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Alkaline fuel cells for road traction

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Abstract

Alkaline fuel cells, until recently the only type of fuel cell reliable enough to be used in space, are being neglected for road traction in favour of the supposed advantages of proton exchange membrane (PEM) cells. In practice, the alkaline cell is very well developed, simple to operate with a built-in cooling system, has excellent reliability, and is inexpensive to manufacture, even in small quantities. The paper describes the development (the adoption of modern catalysts, system packaging) and operation of alkaline fuel cells when installed as on-board chargers within a range of rapidly re-fuelled but zero-emission electric vehicles with immediate potential. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

The alkaline fuel cell (AFC) was invented by Sir William Grove in the middle of the last century and developed into a workable system by Francis Bacon, who started his developments in the UK in the 1930s. As a result of the work by Bacon, the AFC was adopted as the primary power source on the NASA space flights throughout the 1960s and 1970s, and is now used on the space shuttle for this purpose. When as a power source for spacecraft, reliability is of paramount importance and the AFC was developed to operate with the required level of reliability in this demanding application. There is no doubt that this version of the AFC was a complex and costly power source, operating at up to pressures of 5 bar, at temperatures up to 250°C and fed with pure hydrogen and oxygen. This has given rise to a number of myths about the fuel cell for other applications. As examples, it is often reported that the AFC is only useful for aerospace applications, that the AFC cannot be used for traction applications, that the AFC must be fed with pure oxygen because it is poisoned by the CO_2 in the atmosphere, that the AFC is costly and that the AFC cannot be used with reformed fuel. None of these myths can be substantiated.

The true picture is that the AFC is an efficient, market-ready device with low materials cost and with wide applications. Not only this, but the AFC operates well at pressures that are only a few tens of mbar above ambient, it is completely insensitive to ambient humidity and has a built-in thermal management system namely, the circulating electrolyte. The Zevco system is designed to be used as a continuously operating on-board charger for zero emission electric vehicles or as a stationary energy source.

Present development efforts are focused on commercially available electric vehicles such as airport tractors and fork lift trucks, on stationary power sources, including marine applications, and on applications in the larger electric road vehicles such as vans, buses and taxis.

The only emission from the fuel cell is pure water, and the system is almost silent in operation.

2. Description of the alkaline fuel cell

The AFC converts controlled quantities of gaseous hydrogen and gaseous oxygen into electricity using a direct, low-temperature, electrochemical reaction. The hydrogen is usually compressed and the oxygen is taken from the air. It uses a circulating liquid alkaline electrolyte, potassium hydroxide (KOH), that is also an effective heat transfer and water management medium. The fuel cell can produce power at ambient temperature but is designed to deliver full power at about 70°C which, with electrical heating, it

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will normally reach within 10 min of a cold start. The semi-porous electrodes, which currently use the low platinum loadings of 0.3 mg cm^{-2}, operate satisfactorily in all ambient humidities with little variation in the cell output. Additional work on modern, non-noble metal catalysts based on silver and cobalt, will allow replacement of much of this platinum while, at the same time, considerably improving the system performance.

The potential problems of electrolyte contamination by atmospheric CO_2 are completely overcome by using an atmospheric scrubber to remove the CO_2 or by changing the electrolyte at the service intervals. The present Zevco system uses chemical scrubbing of the input air but regenerative scrubbers are under development.

3. Working principle

A single AFC consists of two porous electrodes with the liquid KOH electrolyte between them. The hydrogen fuel is supplied to the anode electrode, while oxygen from air is supplied to the cathode. The electrical voltage between the anode and the cathode of a single fuel cell is between 0.9 V and 0.5 V depending on the load and the electrochemical reactions are shown in Fig. 1.

At the positive electrode (cathode) the oxygen is catalytically reduced:

$$1/2\,O_2 + 2e^- + H_2O \rightarrow 2\,OH^-$$

At the negative electrode (anode), the hydrogen is catalytically oxidized:

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

The overall reaction becomes:

$$H_2 + 1/2O_2 \rightarrow 2H_2O + \text{electrical energy} + \text{heat}$$

Through the combination of oxygen and hydrogen, water is produced at the anode and electrical energy and heat are generated by the fuel cell.

4. Components of an alkaline fuel cell

4.1. Electrodes

The anodes and cathodes are multi-layer gas diffusion electrodes. The active layer consist of an organic powder and carbon–catalyst mixture which is rolled at room temperature to cross-link the powder so that the active component of the electrode is self-supporting. There are no high temperature or wet processes involved in electrode production. The hydrophobic layer, which prevents the liquid electrolyte from flooding the gas chambers, is made by rolling a porous organic layer, again to cross-link the layer to form a self-supporting sheet. The layers are then pressed onto a conducting metal mesh with the active layer in the mesh and the hydrophobic layer on the gas side of the electrodes. Total electrode thickness is only 0.4 mm and the active area of each electrode is 170 mm × 170 mm. A plastic frame, with the various fluid passages designed into the mould, is injection moulded round the pressed assembly. The components of the electrode are shown in Fig. 2.

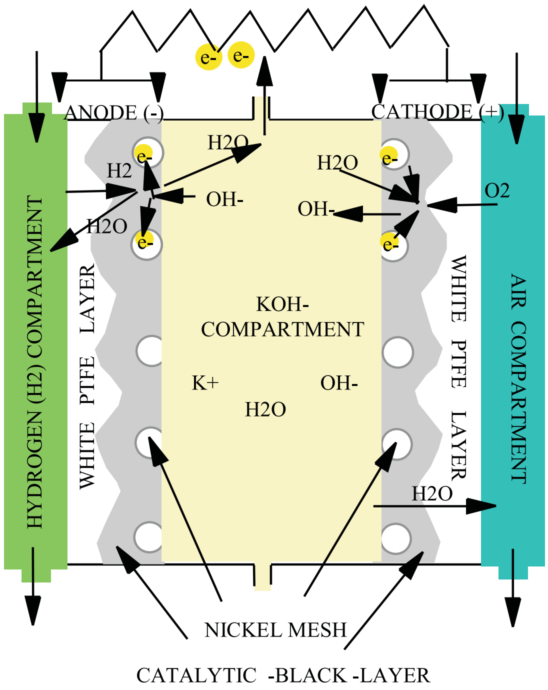

Fig. 1. Electrochemical reactions in the AFC.

4.2. Modules

These are the basic building blocks of the fuel cell system, combining the electrodes with the local fluid distribution channels into a fully sealed and stand alone unit. Connections are made for the fluids, hydrogen, air and KOH electrolyte, and the electrical connections to determine the module voltage are made at this level. The completed electrodes are friction welded into self-supporting and leak-tight modules, with the electrical connections being made by connecting the conducting mesh into the chosen configuration. The basic module, rated at 432 W, contains 24 cells (48 electrodes), connected in series/parallel to give an operating voltage of 4 V at a current of 108 A but there is considerable flexibility in making these electrical connections. The cells are connected with a minimum of two in parallel though the normal module configuration with the present generation electrodes has four cells connected in parallel.

As the development increases the power of the cells, fewer cells will be needed to maintain the output of the

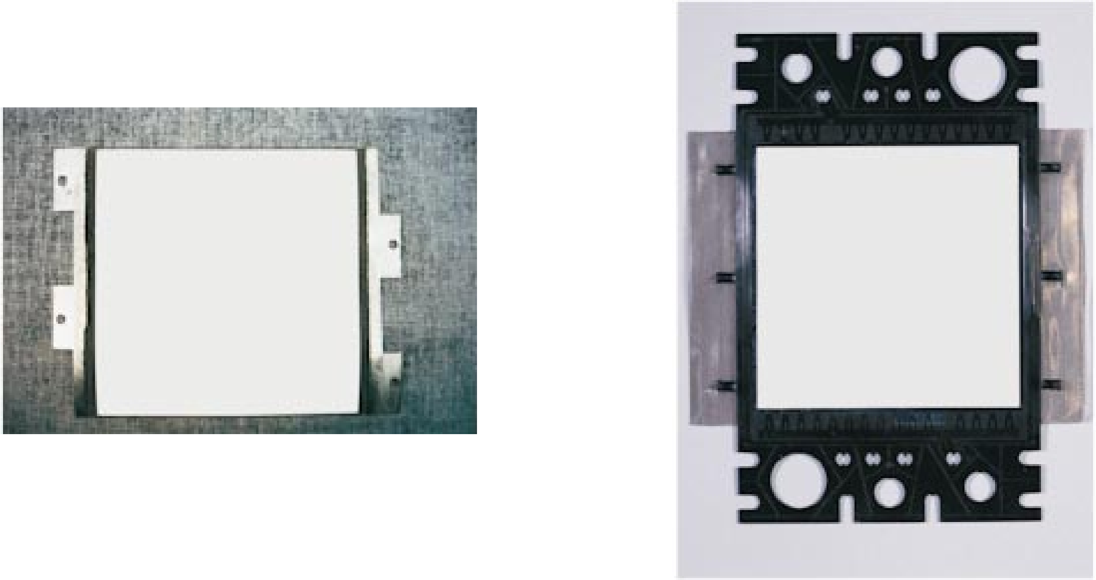

Fig. 2. Components of the AFC electrode.

fuel cell stack and the number of cells in parallel will be reduced to maintain a consistent system voltage.

4.3. Fuel cell stacks

The modules are then physically combined into fuel cell stacks to form the larger power units needed to provide power outputs up to 10 kW needed for the larger applications. Again, the gas manifolding and electrolyte distribution system are built in to the stack. The individual module and the stack are shown in Fig. 3.

4.4. Peripheral systems

The peripheral systems are the components needed to support the three principal fluid loops (hydrogen, air and electrolyte), as shown in Fig. 4, the interface between the

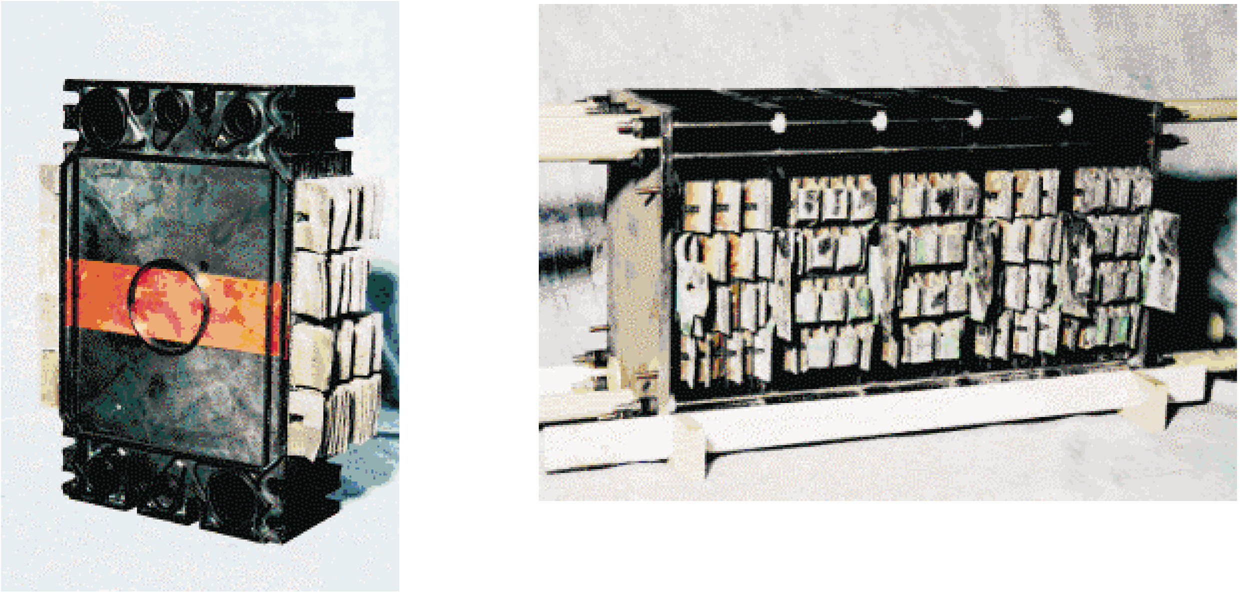

Fig. 3. Module and assembly of modules to form a fuel cell stack.

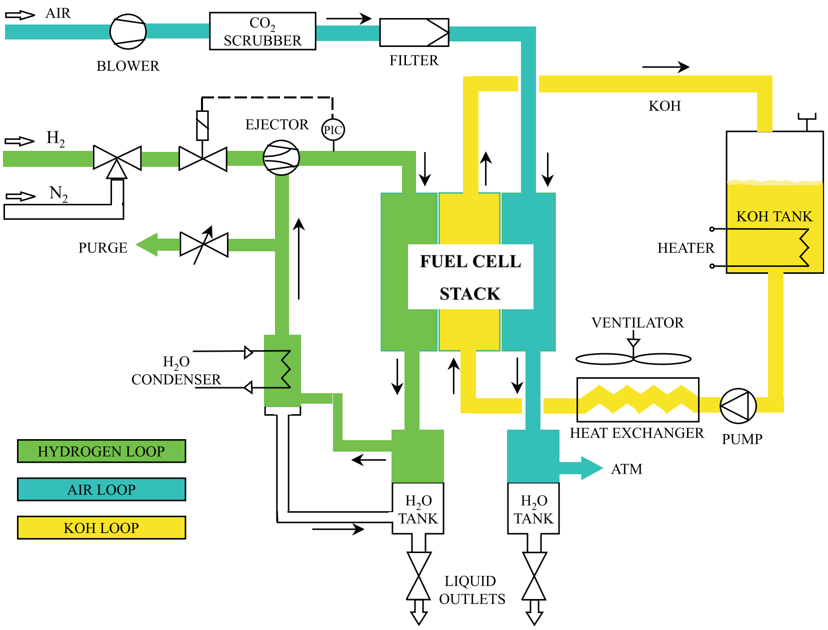

Fig. 4. Fluid flows in the AFC system.

fuel cell stack and the buffer battery, and the process controller.

The gas systems control and direct the pressure and flow of the gases to the fuel cell stack. The pressures are low and the powers involved are modest. The hydrogen is fed from a pressurised supply and additional energy used to promote a vigorous flow across the active surface of the electrode is minimal. The pump for the air circuit, operating at only 40 mbar, requires only 350 W to provide the necessary flow for a 5 kW system and simple developments in the airflow path will soon reduce this by a factor of at least five.

Electrolyte circulation is not necessary for the fuel cell to function since the electrolyte acts only as an ionic conductor. However, there are a number of advantages for electrolyte circulation in a land-based system, including temperature and humidity management. Circulation also allows any gas that may diffuse through the electrodes to be swept away, though the flow rate is determined by the requirements for thermal control. The electrolyte in the Zevco fuel cell is circulated using a 50 W pump.

4.5. The power electronics interface between fuel cell and batteries

The fuel cell/battery system interface conditions the power flow from the fuel cell to the load, usually a traction battery, in accordance with the load demand. It isolates the fuel cell from the battery transients and prevents variations in the electrical load on the traction battery from being reflected back into the fuel cell. The system normally controls the fuel cell to operate at its maximum power output.

In the case of a battery load, the current is regulated to follow a defined profile so that the battery is correctly charged in preparation for the next cycle of duty.

4.6. The system controller

The system controller switches the fuel cell on and off in accordance with the load demands. Both the switch on and switch off procedure are closely monitored to ensure that the cells are working before the load is applied and that the modules are passivated before they are finally shut down. A micro controller, programmed to respond to the demands of the system, performs this task.

5. General performance characteristics

5.1. Electrodes

Current densities for the existing Mark II electrodes, assembled in a module, can reach 120 mA/cm^{-2} at 70°C, though the normal operating point is 100 mA/cm^{-2} at 0.67 V per cell. Mark III electrodes that use non-noble catalysts such as silver, and which have higher operating current densities of 200 mA/cm^{-2}, are now being developed for production. Current densities of 400 mA/cm^{-2}, are a realistic goal for the medium term developments. These changes will have a dramatic effect on system cost since the catalyst materials are less expensive and the production plant can manufacture of fuel cells with a greater power output using the same equipment.

The performance of a fuel cell is represented by the voltage vs. current density or polarisation curve as shown

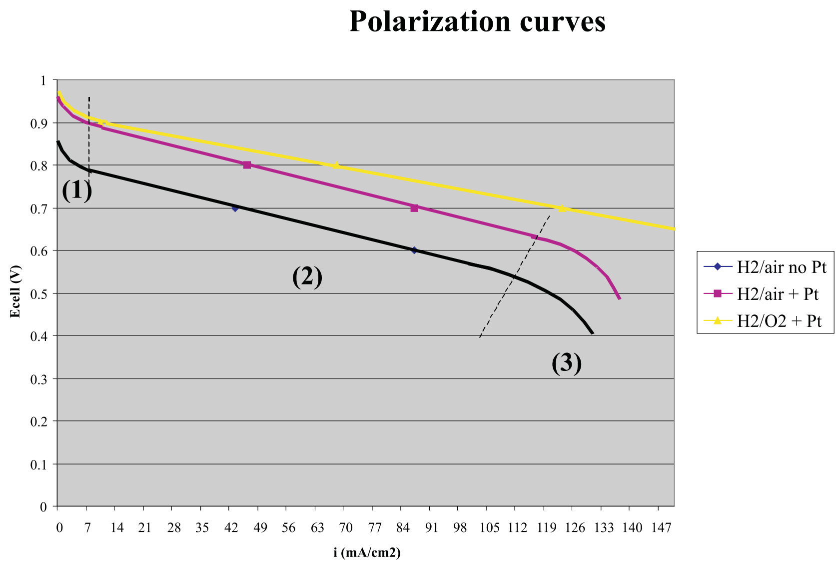

Fig. 5. Electrode polarisation curves, current production.

in Fig. 5. Ideally, a single fuel cell fed with hydrogen and pure oxygen could produce 1.23 V at no load, in practice fuel cells produce voltage outputs less than the maximum value and which decrease with increasing load.

5.2. Fuel cell modules

The efficiency of the AFC is a function of the output and is shown in Fig. 6. The figures reflect the voltage drops on the electrodes as the current is increased, plus an allowance for the resistive losses of the electrolyte.

The operating life of the modules is more than 5000 h, with some modules operating in fuel cell stack operating at full output.

5.3. The complete system

The peripherals described in Section 4.4. absorb some of the output of the fuel cell and reduce the overall system efficiency. In this respect, the low-pressure AFC fares much better than the high-pressure membrane cells since the energy loss, particularly in compressing the air, is much lower. The overall efficiency of the complete system is shown in Fig. 7. This takes into account the fixed losses, for instance the electrical consumption of the power management system and the circulation pumps, plus a power dependent loss to reflect the increased pumping and electronic losses at higher outputs. The normal operating point is chosen to give an acceptable commercial compromise

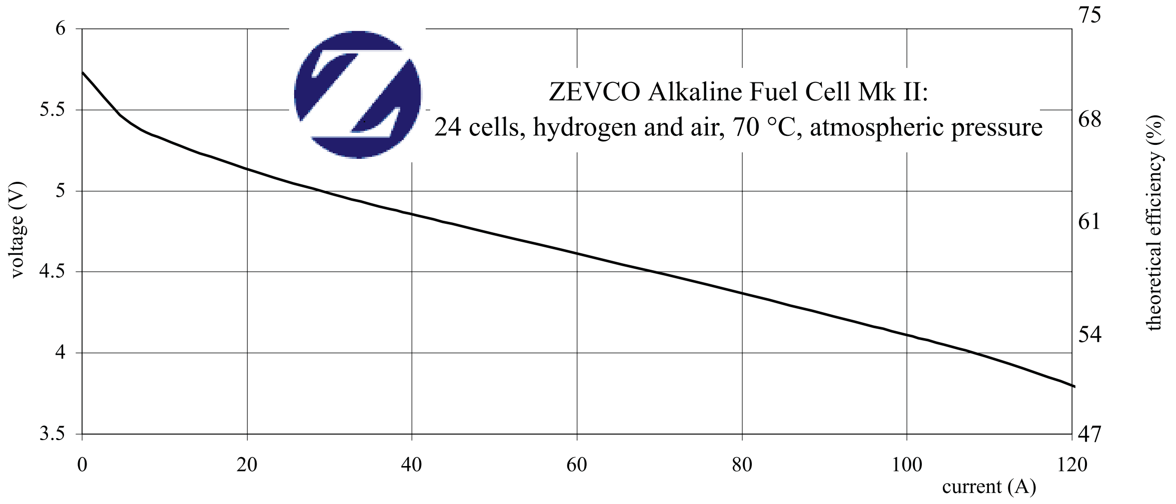

Fig. 6. Efficiency of the Zevco AFC modules.

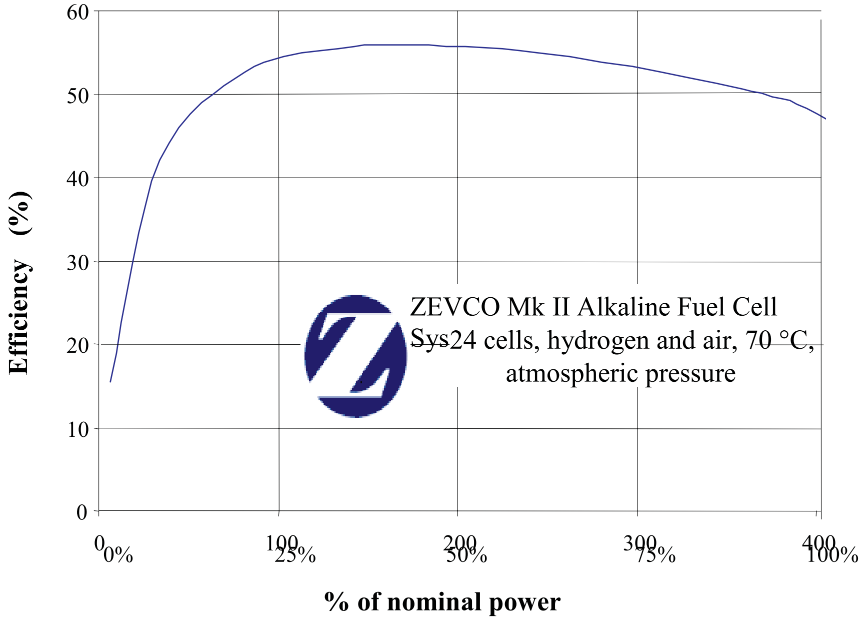

Fig. 7. Efficiency of the complete Zevco fuel cell system.

between the efficiency and the output power, with the fuel cell stack operating at full output.

6. Power ratings of the fuel cell system

The Zevco fuel cell system is designed as an on-board charger for electric vehicles or as a stationary power source. Conventional and inexpensive batteries provide very high power peaks with good life and further battery developments in this field are progressing rapidly. The fuel cell is therefore sized to provide the base load while the battery provides the short term peaks and the longer term power demands of any particular application.

In a town vehicle, the average speed is generally low and the average power demands are also low. Duty cycle studies, backed up by general information about the energy consumption of existing electric vehicles, are used to determine the actual values. As an example, the energy consumption of a modern electric vehicle will be about 100 Wh per tonne-km. At an average speed of 30 km h^{-1} in city driving, the average power from the battery is only 3 kW per tonne of vehicle weight. In normal operation, the vehicle will be stopped for part of the duty cycle while goods are being delivered or passengers are being handled. The fuel cell will operate during these periods and also at the end of the duty when the vehicle is parked.

Measured average energy consumption over a 9-h working day for a London ‘Black Cab’ is in the region of 5 kW and a fuel cell of this output will propel the vehicle continuously. Selection of battery size is similarly straightforward with the battery having three main tasks. These are to drive the vehicle for the first 10 min or so until the fuel cell is delivering full output, to provide the heating power to promote rapid fuel cell warm-up and to provide a margin of stored energy to open-road cruising. In a town vehicle, the battery is sized to allow about 40 min of operation on electric power alone.

The selection of battery capacity for use industrial electric vehicles is made in the same way. Normally, the efficiency of these vehicle is lower that of the modern road vehicle. So the battery capacity and fuel cell power is increased accordingly.

7. Summary

Alkaline fuel cells are excellent and efficient performers with an excellent pedigree of reliability and life. While the AFC s used in space applications are complex and costly, the terrestrial versions, operating as hybrid systems with a buffer battery, are not. Furthermore, the AFC does not rely on high volume manufacture to reduce the cost to an affordable level since the materials are inexpensive and the processing is straightforward. Use of the AFC in a hybrid mode removes the need for complex system management because the power output from the fuel cell does not have to respond to the immediate demands of the vehicle. This cost-effective system is an ideal way of providing rapid refuelling for a whole range of commercially available, battery-powered electric vehicles.