THE KEY TO UNLOCKING FUEL CELLS?

Carlo Locci, global application specialist for hydrogen fuel cells at Siemens, tells **Chris Pickering** why motorsport could be the ideal testbed for this new technology

WE live in uncertain times. Whether it's climate change, Brexit or the coronavirus, 2020 never seems to be far away from another calamity. And yet there's possibly a flipside to all this disruption. While it must be tempting for policymakers to play it safe, it's also a great time to press ahead with new ideas.

In Germany, for instance, a post-COVID stimulus package has been announced that includes €50 billion allocated to future technologies. More precisely, €10 billion of that is specifically aimed at positioning Europe's biggest economy as a leader in hydrogen technology. This comes 12 months after China announced its own dramatic increase in subsidies for fuel cell development. The last time the country did something similar, it surged ahead in battery production, sweeping the global car industry along with it.

What – you might ask – does this have to do with motorsport? Well, in short, it means that hydrogen is back on the agenda. And where new technology is being developed, there's a natural desire to showcase its abilities.

"Extreme environments usually make for good test cases. Let's remember that jet engines were first used for extreme military applications, and were then transferred to civilian passenger aircraft," comments Carlo Locci, global application specialist for hydrogen fuel cells at Siemens. "Similarly, you can trace the motorsport influence in everything from dual clutch gearboxes to turbochargers on road cars. It allows us to push the boundaries, even when the application itself is quite different. The same applies to fuel cells, where the extreme conditions of racing could be a good testbed."

Locci's area of responsibility covers the use of Siemens' multiphysics simulation software for powertrain and fuel cell development, so it gives him an interesting perspective on the technology. "Motorsport customers are always very interesting to work with," he comments. "They're extremely demanding and really help us to push forwards the capabilities of modelling software."

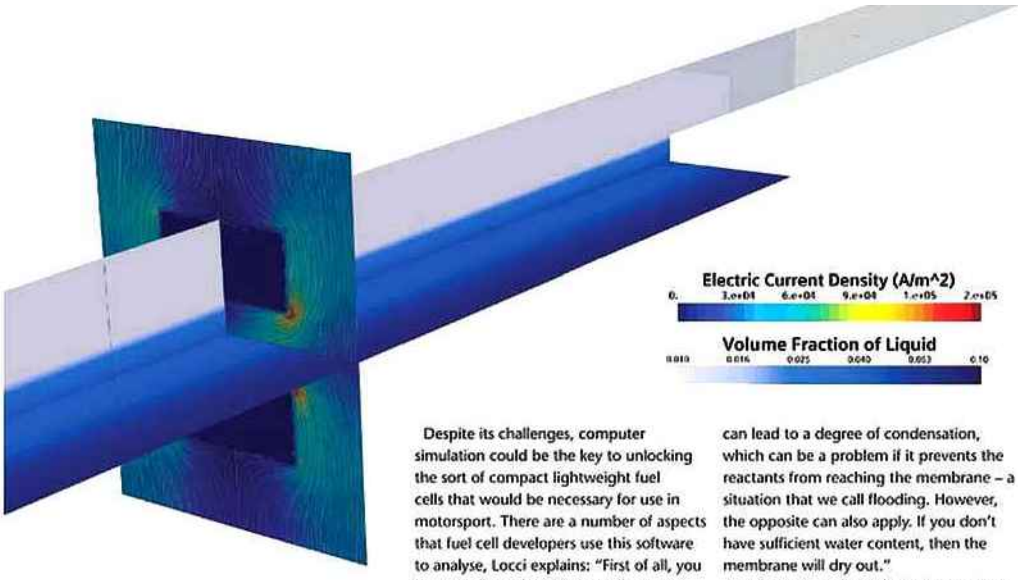
At present, fuel cell cars are pretty marginal for motorsport use. The ground-breaking efforts of organisations like GreenGT and Delft University have shown that a fuel cell-powered racing car is possible, but we've not quite reached the stage where one could reliably lap a track like Le Mans at GTE pace or above. That's a prerequisite if these cars are to safely mix it with the forthcoming LMDh and Hypercar machines.

MODELLING CHALLENGES

Refining the power output and energy density of fuel cells is exactly the sort of challenge that fuel cell manufacturers are looking at, but it's by no means a simple task. The fundamental principle behind a fuel cell is deceptively simple: it reacts hydrogen and oxygen to liberate electrons, which are forced to flow around a circuit, creating an electric current. The reality, however, is that high-power fuel cells are complex pieces of engineering that can be difficult – and computationally expensive – to model, comments Locci.

ABOVE Electric current density distribution and volume fraction distribution in a single cell configuration. In this picture, we can observe the electric current distribution in a plane perpendicular to the flow direction. Also, the volume fraction of liquid at the cathode side is shown. Liquid water is mainly produced at the interface and then escapes from the outlet

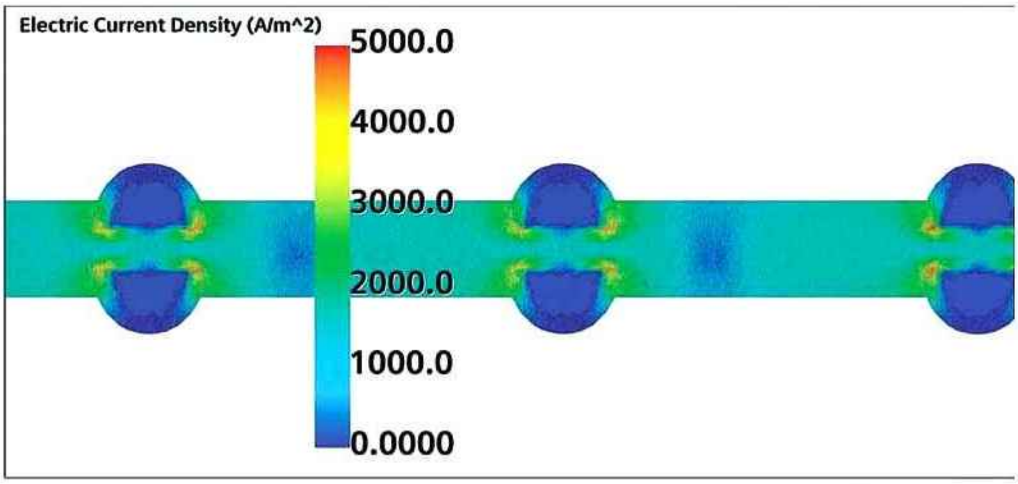
RIGHT Refuelling stops could provide a strategic element missing from battery-electric series. Total pioneered the world's first mobile hydrogen refuelling station for the ACO's Mission H24 project



Despite its challenges, computer simulation could be the key to unlocking the sort of compact lightweight fuel cells that would be necessary for use in motorsport. There are a number of aspects that fuel cell developers use this software to analyse, Locci explains: "First of all, you have the flow of hydrogen and oxygen through the fuel cell. Next, there's the water management. At the cathode side of a fuel cell you basically have a chemical reaction that forms gaseous water. This can lead to a degree of condensation, which can be a problem if it prevents the reactants from reaching the membrane – a situation that we call flooding. However, the opposite can also apply. If you don't have sufficient water content, then the membrane will dry out."

Another critical factor is the temperature distribution, he explains: "Inside the fuel cell, you have all sorts of gradients: gas gradients, electric current density gradients, velocity gradients. When you ▶

GreenGT/Charles Guenant



have a pronounced temperature gradient in one area, that might jeopardise the life of the fuel cell; ideally, you want the temperature distribution to be as homogenous as possible."

Finally, there's the ageing of the fuel cell: "Generally, long-term ageing would not be as critical for motorsport, but it's also linked to the reliability. That comes back to temperature distribution, as well as the electric current distribution. You have a series of parasitic reactions that reduce the thickness of the membrane over time. We have models that can predict that effect. Plus, you have what's known as compression ageing. That's a result of the thickness of the membrane continuously changing, creating a fatigue condition."

Understanding these issues is one thing, but modelling them is another challenge altogether. Much of the complexity inherent with fuel cell models comes down to the multi-phase physics that's required. Like all forms of computational fluid dynamics (CFD), these use the Navier-Stokes equations to describe fluid flow, but the properties of the fluids can change dramatically according to their phase. For instance, viscosity and thermal conductivity will behave in different ways for a liquid or a gas.

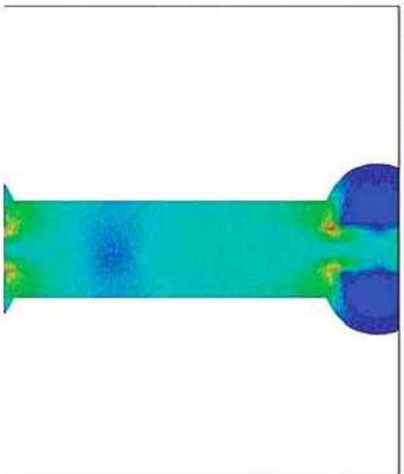
"The problem arises when the gas phase and the liquid phase interact with each other," explains Locci. "Generally, multi-phase CFD simulations use a volume of fluid (VoF) approach, where liquid and gas continuous phases interact with each other, which means you solve a set of transport equations for both the liquid and the gas, to keep track of what's known as the free surface.

"In reality, the situation in a fuel cell is even more

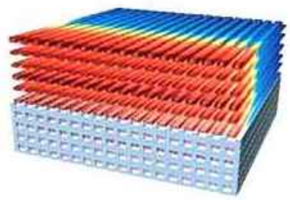
ABOVE Electric current distribution layers in a fuel cell layer. In this image, the electric current distribution is shown on a plane perpendicular to the reactants' flow direction. Naturally, the electric current distribution increases as the voltage decreases. The red spots occur at the triple boundary interface, in which the bipolar plate, the gas diffusion layer and the channel meet

RIGHT GreenGT's LMPH2G prototype is the ACO's poster boy for hydrogen motorsport

> *"The physics inside a fuel cell present just about the most challenging conditions for CFD"*



complicated, because this interaction between the two phases occurs mainly in the gas diffusion layer [a layer that allows the gas to pass from the flow channels to the catalyst material, as well as providing a conduit for the flow of current]. This is a porous environment where a traditional VoF approach would



ABOVE The distribution of temperature in a fuel cell stack. Such information is fundamental to observe the thermal gradients that strongly affect the life and reliability of a fuel cell

be very computationally demanding. Instead, we use a simplified approach, which mimics the behaviour of the free surface rather than directly calculating it. We do that by modifying the transport equations to account for the presence of the free surface."

The main substances that need to be modelled in a fuel cell are gaseous hydrogen (which is sometimes injected with water vapour) at the anode, plus air (principally nitrogen and oxygen) and liquid water at the cathode side. This means that there is a complex three-dimensional distribution of five main substances in three different physical states throughout the fuel cell. On top of that, you have the bipolar plates, which are solid and can be made from graphite, metal, polymers or composites.

"I would say that the physics inside a fuel cell presents just about the most ▶

> ***"Fuel cells are very promising for long-distance applications where endurance is critical"***

challenging conditions for CFD," comments Locci. "That's firstly because you have multi-physics. You need to work with several different sets of equations and you need to satisfy the criteria for the stability of all those equations or you can end up with a conflict between them.

"Secondly, you're solving for environments that are extremely heterogeneous; that includes conventional gas flow within the channels, but also solids [the bipolar plates and membranes] and porous environments. It's also extremely complex from a meshing point of view, because you need to think about balancing the detail of the geometry against the processing time."

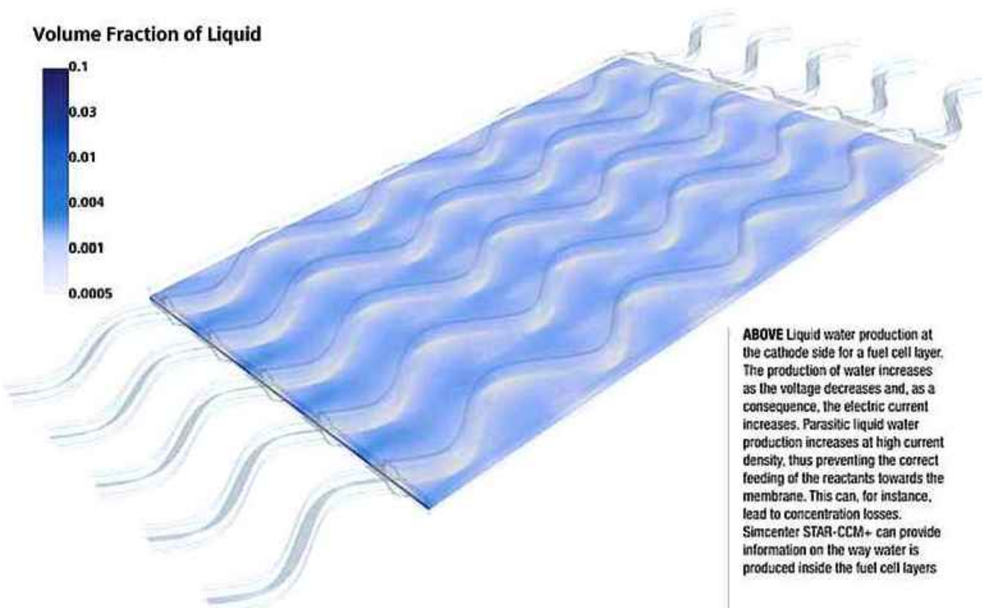
As with any CFD simulation, there are approximations that can be used to simplify the model and reduce computational time, but they risk losing important detail. "With complexity comes computational cost. You can use a 1D code to get very important information on things like the dynamic behaviour of the fuel cell and its control. That would be very costly to achieve in 3D, but you have to understand the simplifications that you're applying and their limitations," notes Locci.

LEFT Locci is opening up new frontiers

RACE TO DEVELOP

The sheer complexity of fuel cells, allied to the fact that the technology has only just started attracting mainstream interest, means that there's still plenty of scope for development. "There are many, many configurations of the bipolar plates, for instance," Locci observes. "That covers lots of different materials, some with wavy channels, some with square channels... Motorsport would provide a great R&D ▶

BELOW Fuel cell vehicles could ultimately be well suited to endurance events like rally raids



ABOVE Liquid water production at the cathode side for a fuel cell layer. The production of water increases as the voltage decreases and, as a consequence, the electric current increases. Parasitic liquid water production increases at high current density, thus preventing the correct feeding of the reactants towards the membrane. This can, for instance, lead to concentration losses. Simcenter STAR-CCM+ can provide information on the way water is produced inside the fuel cell layers

> ***"Motorsport would provide a great R&D environment to try these new ideas"***

environment to try these new ideas."

One common concern is safety. It's often pointed out that the total mass of hydrogen carried onboard a fuel cell car remains quite small, and it arguably poses less risk on the electrical side than a battery-powered vehicle, as the voltage is produced on-demand. Nonetheless, the idea of carrying tanks of pressurised hydrogen around a racetrack in what is potentially a contact sport does bring its own challenges.

"You do need to be very careful with hydrogen, because it can explode, but the same applies to gasoline to a certain extent," notes Locci. "It's something that the teams and the race organisers would need to adjust to, but it's not an insurmountable challenge."

Refuelling is also a consideration. It certainly wouldn't be easy, with high pressures involved in the onboard tank and the refuelling, as well as the off-vehicle storage, but it could add something to green racing that's absent from series with battery electric vehicles like Formula E. "When we used to have refuelling in F1 it was part of the spectacle; it's doubtful that you could do that as quickly using hydrogen, but it could still be a feature of the competition," comments Locci.

This, of course, comes back to what type of competition you wish to enter. For short sprints like rallycross events or hillclimbs,

BELOW LEFT Simulation is one of the keys to moving fuel cells forward

BELOW Delft University has shown that a fuel cell-powered racing car is possible, but they can't yet lap longer circuits at respectable GTE pace

it's already easier to use a battery than a fuel cell, and that situation is unlikely to change as the two technologies develop. Once you start talking about endurance racing, however, it's hard to imagine that a battery electric vehicle will ever fit the bill – the recharging times are simply too long.

FUEL CELL vs BATTERY ELECTRIC

This is a situation that's expected to be mirrored in mainstream applications, Locci points out: "The workflow to get a fuel cell vehicle going is much more complex than a battery electric car, because you have to capture the hydrogen – perhaps with an electrolyser powered by a wind turbine – then you need to store it, to fill the car and to release the energy in a fuel cell. All four of those stages are complicated.

"With a battery electric vehicle you basically just get your wind turbine and plug it straight in, so I think that's the way the market will go for typical passenger cars. But fuel cells are very promising for long-distance applications where endurance is critical and I think that could be reflected in motorsport. I'd love to see fuel cell vehicles in something like the Le Mans 24 Hours or a rally raid competition, to fully highlight these aspects."

There is, of course, already some movement in this direction. This month's running of Le Mans is likely to provide an update on the Mission H24 project, which was set up to create the framework for hydrogen fuel cell vehicles to join the competition from 2024.

There have also been hints from a number of major OEMs that hydrogen racing is on their radar. Two years ago BMW Motorsport boss Jens Marquardt commented: "[Hydrogen] is something we have seen from a study point of view that is feasible. It would be a technology to consider for a race application in endurance racing and it is something we could look at in the future from a prototype point of view."

By far the biggest factor in making this a reality will be the development work that goes into the fuel cells themselves. That's where the simulation comes into play. As for the motivation to go down the hydrogen route, and the funding to pursue it, that's in the realm of the CEOs and the politicians. But recent events suggest that they're going to be taking a keen interest in hydrogen.