Fuel Cells Science and Technology 2010

Scientific advances in fuel cell systems highlighted at the semi-annual event

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This was the fifth conference in the Fuel Cells Science and Technology series following meetings in Amsterdam, Munich, Turin and Copenhagen (1–4). It was held on 6th and 7th October 2010 at the World Trade Center in Zaragoza, Spain, with the theme 'Scientific Advances in Fuel Cell Systems'. This conference series alternates with the Grove Fuel Cell Symposium (5), placing more emphasis on the latest technical developments. The two-day programme was compiled by the Grove Symposium Steering Committee from oral papers and posters submitted from around the world, and the conference was organised by Elsevier (6). The meeting was attended by delegates from universities, research organisations and the fuel cell industry, and as before, many of the papers will be subjected to peer review and published in full in a special edition of *Journal of Power Sources* (7).

There were over 200 delegates from 37 countries, including Spain, Germany and the UK. Although the majority were from Europe, the significant numbers from Japan, Iran and South Korea reflected the high level of interest in fuel cells from those countries, as well as others from the Middle East, Asia, Africa and South America.

The Science and Technology conferences present the latest advances in research and development on fuel cells and their applications. There were three plenary papers, together with eight keynote speakers and 40 oral papers, together with 210 high-quality poster presentations divided into seven categories. Topics for the oral sessions included Fuels, Infrastructure and Fuel Processing; Modelling and Control; Materials for Fuel Cells; Fuel Cell Systems and Applications; Fuel Cell Electrochemistry; and finally Cell and Stack Technology. For this review, only papers involving the use of the platinum group metals (pgms) are discussed.

An exhibition accompanying the conference included displays of demonstration fuel cell systems designed for education and training use (Figures 1 and 2).

Delegates were welcomed to Zaragoza by Pilar Molinero, Director General of Energy and Mining for the Aragon regional government, who formally

Fig. 1. A 1 kWe polymer electrolyte fuel cell and control equipment designed for teaching purposes, exhibited at the Fuel Cells Science and Technology 2010 conference. Operating on pure hydrogen, it can be used to simulate a wide variety of fuel cell and CHP applications. It is built by HELION, an AREVA subsidiary, and developed in collaboration with teachers from Institut Universitaire de Technologie (IUT) of Marseille, France

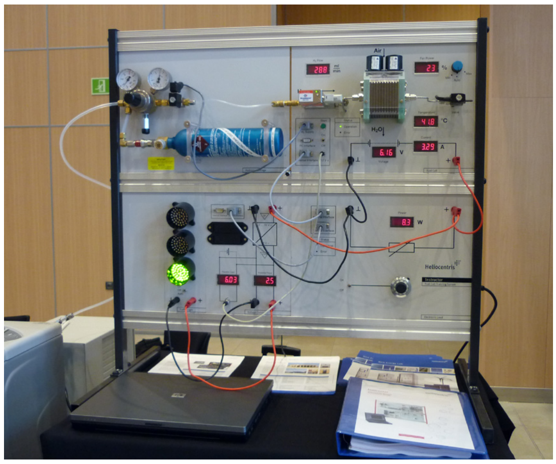

Fig. 2. One of a series of platinum-catalysed fuel cell and solar hydrogen systems for educational purposes designed and built by Heliocentris. This company develops systems and turnkey solutions for training in industry and science, and specialises in hybrid energy storage comprising fuel cells, batteries and energy management devices

opened the conference and briefly described activities in Aragon to encourage hydrogen and fuel cell technologies. The large number of wind farms in the region have created an interest in energy storage using water electrolysis to generate hydrogen during periods of power surplus. A total of 30 hydrogen and fuel cell projects are being supported, including a hydrogen highway from Zaragoza to Huesca to support the introduction of fuel cell vehicles.

Plenary Presentation

Pilar Molinero presented the 2010 Grove Medal to Professor J. Robert Selman (Illinois Institute of Technology (IIT), USA), a leading academic who has devoted more than 30 years to battery and fuel cell research and development, and to global commercialisation of these technologies. This has included the electrochemical engineering of batteries and high temperature fuel cells at the US Department of Energy's Argonne National Laboratory and Lawrence Berkeley National Laboratory, and at the IIT.

Professor Selman presented a talk on his experiences and advances made during this period. One major development is the advent of computer modelling which has led to improved structures and performance of fuel cells and their systems, although there is still a need to experimentally verify the predictions obtained at each stage. Other exciting and relatively new areas include the possibility of direct carbon oxidation fuel cells, and miniaturisation including biofuel systems and bioelectrochemistry. One of his particular interests is the use of phase change materials to maintain the uniform temperatures in batteries by absorbing or evolving heat.

Fuels, Infrastructure and Fuel Processing

Fuel cell technology has moved on from the largely research phase to commercial exploitation. A major market is being developed for combined heat and power (CHP) systems for residential domestic applications operating on natural gas. In a keynote presentation, Sascha T. Schröder (National Laboratory for Sustainable Energy, Technical University of Denmark) outlined the policy context for micro combined heat and power (mCHP) systems based on fuel cells. Systems of up to 50 kW have been considered, although 3–5 kW units are preferred for domestic installations. Low- and high-temperature polymer electrolyte membrane (PEM) fuel cells are the most advanced, although there is still a need for less expensive reformers to make the systems economically viable. Incentives in the form of a regulatory framework and ownership structures are of crucial importance to achieve widespread use of such devices in residential applications. A regulatory review has been conducted as part of the first Work Package of the EU-sponsored 'FC4Home' project, focused on Denmark, France and Portugal. Schröder outlined several types of possible support schemes, such as investment support in the form of capital grants and tax exemptions *versus* operating support in the form of feed-in tariffs, fiscal incentives and other payments for energy generated, and how this impacts on investment certainty. Also, the way in which incentives are offered is critical, for example *via* energy service companies, electrical network operators, natural gas suppliers or network operators or to individual house owners. Schröder reported that in Denmark, there are 65 fuel cell mCHP installations, and in France there are 832, mainly in industry.

Most fuel cells oxidise hydrogen gas using atmospheric air to produce electric power and water. Hydrogen is generally obtained either by reforming natural gas or liquid hydrocarbons, or by electrolysis of water using surplus electrical energy. In recent years there has been great interest in reforming diesel fuel both for military and commercial purposes, since it uses an existing supply infrastructure. The pgms are often used in reforming reactions and also in downstream hydrogen purification.

In a talk entitled 'Experimental and Computational Investigations of a Compact Steam Reformer for Fuel Oil and Diesel Fuel', Melanie Grote (OWI Oel-Waerme-Institut GmbH, Germany) described the optimisation of a compact steam reformer for light fuel oil and diesel fuel, providing hydrogen for PEM fuel cells in stationary or mobile auxiliary applications. Their reformer is based on a catalytically-coated micro heat exchanger which thermally couples the reforming reaction with catalytic combustion, and also generates superheated steam for the reaction (see Figure 3). Since the reforming process is sensitive to reaction temperatures and internal flow patterns, the reformer was modelled using a commercial computational fluid dynamics (CFD) modelling code in order to optimise its geometry. Fluid flow,

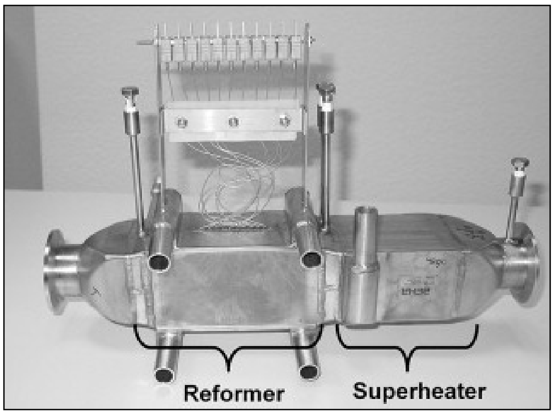

Fig. 3. Steam reformer with superheater for supplying hydrogen to a PEM fuel cell (Reprinted from M. Grote et al., (7), with permission from Elsevier)

heat transfer and chemical reactions were considered on both sides of the heat exchanger. The model was successfully validated with experimental data from reformer tests with 4 kW, 6 kW and 10 kW thermal inputs of low sulfur light fuel oil and diesel fuel. In further simulations the model was used to investigate co-flow, counter-flow and cross-flow conditions along with inlet geometry variations for the reformer.

The experimental results show that the reformer design used for the validation allows inlet temperatures lower than 500ºC because of its internal superheating capability. The simulation results indicate that another two co-flow configurations provide fast superheating and high fuel conversion rates. The temperature increase inside the reactor is influenced by the inlet geometry on the combustion side. In current investigations the optimised geometry configurations are being tested in downscaled reformer prototypes in order to verify the simulation results. Because of the great detail of their model, the effect of mass transfer limitations on reactor performance can now be investigated. Hydrogen of 73% concentration is typically produced.

Successful extraction of hydrogen from heavy hydrocarbons largely depends on the development of new catalysts with high thermal stability and improved resistance to coke formation and sulfur poisoning. A new range of ruthenium-containing perovskite oxide catalysts is being examined for diesel fuel reforming. In a talk entitled 'Hydrogen Production by Oxidative Reforming of Diesel Fuel over Catalysts Derived from $LaCo_{1-x}Ru_xO_3$ (x = 0.01–0.4)', Noelia Mota (Instituto de Catálisis y Petroleoquímica del Consejo Superior de Investigaciones Científicas (CSIC), Spain) explained how under reforming conditions these LaCo oxides form well-dispersed cobalt metallic particles over a matrix of lanthana. This increases hydrogen formation and prevents deactivation by coke and sulfur. To improve the activity and stability of $LaCoO_3$-derived catalysts, structural and electronic modifications can be introduced by partial substitution of Co by other transition metals, and among these, ruthenium is a highly effective catalyst. This work studied the influence of the partial substitution of Co over the physicochemical properties of $LaCo_{1-x}Ru_xO_3$ perovskite where x = 0, 0.01, 0.05, 0.1, 0.2 or 0.4 and the effect on the structure and activity of the derived catalysts in the reforming of diesel fuel to produce hydrogen. There was an increase in the rate of hydrogen production associated with the higher ruthenium content.

Fuel Cell Systems and Applications

The fourteen member countries of the International Energy Agency Hydrogen Implementing Agreement (IEA–HIA) have been instrumental in summarising and disseminating information on integrated fuel cell and electrolyser systems. In a keynote presentation entitled 'Evaluation of Some Hydrogen Demonstration Projects by IEA Task 18', Maria Pilar Argumosa (Instituto Nacional de Técnica Aeroespacial (INTA) Spain) summarised some of their findings since the programme was established in 2003. In addition to establishing a database of demonstration projects worldwide, the programme has reported in detail on lessons learned from several demonstrations of hydrogen distribution systems. The project concentrated on fuel cells in the power range 2–15 kW and exceptionally up to 150 kW. PEM and alkaline electrolysers were studied as hydrogen generators. No safety incidents occurred during the project, although the fuel cells tested showed relatively high performance degradation in field operation. Capital costs of electrolysers are still high, and maintenance costs for some systems have ranged up to €15,000 per year although the warranty protocol was stipulated to be less than €3000 per year for the first three years. Electrolysers ranged from 50% to 65% efficiency based on the higher heating value of the fuel.

Future electrical networks will need active distributed units able to ensure services like load following, back-up power, power quality disturbance compensation and peak shaving. In his talk 'PEM Fuel Cells Analysis for Grid Connected Applications', Francesco Sergi (Consiglio Nazionale delle Ricerche, Italy) outlined their investigation of PEM fuel cell systems as components of power networks. The paper highlighted the performances of PEM fuel cells using MEAs supplied by ETEK containing 30% Pt on Vulcan XC, and their behaviour during grid connected operation, particularly the phenomena of materials degradation that can appear in these applications. Several tests were conducted both on fuel cell systems and single cells to compare the performances obtained with DC and AC loads. Power drawn by single phase grids contains low frequency fluctuations which cause a large ripple on the stack output current. During tests on single cells, degradation of the MEA catalysts has been observed due to these dynamic loads. A dedicated inverter designed to minimise the ripple current effect on the fuel cell stack has enabled durability tests to be performed on a 5 kW Nuvera PowerFlow™ PEM fuel cell system which showed no decay in the ohmic region of operation of the cell after 200 hours, even with the fuel cell systems operating on the utility grid.

Materials handling using forklift vehicles is proving to be one of the most exciting early markets for fuel cells, with over 70 publicly reported demonstration programmes since 2005 (8). In this application, lifetime and reliability are key parameters. A typical forklift work cycle is characterised by heavy and fast variations in power demand, for example additional power is required during lifting and acceleration. This is not ideal for a fuel cell and hence it is preferred to form a hybrid with an energy store. In his talk 'Integrated Fuel Cell Hybrid Test Platform in Electric Forklift', Henri Karimäki (VTT Technical Research Centre of Finland) described how a hybrid power source has been developed for a large counterweight forklift consisting of a pgm-catalysed PEM fuel cell, ultracapacitors and lead-acid batteries. The project was carried out in two phases, firstly in the laboratory with an 8 kW PEM fuel cell, a lead-acid battery and ultracapacitor to validate the system, then a second generation 16 kW hybrid system was built into a forklift truck (Figure 4). The latter power source consisted of two 8 kW NedStack platinum-catalysed PEM fuel cells with two 300 ampere-hour (Ah) lead-acid batteries and two Maxwell BOOSTCAP® 165F 48V ultracapacitors, providing 72 kW of power.

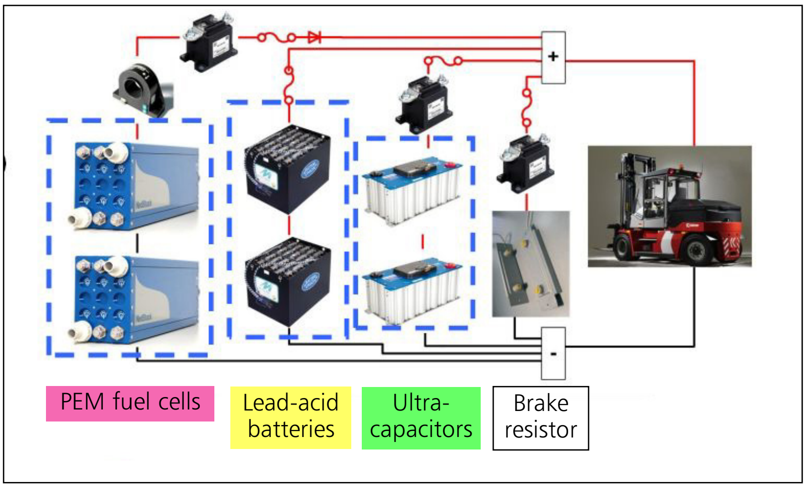

Fig. 4. Hybrid forklift power source with 2 PEM fuel cell stacks (total fuel cell peak power 16 kW); 2 lead-acid battery packs (total battery capacity 24 kWh); 2 ultracapacitor modules (capacity ~72 kWs assuming 20% utilisation). Hybrid system peak power in the forklift is ~50 kWe (Reprinted from 'Integrated PEMFC Hybrid Test Platform for Industrial Vehicles', Fuel Cell Seminar 2010, 18th–21st October 2010, San Antonio, Texas, USA, by courtesy of T. Keränen, VTT Technical Research Centre of Finland)

Hydrogen for the PEM fuel cell is stored on board in metal hydride canisters connected in common with the liquid cooling circuit. The energy stores were connected directly in parallel without intermediate power electronics to achieve a simple structure and avoid conversion losses. Drawbacks of this arrangement include limited ultracapacitor utilisation and lack of direct control over the load profile seen by the PEM fuel cell. The fuel cell voltage varied from 96 V to 75 V during operation. Control system hardware and software were developed in-house and are available as open source. The 16 kW system was tested both in the laboratory with an artificial load and outdoors installed in a real forklift (Kalmar ECF556) utilising regenerative braking. After start-up from warm indoor conditions, outdoor driving tests were performed in typical southern Finnish winter weather (–5ºC to –15ºC). The experimental results allow direct comparison of system performance to the original lead-acid battery installation.

Many submarines currently under construction are being fitted with fuel cell power plants and existing boats are being retrofitted, following pioneering work by Siemens in Germany and United Technologies Corporation in the USA. A contract has been awarded by the Spanish Ministry of Defence to design, develop and validate an air-independent propulsion (AIP) system as part of the new S-80 submarine. This programme was described by A. F. Mellinas (Navantia SA, Spain). It is intended that S-80 submarines will exhibit many performance features currently only available in nuclear-powered attack boats, including three-week underwater endurance and the possibility of firing cruise missiles while submerged. The system is based on an on-board reformer supplying hydrogen to a fuel cell power module. Their system will operate as a submarine battery charger, generating regulated electrical power to allow long submerged periods. This application imposes the strictest safety constraints while performing under the most demanding naval requirements including shock, vibration and a marine environment. It is also intended to combine high reliability with a minimum acoustic signature to provide a stealthy performance.

Fuel cell/electrolyser systems are being actively developed as a means to support astronauts on the surface of the moon, as explained by Yoshitsugu Sone (Japan Aerospace Exploration Agency (JAXA)). JAXA is developing a regenerative fuel cell system that can be applied to aerospace missions (Figure 5). For lunar survival, a large energy store is essential to allow for the 14 day-14 night lunar cycle. The limited energy density of the lithium-ion secondary cells (currently 160–180 Wh kg^{-1}, and likely to be less than 300 Wh kg^{-1} even in the future) means that over a tonne of batteries would be needed to last the lunar night, even for modest power demands.

Initially, PEM fuel cell systems that can be operated under isolated low-gravity and closed environments have been studied. Subsystems and operating methods such as closed gas circulation, with the working gases in a counter-flow configuration, and a dehydrator were developed to simplify assembly of the fuel cell system. Fuel cells were combined with electrolysers and water separators to form regenerative fuel cell systems, and the concept has been demonstrated

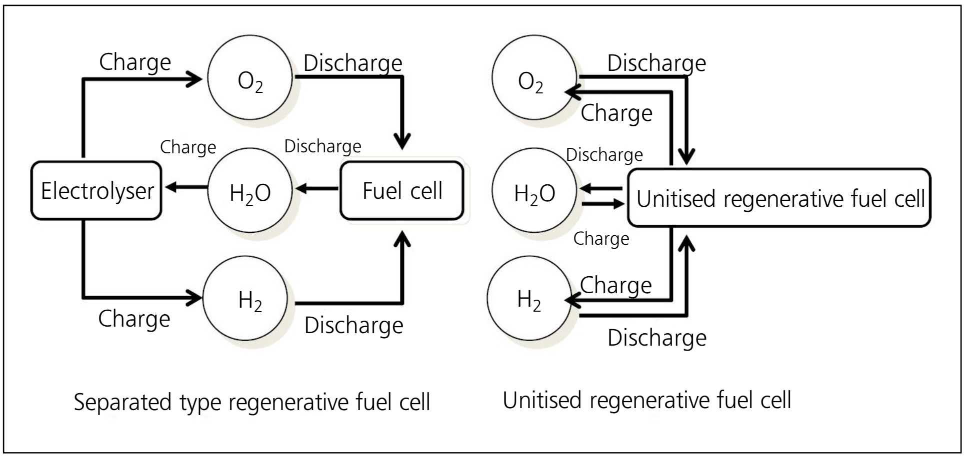

Fig. 5. Schematic of the concept for a 100 W regenerative fuel cell system for use in lunar and planetary missions (Reprinted from Y. Sone, (7), with permission from Elsevier)

for 1000 hours in an isolated, closed environment. Practical performance has also been demonstrated, initially using a thermal vacuum chamber, and also in a stratospheric balloon in August 2008.

In addition to separate fuel cell stacks and electrolysers, JAXA has developed a regenerative fuel cell, where the polymer electrolyte fuel cell is combined with the electrolyser to fulfil both functions. A 100 W-class regenerative fuel cell has been built and demonstrated as a breadboard model for over 1000 hours. A 17 cell stack of 27 cm^2 electrodes provides an output of 100 W at 12 V, while in the electrolysis mode, 'charging' is at 28 V.

Fuel Cell Electrochemistry

One of the main challenges facing PEM fuel cells is to increase the three-phase interface between catalysts, electrolyte and gases, in order to thrift the amount of pgm catalyst required. These catalysts are typically platinum nanoparticles uniformly dispersed on porous carbon support materials also of nanometre scale. In her talk entitled 'Synthesis of New Catalyst Design for Proton Exchange Membrane Fuel Cell', Anne-Claire Ferrandez (Commissariat à l'énergie atomique (CEA) Le Ripault, France) described grafting polymeric synthon to the surfaces of the platinum nanoparticles, allowing creation of new architectures of catalyst layers that promote both ionic conduction between the solid electrolyte and electronic conduction to the carbon support. The resulting materials appear to be oxidation resistant and stable to voltage cycling up to +1.0 V. By adjusting synthesis parameters, it is possible to optimise the electrical, chemical and mass transfer properties of the electrodes and also reduce the platinum content.

For automotive applications of PEM fuel cells, the US Department of Energy has published a target platinum loading of less than 0.2 mg cm^{-2} for combined anode and cathode by 2015, with performance characteristics equating to a platinum content of 0.125 g kW^{-1} by this date (Figure 6). This is most likely to be achieved by optimising a combination of parameters including catalyst, electrode and membrane structures as well as operating conditions. Ben Millington (University of Birmingham, UK) described their efforts in a talk entitled 'The Effect of Fabrication Methods and Materials on MEA Performance'. Various methods and materials have been used in the fabrication of catalyst coated substrates (CCSs) for membrane electrode assemblies (MEAs). Different solvents (ethylene glycol, glycerol, propan-2-ol, tetrahydrofuran and water), Nafion® polymer loadings (up to 1 mg cm^{-2}) and anode/cathode Pt loadings have been used in the preparation of catalyst inks deposited onto various gas diffusion layers (GDLs) sourced from E-TEK, Toray and Freudenberg, and the performance of the resulting MEAs were reported. Several methods of CCS fabrication such as painting, screen printing, decal and ultrasonic spraying were investigated. All MEAs produced were compared to both commercial MEAs and gas diffusion electrodes (GDEs). They found that MEA performance was dramatically affected by the solvent type, the deposition method of the catalyst ink on the GDE, the GDE

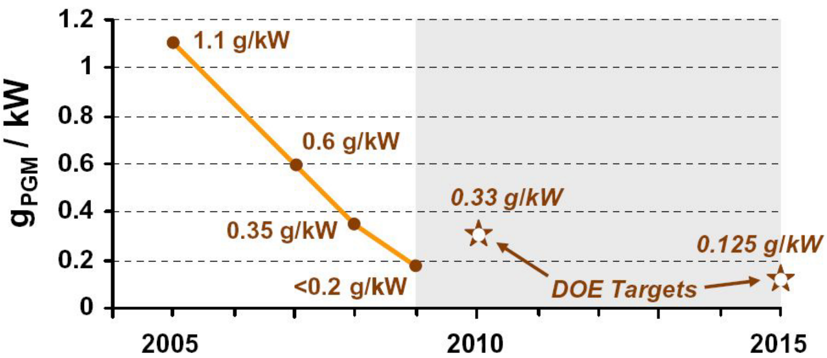

Fig. 6. Status of estimated total pgm content in fuel cell stacks from 2005 to 2009 compared to DOE targets (J. Spendelow, K. Epping Martin and D. Papageorgopoulos, 'Platinum Group Metal Loading', DOE Hydrogen Program Record No. 9018, US Department of Energy, Washington, DC, USA, 23rd March, 2010)

type (woven or nonwoven), the drying process and the amount of Nafion® added to the GDE during fabrication. Currently, the university is able to produce MEAs with similar performance to commercial products.

More widespread commercial development of fuel cells has identified new challenges such as the effects of impurities in fuel supplies and the atmospheres in which the devices have to operate. One of these has been studied in detail at the Technical University of Denmark, and the results were presented in a paper by Syed Talat Ali entitled 'Effect of Chloride Impurities on the Performance and Durability of PBI (Polybenzimidazole)-Based High Temperature PEMFC'. Chlorides derived from sea salt are present in the atmosphere as an aerosol in coastal areas and salt is also used for deicing roads in many countries during winter. Small traces of chlorides may originate from phosphoric acid in the PBI membrane and from platinum chloride precursors used to prepare some platinum catalysts, while substrate carbons such as Cabot Vulcan® XC72R carbon black contain trace impurities. The possible effect of halogen ions on platinum catalysts are unknown, since they may promote dissolution as complex ions, thereby enhancing metal oxidation and re-deposition processes. The group's present work is devoted to a systematic study at temperatures from 25ºC to 180ºC. Firstly, determination of the chloride content of Pt-based catalysts was carried out using ion chromatography. Secondly, the effect of chloride on the dissolution of a smooth Pt electrode was studied in 85% phosphoric acid at 70ºC using cyclic voltammetry. It was found that the presence of chlorides is likely to be very harmful to the long-term durability of acid doped PBI-based high-temperature PEM fuel cells.

Materials for Fuel Cells

The pgms are also finding applications in hydrogen generation by water electrolysis as a means of reducing electrode overvoltage and thereby improving operating efficiency. This represents not only a clean method of hydrogen production, but also an efficient and convenient way of storing surplus energy from renewable sources such as solar, wind and hydroelectric power. In his talk 'An Investigation of Iridium Stabilized Ruthenium Oxide Nanometer Anode Catalysts for PEMWE', Xu Wu (Newcastle University, UK) described the synthesis and characterisation of these catalysts. The electrochemical activity of $Ru_xIr_{1-x}O_2$ materials in the range $0.6 < x < 0.8$ was investigated. A nanocrystalline rutile structure solid solution of iridium oxide in ruthenium oxide was identified. When x was 0.8, 0.75, and 0.7, $Ru_xIr_{1-x}O_2$ exhibited remarkable catalytic activity, while increasing the amount of iridium resulted in improved stability. A PEM water electrolysis (PEMWE) single cell achieved a current density of 1 A cm^{-2} at 1.608 V with $Ru_{0.7}Ir_{0.3}O_2$ on the anode, a Pt/C catalyst on the cathode and Nafion® 117 as the membrane.

Cell and Stack Technology

Considerable progress has been made in developing high-temperature solid polymer electrolyte fuel cells, with particular advances in membrane technology.

In a keynote presentation entitled 'High Temperature Operation of a Solid Polymer Electrolyte Fuel Cell Stack Based on a New Ionomer Membrane', Antonino S. Aricó (Consiglio Nazionale delle Ricerche – Istituto di Tecnologie Avanzate per l'Energia (CNR-ITAE), Italy) gave details of tests on PEM fuel cell stacks as part of the European Commission's Sixth Framework

Programme 'Autobrane' project. These were assembled with Johnson Matthey Fuel Cells and SolviCore MEAs based on the Aquivion™ E79-03S short-side chain (SSC) ionomer membrane, a chemically stabilised perfluorosulfonic acid membrane developed by Solvay Solexis (Figure 7). An in-house prepared catalyst consisting of 50% Pt on Ketjen black was used for both anode and cathode, applied at 67 wt% catalyst with a Pt loading of 0.3 mg cm^{-2}. Electrochemical experiments with fuel cell short stacks were performed under practical automotive operating conditions at absolute pressures of 1–1.5 bar and temperatures ranging up to 130ºC, with relative humidity varying down to 18%. The stacks using large area (360 cm^2) MEAs showed elevated performance in the temperature range from ambient to 100ºC, with a cell power density in the range of 600–700 mW cm^{-2}, with a moderate decrease above 100ºC. The performances and electrical efficiencies achieved at 110ºC (cell power density of about 400 mW cm^{-2} at an average cell voltage of about 0.5–0.6 V) are promising for automotive applications. Duty-cycle and steady-state galvanostatic experiments showed excellent stack stability for operation at high temperature.

Poster Exhibits

The poster session was combined with an evening reception to maximise the time available for oral papers and over 200 posters were offered. These included a wide range of applications of the pgms in fuel processing, fuel cell catalysis and sensors. There were a considerable number of posters featuring the preparation and uses of pgm fuel cell catalysts, which were too numerous to mention in detail.

Several posters featured preparation of Pt and PtRu catalysts supported on carbon nanofibres. It is evident that while materials such as graphitised carbon nanofibres can be highly stable and oxidation resistant, with existing catalyst preparation techniques it is difficult to make high surface area, uniform platinum dispersions which can compete with catalysts on more conventional carbon supports such as Vulcan® XC72. One poster which highlighted this difficulty was 'Durability of Carbon Nanofiber Supported Electrocatalysts for Fuel Cells', by David Sebastián *et al.* (Instituto de Carboquímica, CSIC, Spain).

Other posters featured studies of the effects of carbon monoxide on high-temperature PEM fuel cells, and the effects of low molecular weight contaminants on direct methanol fuel cell (DMFC) performance. Studies are also in progress on more fundamental aspects such as catalyst/support interactions, for example 'Investigation of Pt Catalyst/Oxide Support Interactions', by Isotta Cerri *et al.* (Toyota Motor Europe, Belgium).

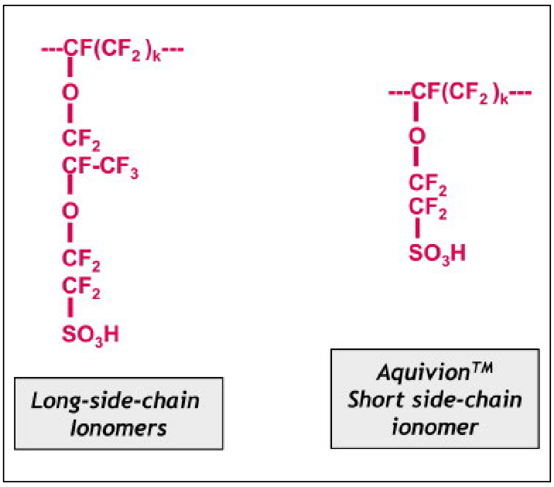

Fig. 7. Polymer structure of long side-chain Nafion® and short side chain Aquivion™ perfluorosulfonic ionomer membranes (Reprinted from A. Stassi et al., (7), with permission from Elsevier)

Summary

Conclusions from the Fuel Cells Science and Technology 2010 conference were summed up by José Luis García Fierro (Instituto de Catálisis y Petroleoquímica, CSIC, Spain). He remarked that the high level of interest in the conference partly reflects more strict environmental laws combined with the high prices of gas and oil (oil was US$75 per barrel at the time of the conference), emphasising the need for the best possible efficiency in utilising fuels. Biofuels appear to be making a more limited market penetration than originally expected. He also mentioned that of the posters exhibited at the conference, no fewer than 45 involved PEM fuel cell catalysts and components, direct methanol and direct ethanol fuel cells. One potentially large market for fuel cells is in shipping, where marine diesel engines currently produce 4.5% of the nitrogen oxides (NOx) and 1% of particulates from all mobile sources. This becomes a sensitive issue, especially when vessels are in port. The marine market consists of some 87,000 vessels, the majority of which have propulsion units of less than 2 MWe. Among the actions currently in progress to promote exploitation of hydrogen technology and fuel cells are hydrogen refuelling stations for vehicles together with codes and standards for the retail sales of hydrogen fuel, with support for early market opportunities.

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The Reviewer

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