Micro SOFCs: why small is beautiful

Darius Nikbin

Early-stage work on miniaturization suggests that there's a lot more to come from solid-oxide fuel cells than just stationary power generation.

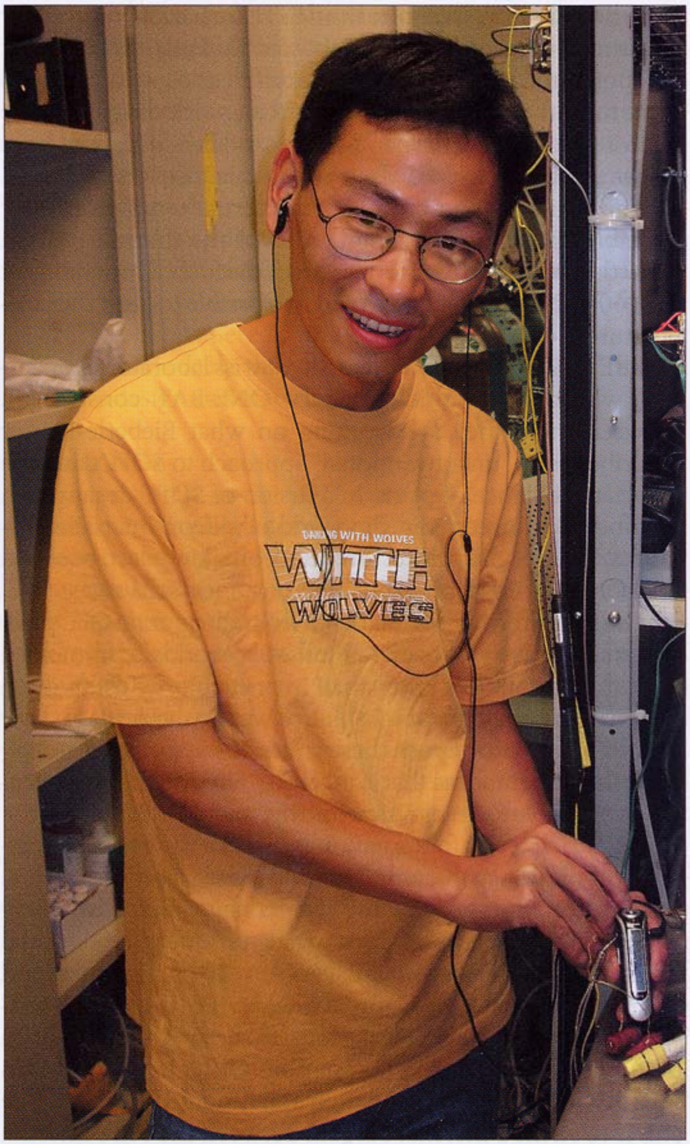
WITHIN THE next decade it is expected that highly efficient solid-oxide fuel-cell (SOFC) power systems will be deployed in a number of ways, including stationary (residential, commercial, remote), mobile (auxiliary power units for land, air and water vehicles) and military applications. For the system developers, SOFC technology ticks a lot of the boxes, not least on fuel flexibility, solid-state construction, an invariant (solid) electrolyte, high-quality waste heat and the absence of precious-metal catalysts. Taken together, these are compelling characteristics. So compelling are they, in fact, that a number of research groups around the world are now asking the same question: can the technology be scaled down to yield micro SOFCs that are suited to volume applications in consumer electronic devices and related portable applications?

The answer to this question isn't going to come easy. "For any fuel cell, replacing a lithium-ion battery is a big challenge," explained Jerry Hallmark. He should know, given that he's manager of the Energy Technologies team at Motorola Labs in Tempe, Arizona, US. Two of the biggest issues are size – getting the entire fuel-cell system as small as a current battery (~10 cm^3); and energy density – being able to fit the fuel cell, electronics, hybridizing battery, etc into 10 cm^3 and still have room for enough fuel to give reasonable energy density. "These issues are no different for SOFCs," added Hallmark.

Questions of scale

The principal advantage of micro SOFCs is their ability to operate on higher-energy-density fuels (e.g. butane) than the lower-temperature direct-methanol fuel cells. The downside, though, is the SOFC's elevated operating temperature (traditionally as high as 1000 °C). This means that some form of insulation is required to mitigate safety concerns. "For larger fuel cells (20 W for a laptop), these issues appear to be manageable," said Hallmark. "For smaller fuel cells (1 W for a cell phone), these are very difficult challenges. That's not to say that it can't be done, but it's a lot of work."

Undeterred, researchers are now working to demonstrate microscale SOFCs with operating temperatures at or below 600 °C. Hallmark added: "If the fuel energy density and fuel-cell power density can be shown to scale to a very small size –



Rock on: Zingping Shao of Caltech listens to his MP3 player powered by a two-cell micro SOFC stack. Sossina Haile's team has developed a single-chamber micro SOFC, with one inlet for premixed oxygen and fuel and a single outlet for exhaust gases.

including system/insulation overhead – and be rugged/reliable, they'd be hard to beat. Also, the waste heat from the fuel cell can be used to preheat the incoming fuel, thus increasing the effective conversion efficiency."

Scientists in Switzerland, for example, are working on a micro SOFC concept that, they claim, could ultimately deliver an energy density three times as greater as that of the US Department of Energy's long-term goal for lithium-ion batteries. If the work progresses as hoped, they say that their SOFC device could provide 2 W in a single unit and, with a modular approach, 10 W of continuous power at an efficiency of 30%. Its size – currently 75 cm^3 including a 5 cm^3 liquid butane store – corresponds to the upper range of today's batteries for PDAs, laptop computers and other portable electronic devices.

"The short-term goal is to prove the concept because it's still at the very beginning of the development process," Anja Bieberle-Hütter, a researcher from ETH Zurich's laboratory for non-metallic inorganic materials, told *The Fuel Cell Review*. "At the moment we're working on the different components and want to find out whether an SOFC can work on-chip at the microscale." To date, Bieberle-Hütter and her colleagues have demonstrated an SOFC design that can run on reformed butane while maintaining a safe external temperature for portable applications. "Simulations of the thermal system show that you can have the hot part of the fuel cell operating at 550–600 °C, and outside it would be possible to keep the temperature at 40 °C," she said.

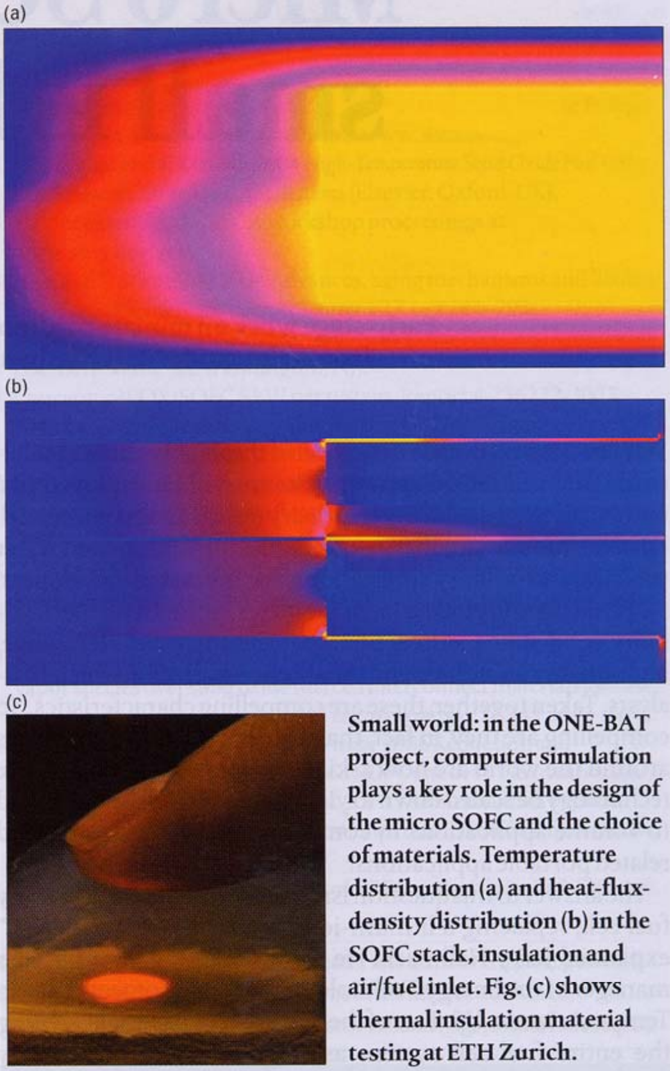
The ETH Zurich team heads up five Swiss laboratories operating within the multidisciplinary ONE-BAT consortium. Between them they are working on what Bieberle-Hütter describes as an "unconventional" approach to SOFCs and the associated balance of plant. In a fusion of SOFC design with methods borrowed from the world of silicon microelectromechanical systems, the researchers are making electrodes and electrolytes by depositing thin films onto inert substrates.

"It's a mixture of silicon platform technology and SOFC principles, so we are trying to combine the two worlds," commented Bieberle-Hütter. "We know that, in principle, by using these materials we are able to obtain high power. So the aim is to show that it's possible to deposit these layers, to have a free-standing triple-layer membrane that is mechanically and thermally stable and suitable for integration into the micro SOFC."

The Zurich team, for its part, has tested a variety of deposition techniques, such as spraying and pulsed laser deposition. Some of the most promising results have been with spray pyrolysis. Thus far the group has produced and tested anode/electrolyte/cathode trilayers of 1–10 µm thickness and with an area of about 200 µm^2. However, the challenges confronting ONE-BAT are not restricted to the micromanufacture of the electrode-electrolyte assembly. Other big obstacles in micro SOFC design are insulation and heat management. The aim is to strike a thermal bargain between the cell's internal temperature, which needs to be high enough to ensure adequate electrolyte conductivity, and its outside temperature, which has to be safe enough for the end user.

One way of improving the thermomechanical stability of the materials is, quite simply, to continue lowering the SOFC operating temperature. "We would like to lower the operating temperature from 600 to 550 °C and then ultimately 500 °C," said Bieberle-Hütter. To achieve this, the laboratory for thermodynamics in emerging technologies at ETH Zurich is performing experiments and simulations to assess the viability of butane reforming at such low fuel-cell temperatures. Indeed, the feasibility has already been demonstrated at 550 °C. However, if operating temperature provides the near-term focus, it's encouraging to see that there's also a longer-term vision. "In terms of timescale, I would say that we could start to design a prototype in two years," said Bieberle-Hütter. "The prototype would then be ready in three or four years."

1. Micro-scale modelling

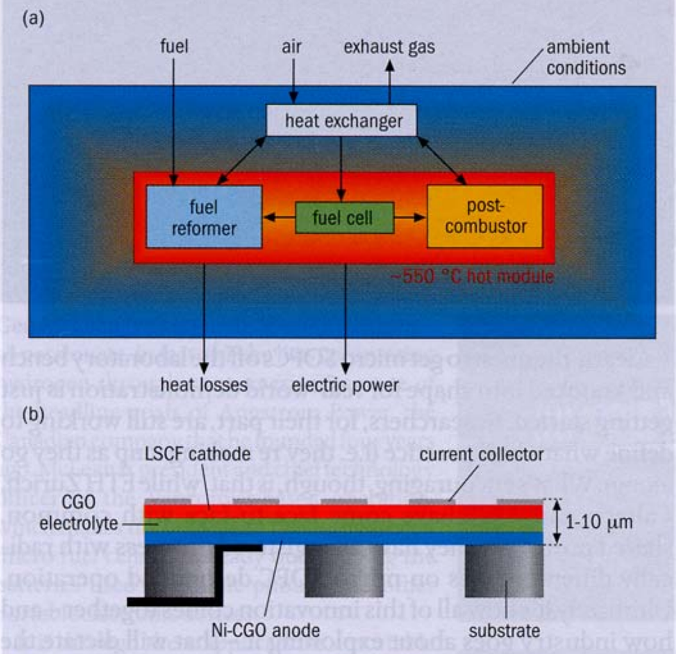


Small world: in the ONE-BAT project, computer simulation plays a key role in the design of the micro SOFC and the choice of materials. Temperature distribution (a) and heat-flux-density distribution (b) in the SOFC stack, insulation and air/fuel inlet. Fig. (c) shows thermal insulation material testing at ETH Zurich.

It's too hot

A team of researchers at California Institute of Technology (Caltech) in Pasadena is developing a propane-burning micro SOFC, the core electrode–electrolyte assembly of which is

2. Design and innovation



(a) The overall concept for the ONE-BAT micro SOFC system, which the researchers anticipate will eventually operate at temperatures as low as 500 °C. There are two main parts: the "hot module" contains all of the high-temperature elements, while the balance of the plant covers the elements providing the air, fuel and power management. (b) The basic materials/component layout in the ONE-BAT fuel cell.

about the size of a watch battery. The choice of propane is down to the material's high energy density and the fact that it can be stored in miniature devices because it is easily compressed into a liquid. The resulting SOFC configuration is simple and compact, with just one inlet for the oxygen and fuel, and one outlet for the exhaust gases. The system works because of the selective activity of the cathode and anode catalysts, which essentially behave as if the oxygen and fuel were supplied separately.

As a proof of concept, the team has even demonstrated a working micro SOFC stack and used it to power an MP3 player. "Using two cells, we've been able to self-sustain a temperature of about 575 °C and a peak power density of about 275 mW/cm^2, which translates into a total peak power of 400 mW," Sossina Haile, team leader in Caltech's materials science department, told *The Fuel Cell Review*. "Adding in all of the auxiliary plumbing, the fuel-cell system is bigger than the electronics that we are powering, but the two-cell stack is small, which means that we have the fundamentals in place for miniaturizing the system as a whole."

In a similar vein to the Swiss programme, Haile and her colleagues are working on ways to lower and maintain the SOFC's operating temperature. "Small fuel cells are challenging because it's hard to keep them at high enough temperatures to get the hydrocarbon fuels to react," said Haile. Consequently, one of the most significant breakthroughs is the fact that the Caltech micro SOFC is able to keep itself hot, which is a prerequisite for producing power.

The researchers achieve this by applying to the ceria-based anode an additional catalyst (developed at Northwestern University, Illinois) that causes enough heat release to maintain the temperature of the cell. Finally, a heat exchanger (designed in collaboration with the University of Southern California) ensures that the hot gases exiting from the fuel cell transfer their heat to the incoming cold gases. This combined strategy minimizes the need for bulky insulation, which would otherwise add to the size of the device. "Once the two-cell stack is ignited in the furnace, it can be maintained in self-sustaining mode with a moderate amount of insulation and heat recirculation," added Haile.

An added bonus of the Caltech micro SOFC design is that the thermomechanical problems that tend to afflict conventional SOFCs – especially those that undergo frequent start-up and shutdown – have largely been eliminated. The near-term priority is increasing not so much the power density of the individual cells, which is quite competitive at this stage, but rather the energy density of the entire system.

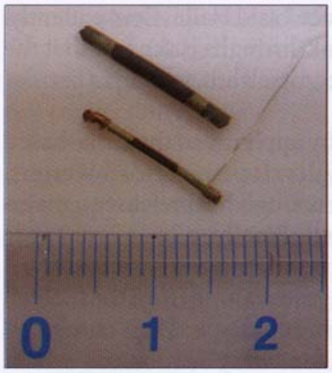
"Right now our device is small and light, but we are just beginning to focus on efficiency and fuel utilization," explained Haile. "I think we need to be at around 10% [efficiency] for the devices to be considered commercially, and we are now only at about 1%. Ultimately, though, I think we can reach 30% or even 50% with design and materials improvements."

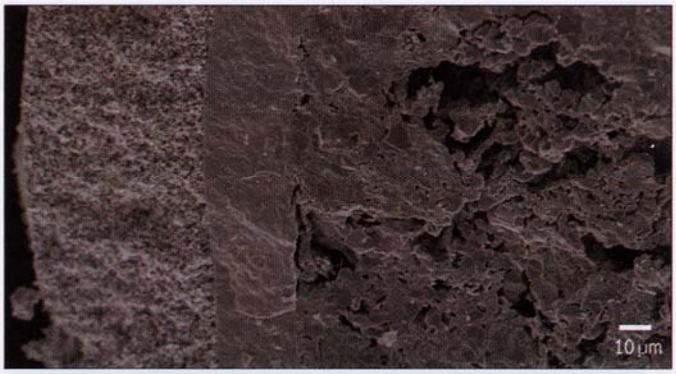
Tubular cells

Not surprisingly, micro SOFCs are also attracting attention within Japan's fuel-cell development community. Specifically, a research team at the National Institute of Advanced Industrial Science and Technology (AIST) is promising to deliver micro SOFC technology that will "open the gateway" for applications in portable electronic devices. The five-year project, which will run until 2009 and involves 13 partners in industry and academia, is funded by the country's New Energy and Industrial Technology Development Organization. By applying advanced ceramic processing techniques, the researchers have developed a microtubular SOFC that is less than 2 mm in diameter and that works in the 500–600 °C region.

The team is using ceramic electrodes and a ceria-based electrolyte material, which exhibits high oxygen-ion conduction at low temperatures. "By optimizing the structures of the ceramic electrodes, we have achieved a cell power density of 1 W/cm^2 at 570 °C – the highest power density achieved [to date] for SOFCs with ceria-based electrolytes," claimed AIST researcher Toshio Suzuki.

He added: "Our project aim, firstly, is to develop materials for an electrolyte and electrodes that can be used at a lower operating temperature; then, to establish a manufacturing process technology for integrating the materials at the micro level. After that we will be in a position to construct a prototype module and to conduct a demonstration of the ceramic reac-





Cellular science: researchers at AIST in Japan believe that the tubular SOFC design has a number of advantages over planar architectures. Left: two AIST micro SOFCs, one measuring 1.6 mm in diameter and the other 0.8 mm. Right: close-up of the end of a micro SOFC tube showing the cathode (outside)/electrolyte/anode trilayer.

tor.” As with the ONE-BAT project and the work at Caltech, the AIST researchers cite miniaturization and thermal robustness (to ensure shock resistance of the cell materials under rapid start-up and shutdown) as being central to their objectives.

Unlike their US and European counterparts, though, the AIST team is motivated by what it sees as the advantages of a tubular design over the more conventional planar SOFC architecture. “Tubular SOFCs are more robust under rapid changes in electrical load and in cell operating temperatures,” said Suzuki. “It is possible to design SOFC stacks with high volumetric power density, when the diameter of tubular SOFCs is in the range of millimetre to submillimetre. This is not possible with the planar SOFC design.”

Clearly the quest to get micro SOFCs off the laboratory bench and knocked into shape for real-world demonstration is just getting started. Researchers, for their part, are still working to define what’s best practice (i.e. they’re making it up as they go along). What’s encouraging, though, is that, while ETH Zurich, Caltech and AIST have come face-to-face with common, shared problems, they have all registered progress with radically different takes on micro SOFC design and operation. Ultimately it’s how all of this innovation comes together – and how industry goes about exploiting it – that will dictate the longer-term commercial prospects for micro SOFCs. ●

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