able to have their products evaluated quicker and at less cost because we are able to rely on the simulation."

— DAVID GROSS, MED INSTITUTE DIRECTOR OF MRI SAFETY EVALUATIONS AND ENGINEERING SIMULATIONS





MED Institute uses the COMSOL Multiphysics® software to accelerate the product development cycle for its clients.

Eden Tech, France

DESIGNING A MINIATURIZED WASTEWATER TREATMENT PLANT FOR MICROPOLLUTANT DEGRADATION

Micropollutants are added to the world's lakes, rivers, and streams every day. Many conventional wastewater treatment plants are not equipped to remove these potentially hazardous chemical residues from wastewater. Eden Tech, a deeptech company based in Paris, France, is using multiphysics simulation to develop a device that can help with this emerging problem.

by RACHEL KEATLEY

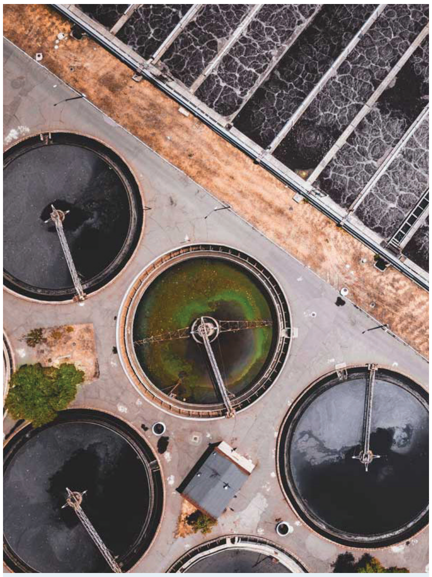


FIGURE 1 Most conventional water treatment plants are not able to remove micropollutants.

The 1985 action-adventure TV series *MacGyver*® showcased the life of Angus MacGyver, a secret agent who solved problems using items he had on hand. For example, in one episode, he made a heat shield out of used refrigerator parts. In another, he made a fishing lure with a candy wrapper. More than three decades later, the show still has relevance. The verb *MacGyver*, to design something in a makeshift or creative way, was added to the Oxford English Dictionary in 2015.

Try putting your MacGyver skills to the test: If you were handed some CDs, what would you make out of them? Reflective wall art, mosaic ornaments, or a wind chime, perhaps? What about a miniaturized water treatment plant?

This is what a team of engineers and researchers is doing at Eden Tech, a company that specializes in the development of microfluidics technology. Eden Tech's R&D department, Eden Cleantech, is developing a compact, energy-saving water treatment system to help tackle the growing presence of micropollutants in wastewater. To analyze the performance of its AKVO system (named after the Latin word for water, *aqua*), which is made from CDs, Eden Tech turned to multiphysics simulation.

» CONTAMINANTS OF EMERGING CONCERN

"There are many ways micropollutants make it into wastewater," says Wei Zhao, a senior chemical engineer and chief product officer at Eden Tech. The rise of these microscopic chemicals in wastewater worldwide is a result of daily human activities. For instance, when we wash our hands with soap, wipe down our sinks with cleaning supplies, or flush medications out of our bodies, various chemicals are washed down the drain and end up in sewage systems. Some of these chemicals are classified

FIGURE 2 AKVO, with all of its components labeled.

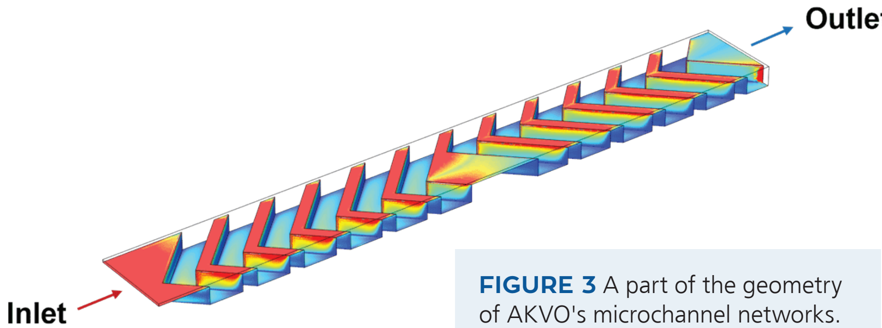


FIGURE 3 A part of the geometry of AKVO's microchannel networks.

as micropollutants, or contaminants of emerging concern (CECs). In addition to domestic waste, agricultural pollution and industrial waste are also to blame for the rise of micropollutants in our waterways.

Unfortunately, many conventional wastewater treatment plants (Figure 1) are not designed to remove these contaminants. Therefore, they are often reintroduced to various bodies of water, including rivers, streams, lakes, and even drinking water. Although the risk they pose to human and environmental health is not fully understood, the increasing amount of pollution found in the world's bodies of water is of concern.

With this growing problem in mind, Eden Tech got to work on developing a solution, and AKVO was born. One AKVO cartridge is composed of stacked CDs of varying numbers, combined to create a miniaturized factory. Each AKVO CD core is designed to have a diameter of 15 cm and a thickness of 2 mm. One AKVO core treats 0.5 to 2 m^3 water/day, which means that an AKVO system composed of 10,000 CDs can treat average municipal needs. This raises the question: How can a device made from CDs decontaminate water?

» A SUSTAINABLE WASTEWATER TREATMENT METHOD

A single AKVO system (Figure 2) consists of a customizable cartridge filled with stacked CDs that each have a microchannel network inscribed on them. It removes undesirable elements in wastewater, like micropollutants, by circulating the water in its microchannel networks. These networks are energy savvy because they only require a small pump to circulate and clean large volumes of water. The AKVO system's cartridges can easily be replaced, with Eden Tech taking care of their recycling.

AKVO's revolutionary design combines photocatalysis and microfluidics into one compact system. Photocatalysis, a type of advanced oxidation process (AOP), is a fast and effective way to remove micropollutants from wastewater. Compared to other AOPs, it is considered safer and more sustainable because it is powered by a light source. During photocatalysis, light is absorbed by photocatalysts that have the ability to create electron-hole pairs, which generate free hydroxyl radicals that are able to react with target pollutants and degrade them. Combining photocatalysis and microfluidics for the treatment of wastewater has never been done before. "It is a very ambitious project," said Zhao. "We wanted to develop an innovative method in order to provide an environmentally friendly, efficient way to treat wastewater." AKVO's current design did not come easily, as Zhao and his team faced several design challenges along the way.

» OVERCOMING DESIGN CHALLENGES

When in use, a chemical agent (catalyst) and wastewater are dispersed through AKVO's microchannel walls. The purpose of the catalyst, titanium dioxide in this case, is to react with the micropollutants and help remove them in the process. However, AKVO's fast flow rate complicates this action. "The big problem is that [AKVO] has microchannels with fast flow rates, and sometimes when we put the chemical agent inside one of the channels' walls, the micropollutants in the wastewater cannot react efficiently with

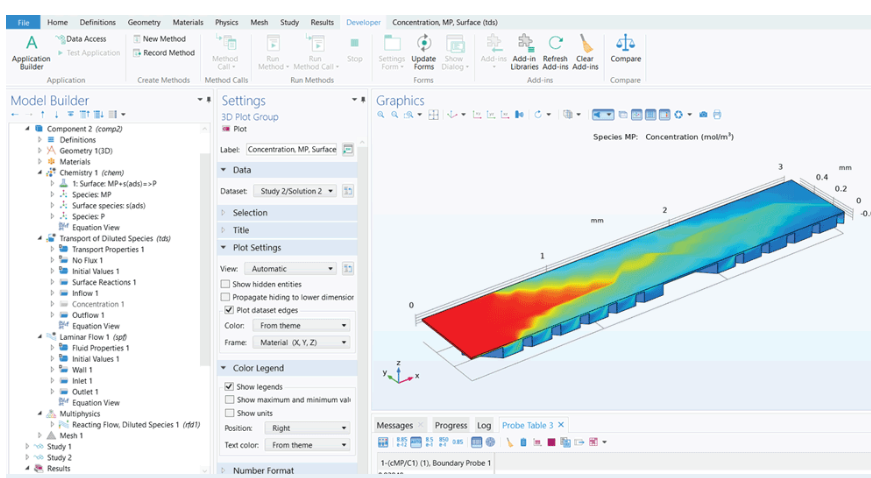


FIGURE 4 In COMSOL Multiphysics®, Zhao used the *Chemistry*, *Transport of Diluted Species*, *Laminar Flow*, and *Reacting Flow*, *Diluted Species* interfaces.

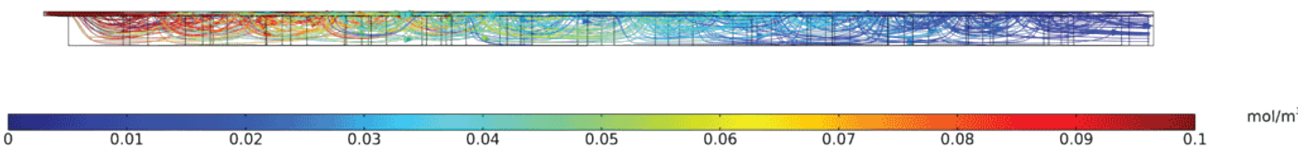


FIGURE 5 Results of the Explicit Surface Adsorption model.

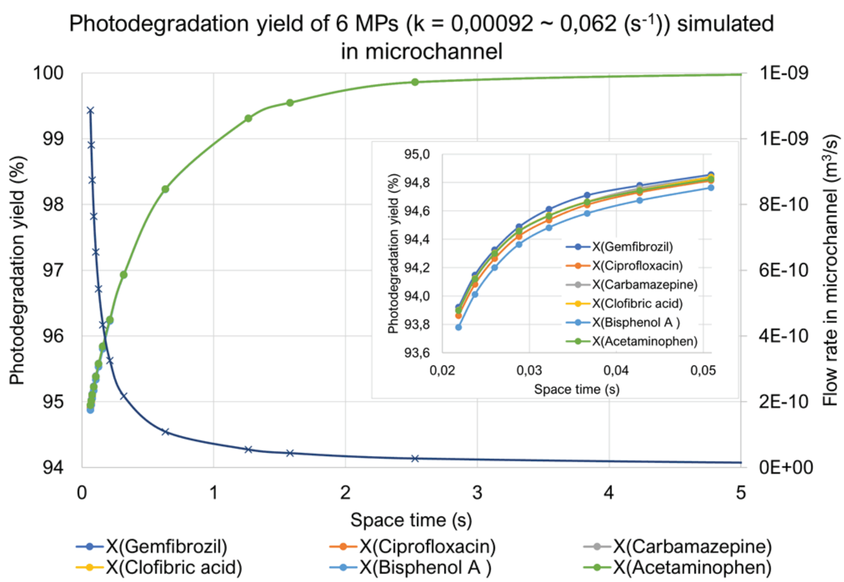


FIGURE 6 Comparison of the performance of the SHM design for the photodegradation of six different micropollutants.

the agent," said Zhao. In order to increase the opportunity of contact between the micropollutants and the immobilized chemical agent, Zhao and his team opted to use a staggered herringbone micromixer (SHM) design for AKVO's microchannel networks (Figure 3).

To analyze the performance of the SHM design to support chemical reactions for micropollutant degradation, Zhao used the COMSOL Multiphysics software.

» SIMULATING CHEMICAL REACTIONS FOR MICROPOLLUTANT DEGRADATION

In his work, Zhao built two different models in COMSOL Multiphysics (Figure 4), named the Explicit Surface Adsorption (ESA) model and the Converted Surface Concentration (CSC) model. Both of these models account for chemical and fluid phenomena.

In both models, Zhao found that AKVO's SHM structure creates vortices in the flow moving through it, which enables the micropollutants and the chemical agent to have a longer reaction period and enhances the mass transfer between each fluid layer. However, the results of the ESA model (Figure 5) showed that the design purified about 50% of the micropollutants under treatment, fewer than what Zhao expected.

Unlike the ESA model, in the CSC model, it is assumed that there is no adsorption limitation. Therefore, as long as a micropollutant arrives at the surface of a catalyst, a reaction occurs, which has been discussed in existing literature. In this model, Zhao analyzed how the design performed for the degradation of six different micropollutants, including gemfibrozil, ciprofloxacin, carbamazepine, clofibric acid, bisphenol A, and acetaminophen (Figure 6). The results of this model were in line with what Zhao expected, with more than 95% of the micropollutants being treated.

"We are really satisfied with the results of COMSOL Multiphysics. My next steps will be focused on laboratory testing [of the AKVO prototype]," said Zhao. The prototype will eventually be tested at hospitals and water treatment stations in the south of France.

Using simulation for this project has helped the Eden Tech team save time and money. Developing a prototype of a microfluidic system, like AKVO, is costly. To imprint microchannel networks on each of AKVO's CDs, a microchannel photomask is needed. According to Zhao, to fabricate one photomask would cost about €3000 (3500 USD). Therefore, it is very important that they are confident that their system works well prior to its fabrication. "COMSOL Multiphysics has really helped us validate our models and our designs," said Zhao.

» PIONEER IN THE TREATMENT OF MICROPOLLUTANTS

In 2016, Switzerland introduced legislation mandating that wastewater treatment plants remove micropollutants from wastewater. Its goal? Filter out over 80% of micropollutants at more than 100 Swiss facilities. Following Switzerland's lead, many other countries are currently thinking of how they want to handle the growing presence of these contaminants in their waterways. AKVO has the potential to provide a compact, environmentally friendly way to help slow this ongoing problem.

The next time you go to throw out an old CD, or any other household item for that matter, ask yourself: What would MacGyver do? Or, better yet: What would Eden Tech do? You might be holding the building blocks for its next innovative design.

Hellenic Cables, Greece

OPTIMIZING SUBSEA CABLE DESIGNS WITH FINITE ELEMENT MODELING

Wind turbines for offshore wind farms are starting to be built farther out into the ocean. This creates a new need for well-designed subsea cables that can reach longer distances, survive in deeper waters, and better connect our world with sustainable power. Hellenic Cables in Greece uses finite element modeling to analyze and validate underground and subsea cable designs.

by **BRIANNE CHRISTOPHER**

The offshore wind (OSW) industry is one of the most rapidly advancing sources of power around the world. It makes sense: Wind is stronger and more consistent over the open ocean than it is on land. Worldwide demand for energy is expected to increase by 20% in 10 years, with a large majority of that demand supplied by sustainable energy sources like wind power.

Offshore wind farms are made up of networks of turbines. These networks include cables (Figure 1) that connect wind farms to the shore and supply electricity to our power grid infrastructure (Figure 2). Many OSW farms are made up of grounded structures, like monopiles and other types of bottom-fixed wind turbines. The foundations for these structures are expensive to construct and difficult to install in deep sea environments, as the cables have to be buried in the seafloor. Installation and maintenance is easier to accomplish in shallow waters.

The future of offshore wind lies in wind farms that float on ballasts and moorings, with the cables laid directly on the seafloor. Floating wind farms are a great solution when wind farms situated just off the coast grow crowded. They can also take advantage of the bigger and more powerful winds that occur farther out to sea.

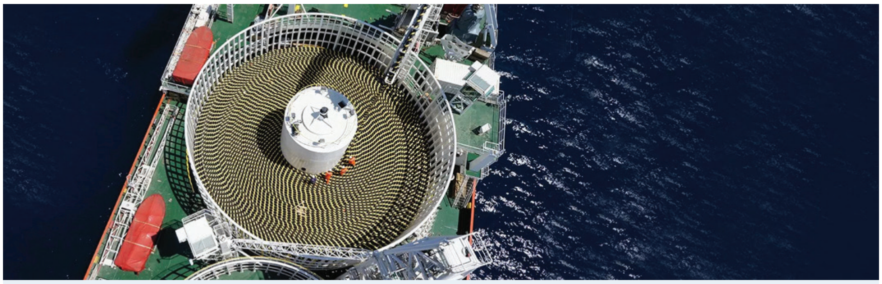


FIGURE 1 A ship hauling coiled cables for subsea installation.

» DESIGN FACTORS FOR RESILIENT SUBSEA CABLES

As the offshore wind industry continues to grow, our need to develop power cables that can safely and efficiently connect these farms to our power grid grows as well.

Before fixing or installing a submarine cable, which can cost billions of dollars, cable designers have to ensure that designs will perform as intended in undersea conditions. This is typically done with the help of computational electromagnetics modeling. To validate cable simulation results, international standards are used, but these standards have not been able to keep up with

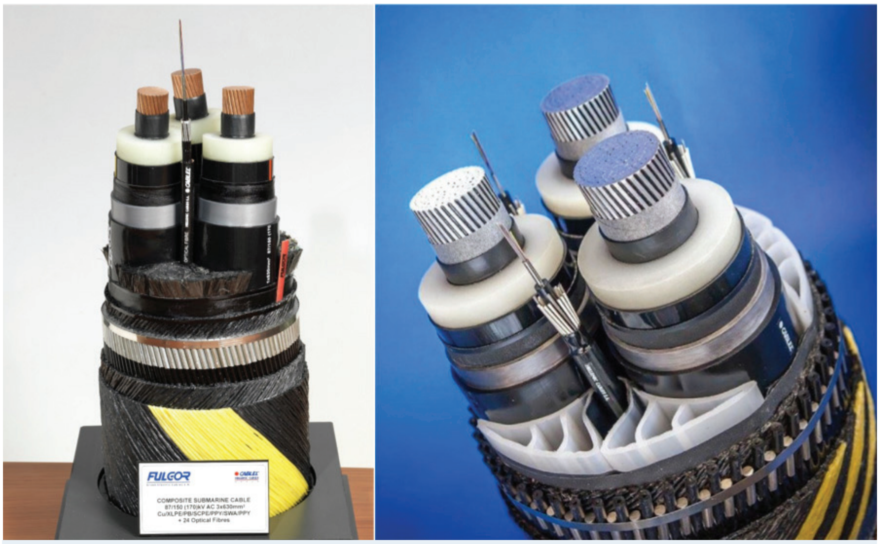


FIGURE 2 Examples of three-core (3C) submarine cables available from Hellenic Cables.

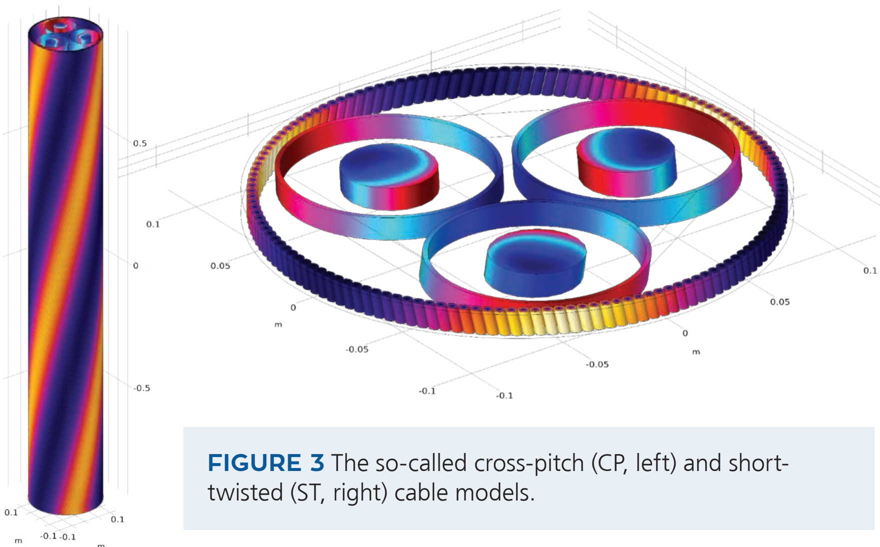


FIGURE 3 The so-called cross-pitch (CP, left) and short-twisted (ST, right) cable models.

recent advancements in computational power and simulation software's growing capabilities. Hellenic Cables, including its subsidiary FULGOR, uses the finite element method (FEM) to analyze its cable designs and compare them to experimental measurements, often getting better results than what the international standards can offer.

» UPDATED METHODOLOGY FOR CALCULATING CABLE LOSSES

The International Electrotechnical Commission (IEC) provides standards for electrical cables, including Standard 60287 1-1 for calculating cable losses and current ratings. One problem with the formulation used in Standard 60287 1-1 is that it overestimates cable losses. Cable designers are forced to adopt a new methodology for performing these analyses, and the team at Hellenic Cables recognizes this. "With a more accurate and realistic model, significant optimization margins are expected," says Dimitrios Chatzipetros, team leader of the Numerical Analysis group at Hellenic Cables. The new methodology will enable engineers to reduce cable cross sections, thereby reducing their costs.

An electric cable is a complex device to model. The geometric structure consists of three main power cores, which are helically twisted with a particular lay length, and hundreds of additional wires — screen or armor wires — that are twisted with a second or third lay length. This makes it difficult to generate the mesh and solve for the electromagnetic fields. "This is a tedious 3D problem with challenging material properties, because some of the elements are ferromagnetic," says Andreas Chrysochos, associate principal engineer in the R&D department of Hellenic Cables.

The Hellenic Cables team first used FEM to model a full cable section of around 30 to 40 meters in length. This turned out to be a huge numerical challenge that could only realistically be solved on a supercomputer. By switching to periodic models with a periodic length equal to the cable's cross pitch, the team reduced the problem from 40 meters down to 2–4 meters. Then they introduced short-twisted periodicity, which reduces the periodic length of the model from meters to centimeters, making it much lighter to solve (Figure 3).

Although the improvements that FEM brings to cable analysis are great, Hellenic Cables still needs to convince its clients that its validated results are more realistic than those provided by the current IEC standard. Clients are often already aware of the fact that IEC 60287 overestimates cable losses, but results visualization and comparison to actual measurements can build confidence in project stakeholders (Figure 4).

» FINITE ELEMENT MODELING OF CABLE SYSTEMS

Electromagnetic interference (EMI) presents several challenges when it comes to designing cable systems — especially the capacitive and inductive couplings between cable conductors and sheaths. For one, when calculating current ratings, engineers need to account for power losses in the cable sheaths during normal operation. In addition, the overvoltages on cable sheaths need to be within acceptable limits to meet typical health and safety standards.

There are three main approaches when it comes to calculating these capacitive and inductive couplings. The first is the complex impedance method (CIM), which calculates the cable system's currents and voltages

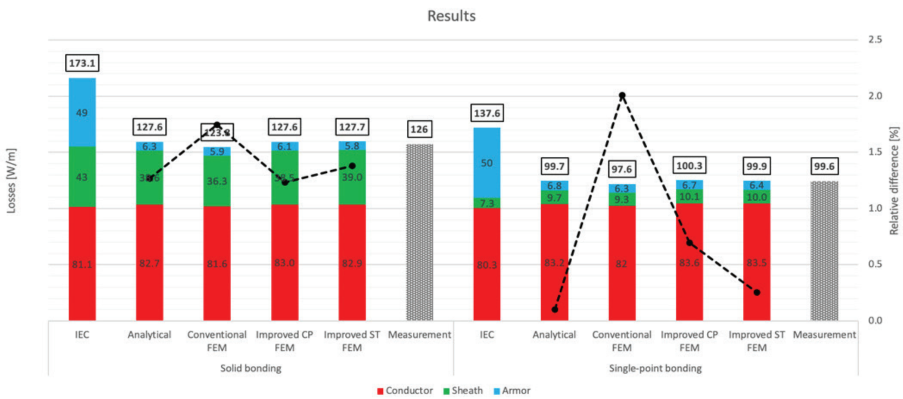


FIGURE 4 The results of two bonding scenarios, solid and single-point bonding, based on a specific cable geometry. The results include losses from IEC 60287 (standard), analytical calculations, conventional FEM, improved CP FEM (based on the cross-pitch model), improved ST FEM (based on the short-twisted model), and measurements.

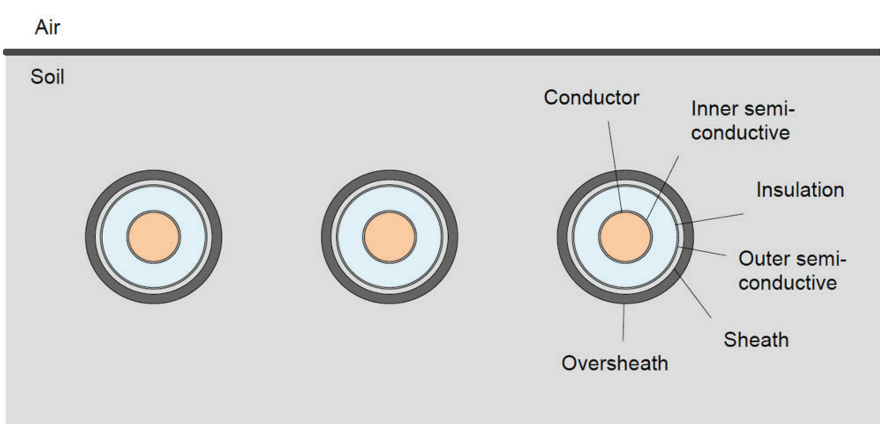


FIGURE 5 Cable model geometry.

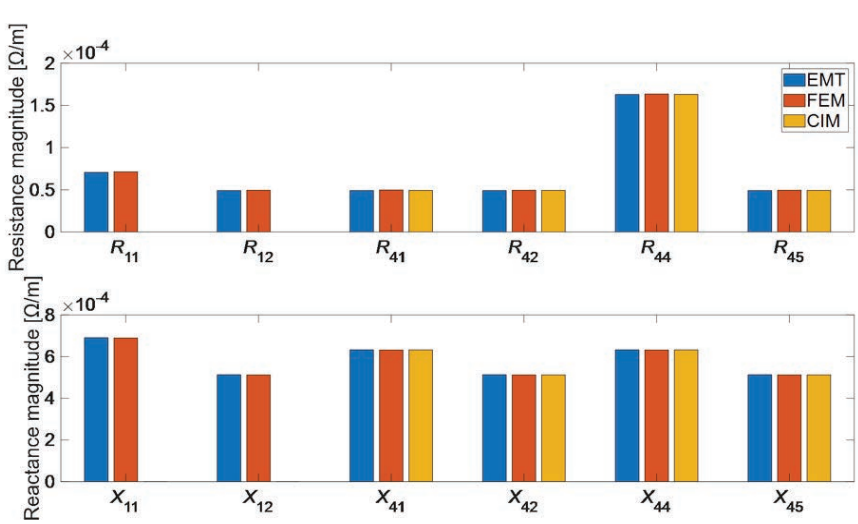


FIGURE 6 Results comparison between EMT, FEM, and CIM.

while neglecting its capacitive currents. Another common method is using electromagnetic transients program (EMT) software, which can be used to analyze electromagnetic transients in power systems using both time- and frequency-domain models.

The third method, FEM, is the foundation of the COMSOL Multiphysics® software. The Hellenic Cables team used COMSOL Multiphysics and the add-on AC/DC Module to compute the electric fields, currents, and potential distribution in conducting media. "The AC/DC Module and the solvers behind it are very robust and efficient for these types of problems," says Chrysochos.

The Hellenic Cables team compared the three methods when analyzing an underground cable system with an 87/150 kV nominal voltage and 1000 mm² cross section (Figure 5). The team modeled the magnetic field and induced-current-density distributions in and around the cable system's conductors, accounting for the bonding type with an external electrical circuit. The results between all three methods show good agreement for the cable system for three different configurations: solid bonding, single-point bonding, and cross bonding (Figure 6). This agreement demonstrates that FEM can be applied to all types of cable configurations and installations when taking into account capacitive and inductive coupling.

» A BRIGHT AND WINDY FUTURE

The Hellenic Cables team plans to continue the important work of further improving all of the cable models they have developed. The team has also performed research into high-voltage direct current (HVDC) cables, which involve cross-linked polyethylene (XLPE) insulation and voltage source converter (VSC) technology. HVDC cables can be more cost efficient for systems installed over long distances.

Like the wind used to power offshore wind farms, electrical cable systems are all around us. Even though we cannot always see them, they are working hard to ensure we have access to a high-powered and well-connected world. Optimizing the designs of subsea cables is an important part of building a sustainable future. ◎

This story has been abridged. Read the full article at comsol.com/stories.

Alfred Wegener Institute, Germany

FORECASTING THE ICE LOSS OF GREENLAND'S GLACIERS WITH VISCOELASTIC MODELING

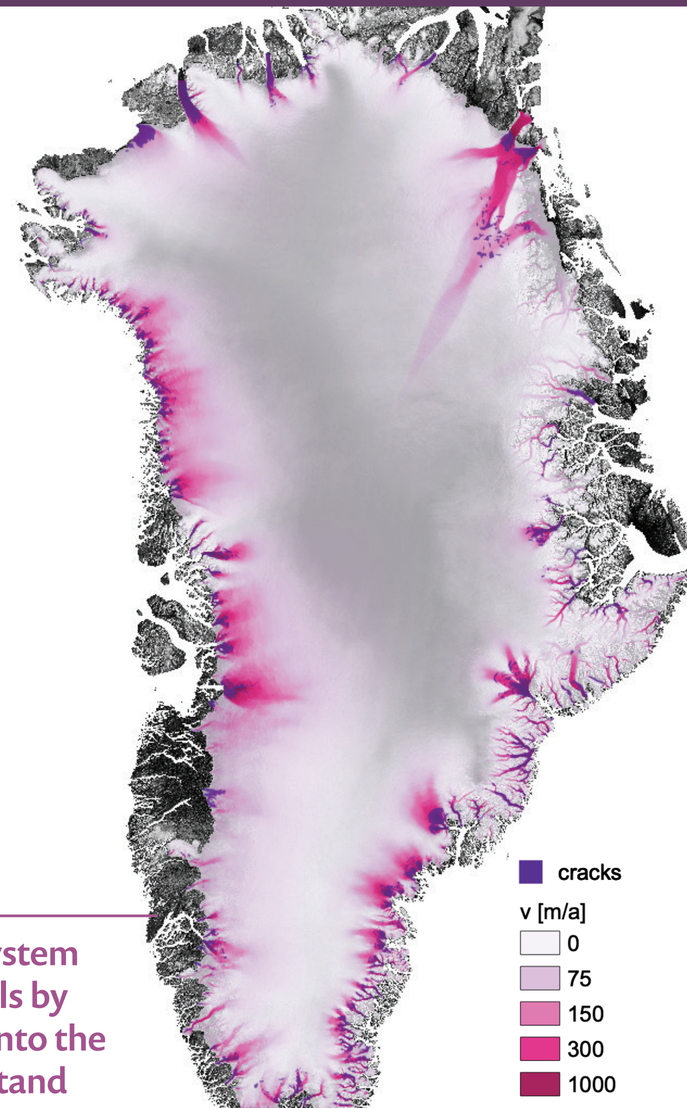


FIGURE 1 A map of Greenland. The color scale indicates the velocity of glacial movement in certain areas. Note that areas of greatest movement tend to be near the coast. Solid purple zones indicate the locations of massive cracks in the ice cover.

The Northeast Greenland Ice Stream glacial system contains enough water to raise global sea levels by more than a meter — and its discharge of ice into the ocean has been accelerating. To better understand and predict this discharge, researchers at the Alfred Wegener Institute have developed an improved viscoelastic model to capture how tides and subglacial topography are contributing to glacial flow.

by **ALAN PETRILLO**

To someone standing near a glacier, it may seem as stable and permanent as anything on Earth can be. However, Earth's great ice sheets are always moving and evolving. In recent decades, this ceaseless motion has accelerated. In fact, ice in polar regions is proving to be not just mobile, but alarmingly mortal.

Rising air and sea temperatures are speeding up the discharge of glacial ice into the ocean, which contributes to global sea level rise. This ominous progression is happening even faster than anticipated. Existing models of glacier dynamics and ice discharge underestimate the actual rate of ice loss in recent decades. This makes the work of Angelika Humbert, a physicist studying Greenland's Nioghalvfjerdsbræ outlet glacier, especially important — and urgent.

As the leader of the Modeling Group in the Section of Glaciology at the Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research in Bremerhaven, Germany, Humbert works to extract broader lessons from Nioghalvfjerdsbræ's ongoing decline. Her research combines data from field observations with viscoelastic modeling of ice sheet behavior. Through improved modeling of elastic effects on glacial flow, Humbert and her team seek to better predict ice loss and the resulting impact on global sea levels.

She is acutely aware that time is short. "Nioghalvfjerdsbræ is one of the last three 'floating tongue' glaciers in Greenland," explains Humbert. "Almost all of the other floating tongue formations have already disintegrated."

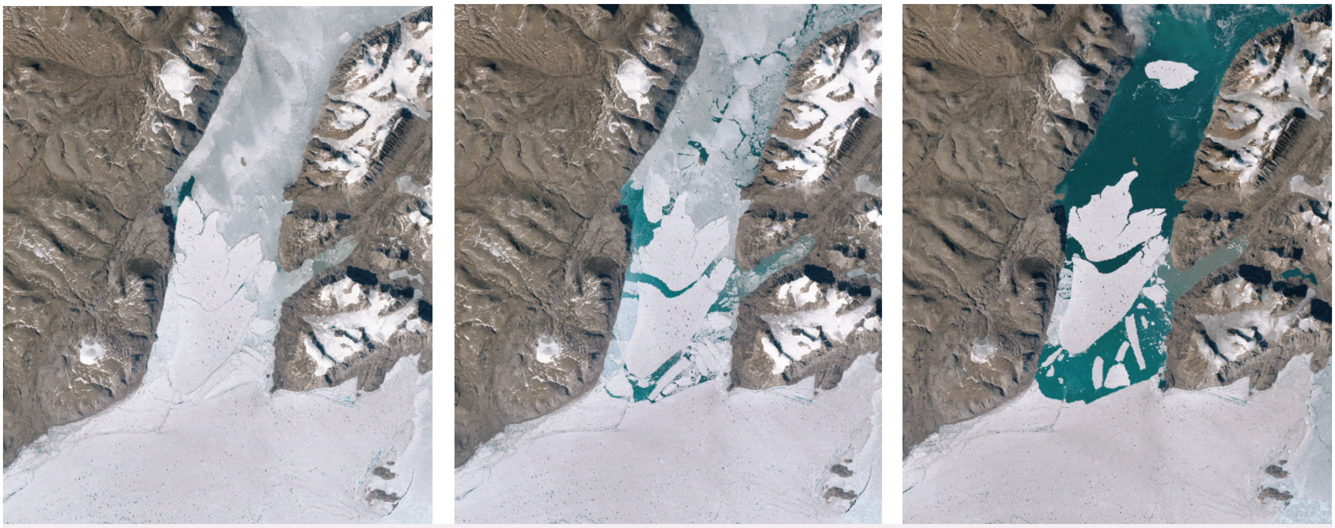


FIGURE 2 A floating portion of the Nioghalvfjerdsbræ outlet glacier fractures and breaks away in this sequence of images from June and July of 2020.

» ONE GLACIER THAT HOLDS 1.1 METERS OF POTENTIAL GLOBAL SEA LEVEL RISE

The North Atlantic island of Greenland is covered with the world's second largest ice pack after that of Antarctica (Figure 1). Greenland's sparsely populated landscape may seem unspoiled, but climate change is actually tearing away at its icy mantle.

The ongoing discharge of ice into the ocean is a "fundamental process in the ice sheet mass-balance," according to a 2021 article in *Communications Earth & Environment* by Humbert and her colleagues. The article notes that the entire Northeast Greenland Ice Stream contains enough ice to raise global sea levels by 1.1 meters. While the entire formation is not expected to vanish, Greenland's overall ice cover has declined dramatically since 1990. This process of decay has not been linear or uniform across the island. Nioghalvfjerdsbræ, for example, is now Greenland's largest outlet glacier. The nearby Petermann Glacier used to be larger, but has been shrinking even more quickly.

» EXISTING MODELS UNDERESTIMATE THE RATE OF ICE LOSS

Greenland's overall loss of ice mass is distinct from "calving", which is the breaking off of icebergs from glaciers' floating tongues. While calving does not directly raise sea levels, the calving process can quicken the movement of land-based ice toward the coast. Satellite imagery from the European Space Agency (Figure 2) has captured a rapid and dramatic calving event in action. Between June 29 and July 24 of 2020, a 125 km^2 floating portion of Nioghalvfjerdsbræ calved into many separate icebergs, which then drifted off to melt into the North Atlantic.

Direct observations of ice sheet behavior are valuable, but insufficient for predicting the trajectory of Greenland's ice loss. Glaciologists have been building and refining ice sheet models for decades, yet, as Humbert says, "There is still a lot of uncertainty around this approach." Starting in 2014, the team at AWI joined 14 other research groups to compare and refine their forecasts of potential ice loss through 2100. The project also compared projections for past years to ice losses that actually occurred. Ominously, the experts' predictions were "far below the actually observed losses" since 2015, as stated by Martin Rückamp of AWI. He says, "The models for Greenland underestimate the current changes in the ice sheet due to climate change."

» VISCOELASTIC MODELING TO CAPTURE FAST-ACTING FORCES

Angelika Humbert has personally made numerous trips to Greenland and Antarctica to gather data and research samples, but she recognizes the limitations of the direct approach to glaciology. "Field operations are very costly and time consuming, and there is only so much we can see," she says. "What we want to learn is hidden inside a system, and much of that system is buried beneath many tons of ice! We need modeling to tell us what behaviors are driving ice loss, and also to show us where to look for those behaviors."

Since the 1980s, researchers have relied on numerical models to describe and predict how ice sheets evolve. "They found that you could capture the effects of temperature changes with models built around a viscous power law function," Humbert explains. "If you are modeling stable, long-term behavior, and you get your viscous deformation and sliding right, your model can do a decent job. But if you are trying to capture loads that are changing on a short time scale, then you need a different approach."

What drives short-term changes in the loads that affect ice sheet behavior? Humbert and the AWI team focus on two sources of these significant but poorly understood forces: oceanic tidal movement under floating ice tongues (such as the one shown in Figure 2) and the ruggedly uneven landscape of Greenland itself. Both tidal movement and Greenland's topography help determine how rapidly the island's ice cover is moving toward the ocean.

To investigate the elastic deformation caused by these factors, Humbert and

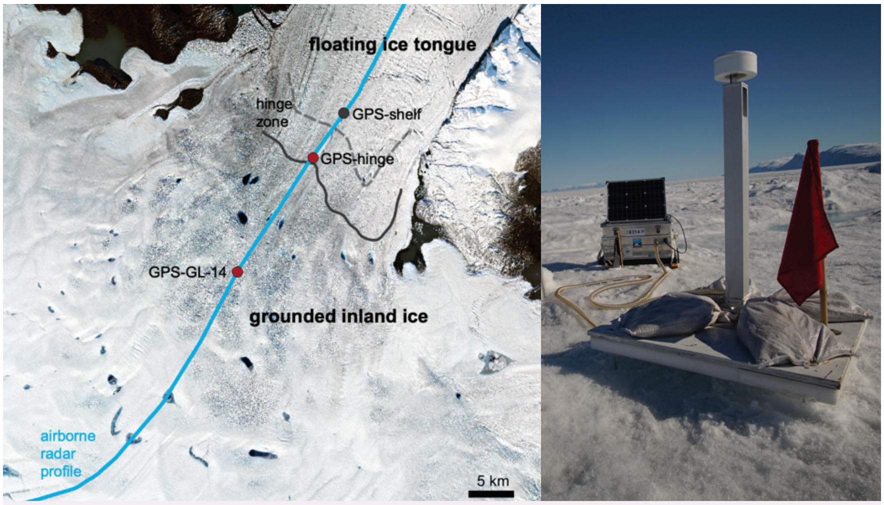


FIGURE 3 Positions of GPS measuring stations mounted on Nioghalvfjerdsbræ (left) and an individual station (right). Photo at right by Ole Zeising of AWI.

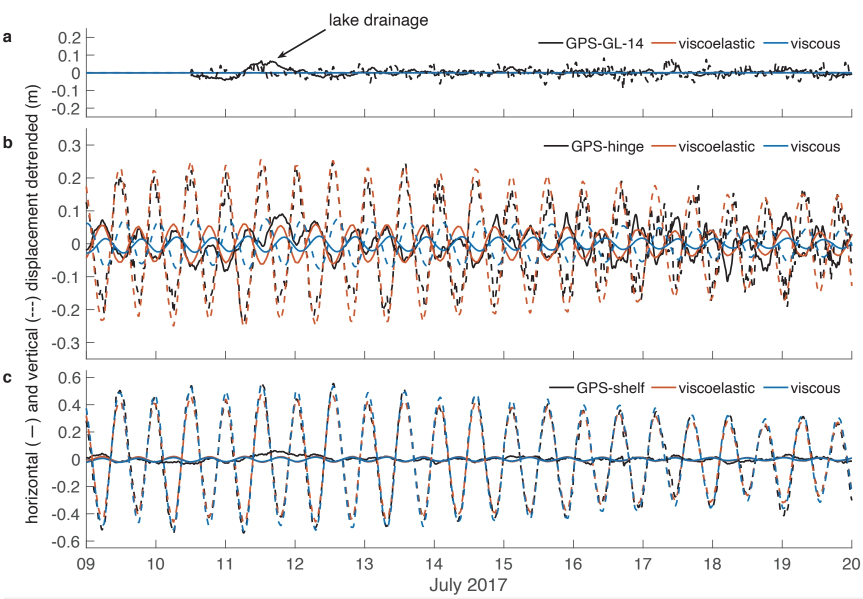


FIGURE 4 Displacement over time of glacier ice at three locations on Nioghalvfjerdsbræ. Black lines show measured displacement, orange lines show simulated displacement according to the "COMice-ve" viscoelastic model that AWI built in the COMSOL® software, and blue lines show simulated displacement in a viscous model.

her team built a viscoelastic model of Nioghalvfjerdsbræ in the COMSOL Multiphysics® software. The glacier model's geometry was based on data from radar surveys. The model solved underlying equations for a viscoelastic Maxwell material across a 2D model domain consisting of a vertical cross section along the blue line shown in Figure 3. The simulated results were then compared to actual field measurements of glacier flow obtained by four GPS stations.

» HOW CYCLING TIDES AFFECT GLACIER MOVEMENT

The tides around Greenland typically raise and lower the coastal water line between 1 and 4 meters per cycle. This action exerts tremendous force on outlet glaciers' floating tongues, and these forces are transmitted into the land-based parts of the glacier as well. AWI's viscoelastic model explores how these cyclical changes in stress distribution can affect the glacier's flow toward the sea.

The charts in Figure 4 present the measured tide-induced stresses acting on Nioghalvfjerdsbræ at three locations, superimposed on stresses predicted by viscous and viscoelastic simulations. Chart *a* shows how displacements decline further when they are 14 kilometers inland from the grounding line (GL). Chart *b* shows that cyclical tidal stresses lessen at GPS-hinge, located in a bending zone near the grounding line between land and sea. Chart *c* shows activity at the location called *GPS-shelf*, which is mounted on ice floating in the ocean. Accordingly, it shows the most pronounced waveform of cyclical tidal stresses acting on the ice.

"The floating tongue is moving up and down, which produces elastic responses in the land-based portion of the glacier," says Julia Christmann, a mathematician on the AWI team who plays a key role in constructing its simulation models. "There is also a subglacial hydrological system of liquid water between the inland ice and the ground. This basal water system is poorly known, though we can see evidence of its effects." For example, chart *a* shows a spike in stresses below a lake sitting atop the glacier. "Lake water flows down through the ice, where it adds to the subglacial water layer and compounds its lubricating effect," Christmann says.

The plotted trend lines highlight the greater accuracy of the team's new viscoelastic simulations, as compared to purely viscous models. As Christmann explains, "The viscous model does not capture the full extent of changes in stress, and it does not show the correct amplitude. (See chart *c* in Figure 4). In the bending zone, we can see a phase shift in these forces due to elastic response." Christmann continues, "You can only get an accurate model if you account for viscoelastic 'spring' action."

» MODELING ELASTIC STRAINS FROM UNEVEN LANDSCAPES

The crevasses in Greenland's glaciers reveal the unevenness of the underlying landscape (Figure 5). Crevasses also provide further evidence that glacial ice is not a purely viscous material. "You can watch a glacier over time and see that it creeps, as a viscous material would,"

FIGURE 5 Aerial view of Nioghalvfjerdsbræ showing the extensive patterns of the crevasses. Photo by Julia Christmann of AWI.

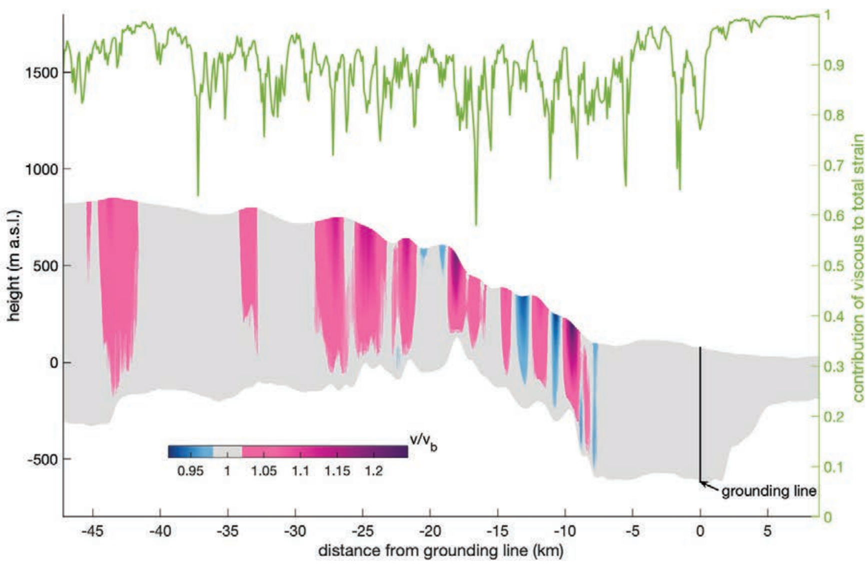


FIGURE 6 A cross section of Nioghalvfjerdsbræ (left scale) showing vertical velocities of ice movement inside the glacier, as compared to movement at the base of the glacier. Blue areas are moving more slowly than basal velocity, while pink and purple areas are moving more quickly than ice at the base. The green line (right scale) shows the proportion of viscous strain to total strain along the cross-section line.

says Humbert. However, a purely viscous material would not form persistent cracks the way that ice sheets do. "From the beginning of glaciology, we have had to accept the reality of these crevasses," she says. The team's viscoelastic model provides a novel way to explore how the land beneath Nioghalvfjerdsbræ facilitates the emergence of crevasses and affects glacial sliding.

"When we did our simulations, we were surprised at the amount of elastic strain created by topography," Christmann explains. "We saw these effects far inland, where they would have nothing to do with tidal changes."

Figure 6 shows how vertical deformation in the glacier corresponds to the underlying landscape and helps researchers understand how localized elastic vertical motion affects the entire sheet's horizontal movement. Shaded areas indicate velocity in that part of the glacier compared to its basal velocity. Blue zones are moving vertically at a slower rate than the sections that are directly above the ground, indicating that the ice is being compressed. Pink and purple zones are moving faster than ice at the base, showing that ice is being vertically stretched.

These simulation results suggest that the AWI team's improved model could provide more accurate forecasts of glacial movements. "This was a 'wow' effect for us," says Humbert. "Just as the up and down of the tides creates elastic strain that affects glacier flow, now we can capture the elastic part of the up and down over bedrock as well."

» SCALING UP AS THE CLOCK RUNS DOWN

The improved viscoelastic model of Nioghalvfjerdsbræ is only the latest example of Humbert's decades-long use of numerical simulation tools for glaciological research. "COMSOL® is very well suited to our work," she says. "It is a fantastic tool for trying out new ideas. The software makes it relatively easy to adjust settings and conduct new simulation experiments without having to write custom code." Humbert's university students frequently incorporate simulation into their research. Examples include Julia Christmann's PhD work on the calving of ice shelves, and another degree project that modeled the evolution of the subglacial channels that carry meltwater from the surface to the ice base.

The AWI team is proud of its investigative work, but Humbert is fully cognizant of just how much information about the world's ice cover remains unknown — and that time is short. "We cannot afford Maxwell material simulations of all of Greenland," Humbert concedes. "We could burn years of computational time and still not cover everything. But perhaps we can parameterize the localized elastic response effects of our model, and then implement it at a larger scale," she says.

This scale defines the challenges faced by 21st-century glaciologists. The size of their research subjects is staggering, and so is the global significance of their work. Even as their knowledge is growing, it is imperative that they find more information, more quickly. Angelika Humbert would welcome input from people in other fields who study viscoelastic materials. "If other COMSOL users are dealing with fractures in Maxwell materials, they probably face some of the same difficulties that we have, even if their models have nothing to do with ice!" she says. "Maybe we can have an exchange and tackle these issues together."

Perhaps, in this spirit, we who benefit from the work of glaciologists can help shoulder some of the vast and weighty challenges they bear. ◎

Virtual Product Development with Acoustic Simulation

by **ROGER SHIVELY**

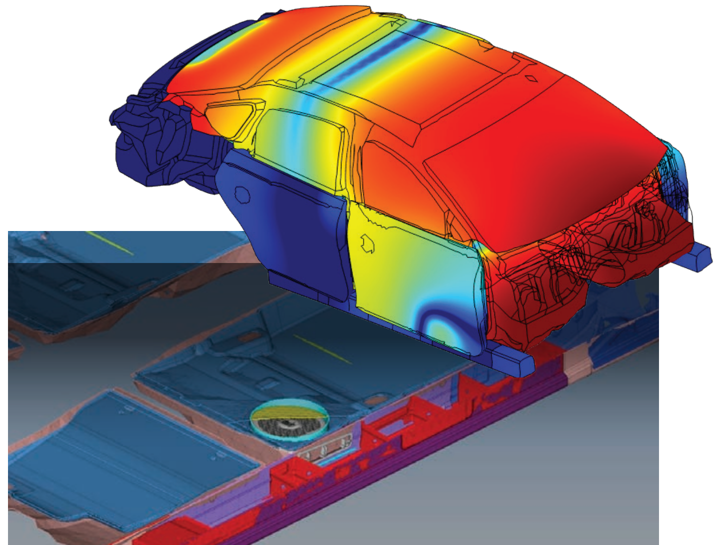
Among original equipment manufacturers (OEMs) worldwide, particularly within the automotive market, the use of simulation software has helped control costs by reducing the need for physical prototypes.

Simulation was first used in the automotive sector for vehicle crash safety, durability, and noise, vibration, and harshness (NVH) research. These simulations have helped pave the way for efficient audio system and vehicle acoustics model building. For example, meshes created for crash, durability, and noise models are being repurposed for acoustic meshes. Whether this is done internally by OEMs and component manufacturers or by independent consulting companies like JJR Acoustics, repurposing these meshes saves the resources required to create them from raw CAD files.

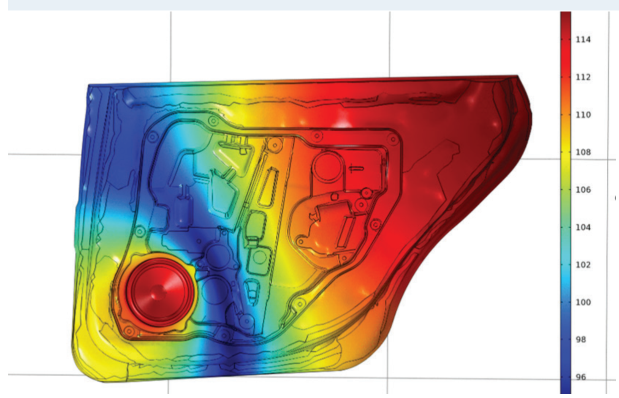
Acoustic simulation powered by COMSOL Multiphysics® helps automotive audio engineers integrate an audio system's loudspeakers into the vehicle while maintaining the integrity of the loudspeakers' design quality. Much of the simulation, tuning, and auralization that's required is being done outside the lab space now. Exploring tuning options — whether virtually or in the lab —helps acoustics engineers develop an understanding of the acoustic space and loudspeaker system to find a path to the optimal in-vehicle audio experience. By then changing the trim, speaker, and speaker location and finding another path, knowledge is built. With multiphysics simulation software, the insights of this optimization and iteration process are now available virtually. Models developed into digital twins or based on existing digital twins are enabling virtual acoustical tuning of concept cars while they are still in the design phase. While this digital workflow is familiar to engineers using traditional physical prototyping and mechanical simulation, it also enables fast and cost-efficient exploration of the entire design space before committing to the interior architecture.

Applications of system-level automotive simulations enabled by COMSOL Multiphysics include optimizing loudspeaker placement and reducing negative structural interactions of loudspeakers and mounting locations. This type of simulation requires the computation of results for a great range of frequencies throughout the car cabin. The acoustic frequency response averaged over the location of a listener's head location is a key factor in determining audio quality. This can be done for multiple listening positions in the vehicle.

Going forward, the design of active noise control along with music playback will be a major focus for audio and acoustics engineers. Multiphysics simulation of the acoustic transfer paths for noise and its cancellation will be crucial for understanding the effects of these phenomena and applying this insight to the design process.

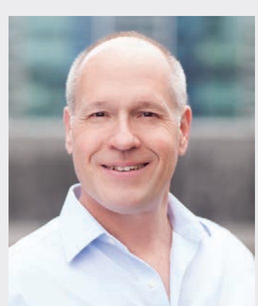


An example of optimizing the location of the subwoofer mounting, the sound pressure level (SPL) mode, and SPL response at the listener.



Structural interaction of woofer and door.

ABOUT THE AUTHOR



Roger Shively is a cofounder and principal of JJR Acoustics (Seattle, WA). He has more than 34 years of experience in engineering research and development, with significant experience in product realization and in launching new products at OEM manufacturers around the world. Before cofounding JJR Acoustics in 2011, Roger worked as chief engineer of acoustic systems as well as functional manager for North American and Asian engineering product development teams in the Automotive Division of Harman International Industries Inc., a journey that began in 1986.