Chimia 58 (2004) 869–878

ISSN 0009–4293

PEFC: Stacks, Systems, and Applications

Felix N. Büchi[a]*, Jean-François Affolter[b], Stefan Camenzind[c], Niels Chmielewski[d], Philipp Dietrich[a], Michael Höckel[b], Martin Ruge[e], and Marco Santis[a]

Abstract: This article gives an overview on the research and development activities pursued in the area of polymer electrolyte fuel cell stacks and systems in Switzerland in 2004. Work is pursued on several different levels for stacks and systems from portable to automotive applications, in the academic as well as in the industrial area. Today's work focuses on the improvement of specific power and cost efficiency of stacks and systems by development and optimization of new concepts for water management and cooling. This is achieved through function integration *i.e.* of the gas humidification into the stack and adaptation of the cooling concepts for the specific application.

Keywords: Fuel cell stack · Fuel cell system · Polymer electrolyte fuel cell

1. Introduction

Polymer Electrolyte Fuel Cell (PEFC) technology has requirements for research on different levels. For most applications better performance, increased stability and cheaper materials are needed. However research on the level of cells, stacks, and systems is also required in order to clearly evaluate the requirements for the different materials, to improve structures and concepts of stacks and to define the characteristics of components for the balance of plant. Last but not least research for development of applications based on existing materials is of great importance to promote applications. Without applications PEFC technology might be in danger of stagnating at the development state and the interest in the economic, public and research communities might fade.

This article describes the various efforts for PEFC cell, stack and system research and development in Switzerland. Efforts are undertaken on a broad range of power levels and a variety of concepts and approaches are pursued.

2. PEFC Stack and System R&D Issues

The voltage of a single PEFC at the rated point of operation is only 0.6–0.8 V. This voltage is too low for almost all technical applications. In order to increase the voltage level to values required by the application, an appropriate number (two to several hundred) of cells have to be connected electrically in series. Generally, a bipolar type series connection is chosen, which interconnects individual cells over the entire active area and leads to filter-press type cell arrangements called stacks (Fig. 1 and 2).

In this bipolar arrangement, the bipolar plate becomes the main construction element of the fuel cell stack. With given electrochemical components, the performance

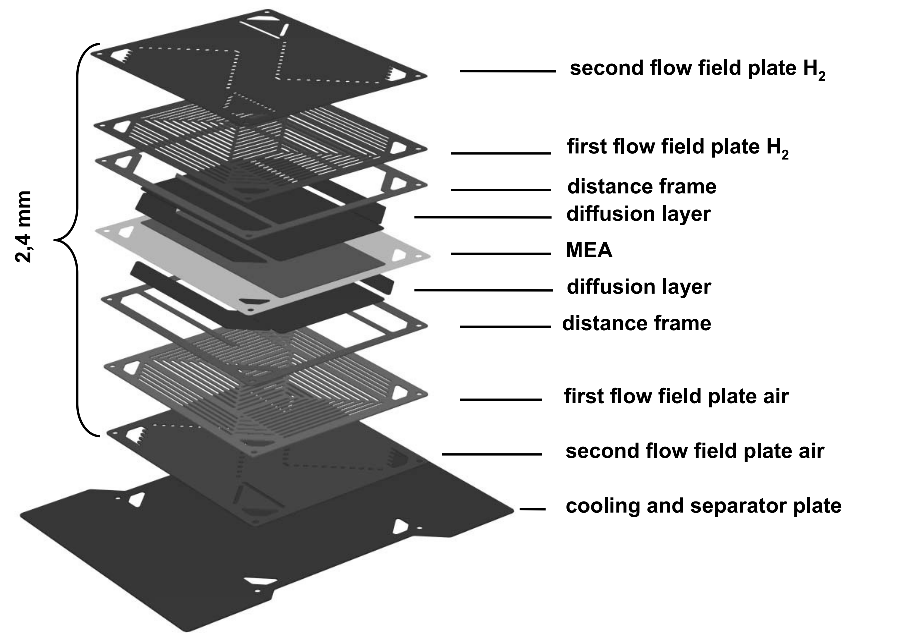

Fig. 1. Explosion view of the complete cell, showing the eight layers of a stack repetition unit

Correspondence: Dr. F.N. Büchi
[a]Electrochemistry Laboratory
Paul Scherrer Institut
CH–5232 Villigen PSI
Tel.: +41 56 310 24 11
Fax: +41 56 310 44 15
E-Mail: felix.buechi@psi.ch
[b]University of Applied Sciences
of Western Switzerland, EIVD
CH–1401 Yverdon
[c]Esoro AG
Tämperlistrasse 10
CH–8117 Fällanden
[d]MES-DEA S.A.
CH-6855 Stabio
[e]Bern University of Applied Sciences – HTI
Quellgasse 21
CH–2501 Biel

CHIMIA 2004, 58, No. 12

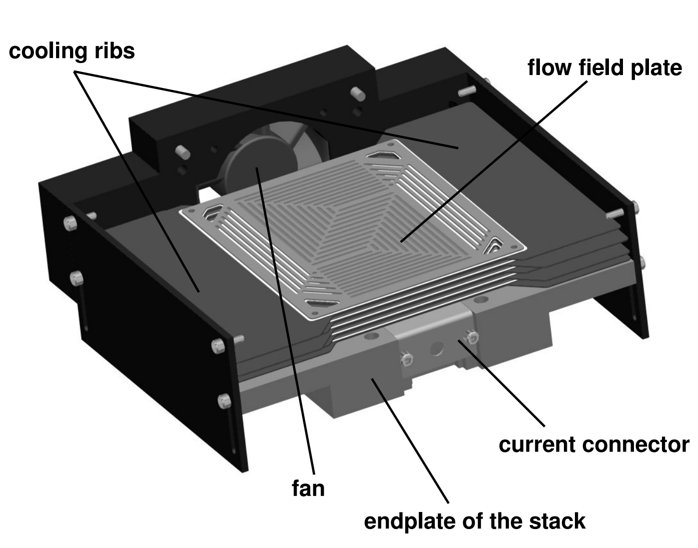

Fig. 2. CAD model of inside view into a 5-cell stack including cooling fan and housing

and specific power of the fuel cell stack is determined by the characteristics of the bipolar plate with regard to structure and material. Research and development with respect to the bipolar plate structure focuses on optimization for low volume, weight, and cost. Further optimal fluid dynamic properties of the reactant gases and coolant are required, in order that all cells in the stack perform uniformly over a maximum possible power range. Research and development on the material of the bipolar plate is focused on materials with high specific conductivity, low gas permeability, low contact resistance, and high chemical stability. Therefore the bipolar plate is made either from corrosion resistant metals or, as in most of the applications discussed here, from different carbon-based materials.

The fuel cells stack is solely the electrochemical reactor, converting the chemical energy of the fuel, in all cases described in this article, pure hydrogen, into electricity. This means that the reactants need to be supplied to the fuel cell and the products and the waste heat have to be removed. Therefore the stack is complemented by auxiliary components which take care of supply and evacuation of the reactants, products, and waste heat as well as control of all subsystems. The stack together with these system components is called a 'fuel cell system'. Only a complete system is capable of delivering electric power to the user. Research and development in this area focuses on layout, integration and function integration of the complete system for the required application. For reasons of cost, weight, and volume, systems are optimized towards simplicity. One basic aspect of the hydrogen-fuelled systems is the cooling concept, the systems can either be air or liquid cooled. Generally air-cooled systems tend to be simpler, but the stack has to be optimized for the function of the electrochemical reactor and the heat exchanger. Liquid-cooled systems can have a more compact stack with higher thermal inertia, but need a more complicated balance of plant. However in this case, the waste heat can be more easily utilized, *i.e.* for heating the hydrogen tanks when a metal hydride storage concept is used or delivering heat to the passenger compartment in boats and cars. This overview article on research and development on PEFC stacks and systems pursued in Switzerland is therefore organized according to the application and concept of system cooling.

3. Portable Systems

For portable power supplies in the range of a few hundred Watts to several kW commonly internal combustion engine generators are used. However, these power generators have disadvantages with respect to the high noise level, toxic emissions affecting the quality of the air and frequent maintenance. Clean portable power can be provided by batteries; however their energy density and long recharge times limit their application. The PEFC technology offers advantages with respect to both competitors. On the one hand, fuel cells operating on pure hydrogen are absolutely free from local toxic emissions and offer a lower noise level than internal combustion power generators. On the other hand, for long operation times, their energy density exceeds that of batteries and their potentially low refueling times make PEFC an attractive alternative for the user.

3.1. *Air-Cooled Systems*

A new design of an air-cooled stack for portable systems was developed by the Bern University of Applied Sciences – HTI. The main motivation for the development of a new cell design is the reduction of the complexity of the fuel cell system for portable applications. Therefore an air-cooled design with internal gas humidification was chosen. The stack is optimized for a fuel cell system with minimized need for auxiliary components. The second goal of this new design is the construction of a simple cell which would also be cheap to produce. Stack and system design boundary conditions were:

- External, edge air cooling of the stack
- Flow field plates based on simple components
- Internal humidification of both process gases
- Optimized system efficiency

The bipolar plate construction (Fig. 1) is based on simple parts stamped from expanded graphite foils. Two complementing parts form one flow field plate. Two flow field plates and two spacers form, together with a separator plate, a complete bipolar plate. The separator plate has two important functions: (i) separation of the two gas chambers (H_2 and air) and (ii) conducting the heat from the inside of the cell to the edge (cooling ribs). The separator plate is made of expanded graphite foil with a higher density (needed for higher heat conductivity). Therefore all parts of the cell are stamped from (different) graphite foil materials, allowing for a cheap construction and a fast production and assembly process. These expanded graphite foil materials are used today for sealing functions in fuel cell stacks [1].

Similar to the development described in Section 3.2., water management is simplified by a stack internal gas humidification concept [2][3]. In this development, both gases, hydrogen and air, are internally humidified. Fresh process air, is humidified by the excess hydrogen and fresh hydrogen by the humid used air. This integration eliminates the need for separate humidifiers and water condensers.

The active area of the cell is 60 cm^2 and as electrochemical components five-layer MEAs (Umicore AG, D) were used. A five-cell stack was built and tested. A CAD model of the stack with the cooling fan directly fitted to it is shown in Fig. 2. Its electrochemical performance is shown in Fig. 3.

With this design a 30–40-cell stack with an expected power of 500 Watt will be constructed. Further developments will include the optimization of the arrangement, size and position of the humidifying area in relation to the active area. This is important because the stack has to operate at the maximum possible temperature for a better performance and easier heat removal.

3.2. *Liquid-Cooled Systems*

The Paul Scherrer Institut (PSI) together with the Swiss Federal Institute of Technology in Zurich (ETHZ) has developed a portable 1 kW power supply system based

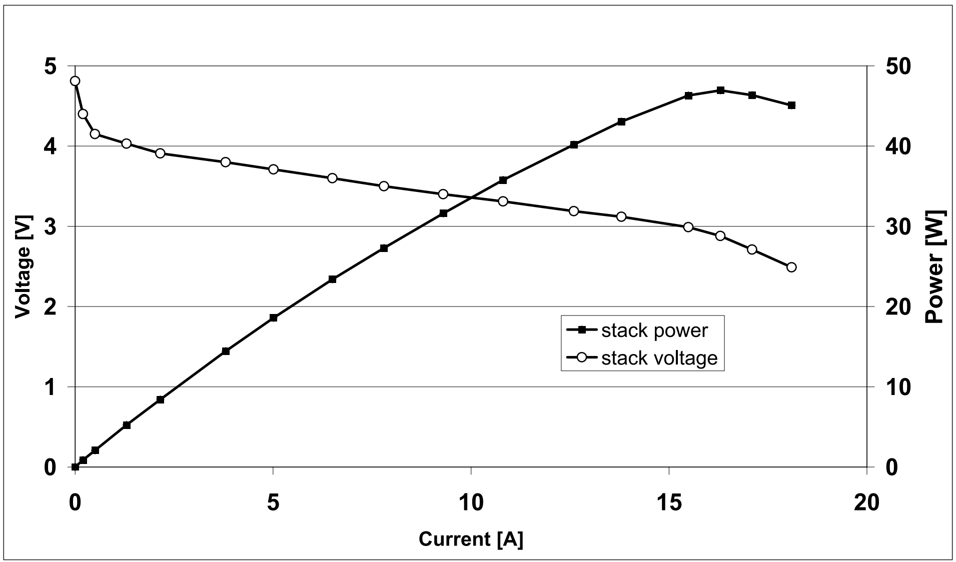

Fig. 3. Current voltage and current power curve of a 5-cell stack at 50 °C; both gases near ambient pressure

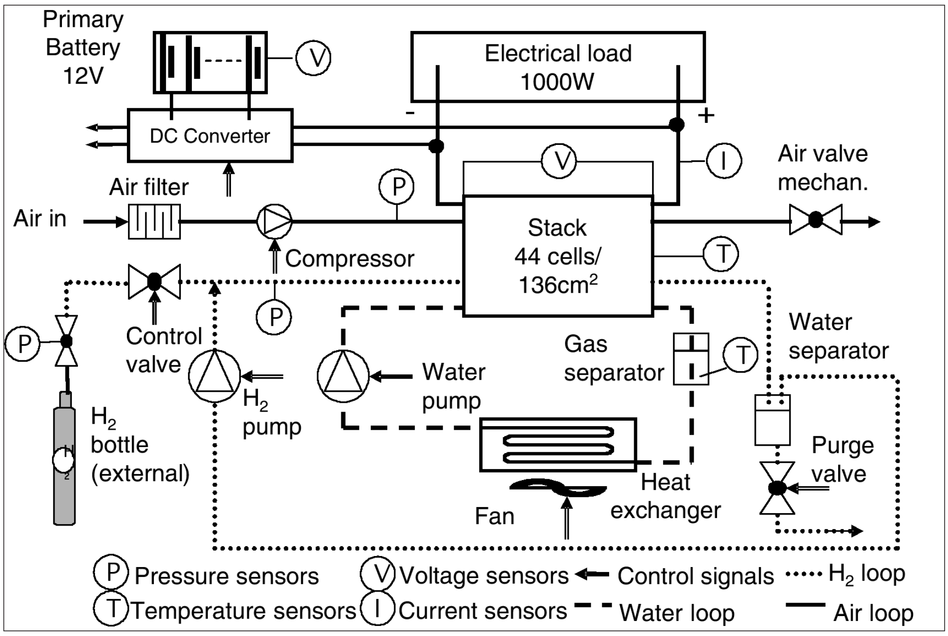

Fig. 4. Scheme of the liquid-cooled PowerPac fuel cell system

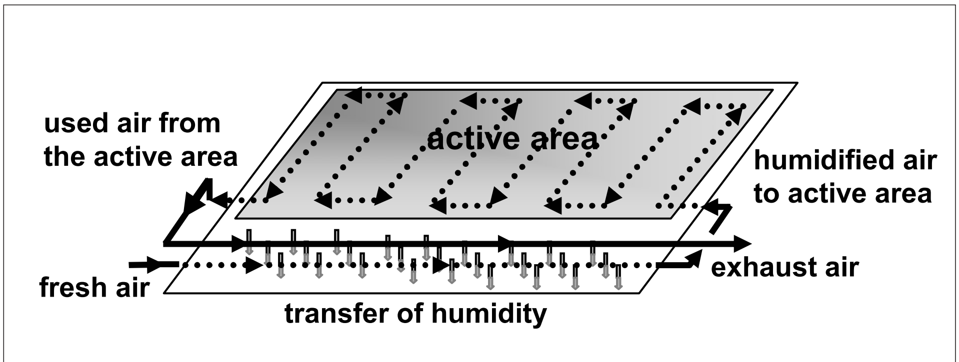

Fig. 5. Concept of internal process air humidification by transfer of humidity through a separate membrane section from the used air to the fresh air within each cell

on liquid-cooled polymer electrolyte fuel cell technology. A new stack concept has been developed for this application with innovative concepts for the sealing of bipolar plates [4], light-weight current collectors and endplates as well as with an integrated modular humidification of the process air [2][3]. By integration of the process air, humidification into the stack, parasitic power consumption by external humidification units is eliminated while at the same time modularity and scalability are achieved since the humidification of the process air takes place in each cell individually.

When going to the kW range, taking into account a system efficiency of typically 40–50%, the amount of heat produced is considerable. In order to maintain an adequate working temperature, effective cooling of the stack is necessary. For a more compact stack liquid cooling is the preferred option, as the heat capacity and heat transfer coefficients of water are higher than those of air, allowing for thinner plates, thereby reducing both, stack volume and weight.

A scheme of the PowerPac fuel cell system is shown in Fig. 4. The system consists of the three media streams, the air path, the hydrogen loop and the coolant loop, as well as an electronics and control unit. The process air is fed to the stack at a pressure of 1.1 to 1.4 bars, depending on the load. The humidification of the incoming fresh air is achieved by transfer of product water from the exhaust air, through part of the membrane, to the dry intake air (Fig. 5) [2]. Tests have shown that the performance of the stack using the concept of internal humidification and being operated with dry air is almost the same as when the process air is additionally humidified with an external humidifier (Fig. 6).

Pure hydrogen is delivered from an external pressure bottle. In each cell the gas flow field for the hydrogen has a stepwise reduction of the number of channels along the active area allowing an almost constant gas speed, even if the volume flow of the gas decreases because of consumption along the channels due to current generation. The constant gas speed guarantees optimum water removal from the channels and results in a hydrogen stoichiometry as low as 1.1 which is sufficient for stable operation and only a small amount (10%) of the hydrogen needs to be recirculated.

The overall architecture of the PowerPac control system, including a control and a power board (microchip PIC18F452), is designed to achieve fully autonomous, safe and easy operation. The user interface is a removable unit on the carrying handle with ON and OFF buttons and an information panel, which displays data regarding current, voltage, gas pressures and temperature of the stack.

CHIMIA **2004**, *58*, No. 12

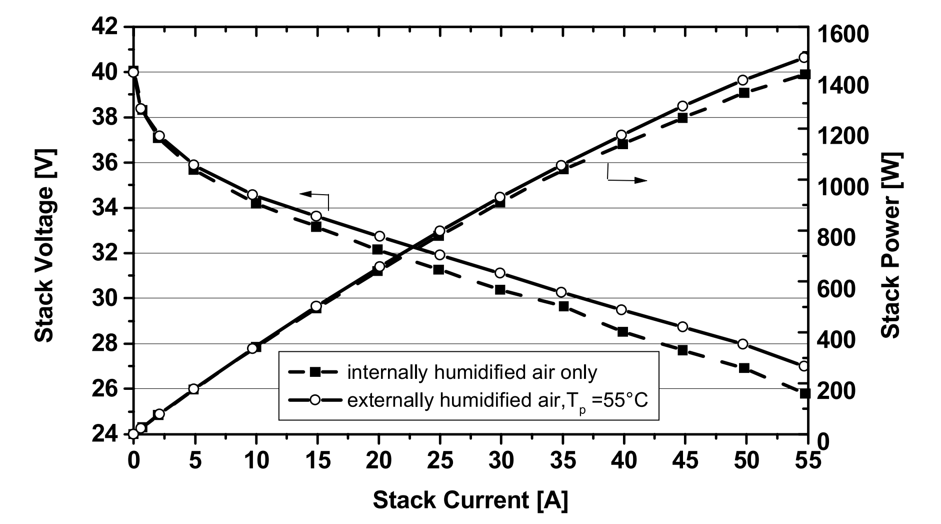

Fig. 6. Current/voltage and current/power curves of the PowerPac stack at 65 °C with and without external humidification of the process air. Hydrogen: stoich. = 1.2, pressure 1.3 bar_a; air: stoich. = 1.8, pressure 1.4 bar_a.

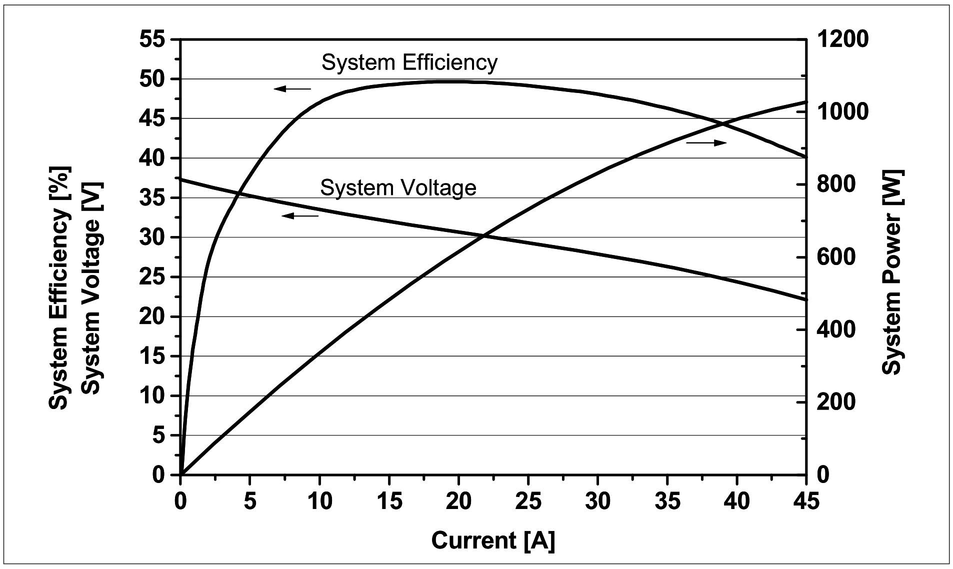

Fig. 7. Current/efficiency, current/voltage and current/power curves for the PowerPac system at an operating temperature of 65 °C

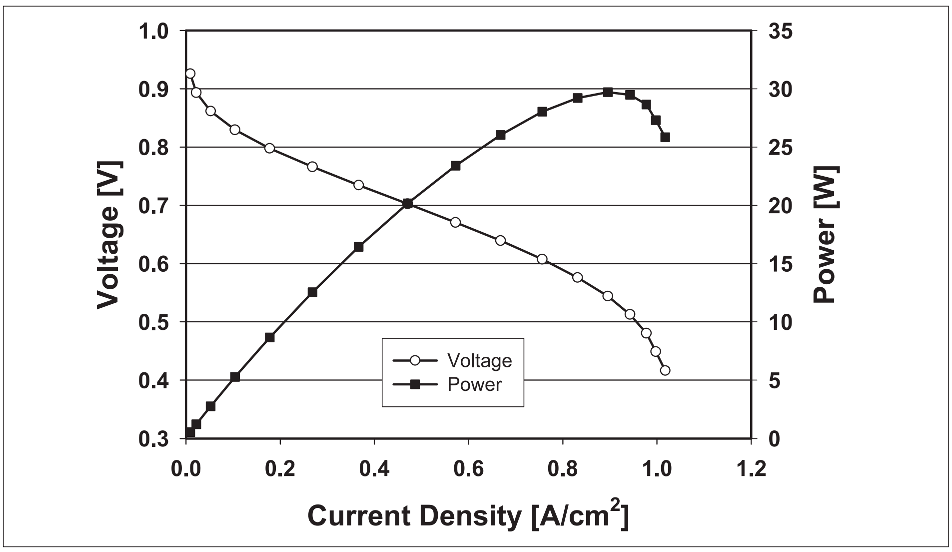

Fig. 8. Current/voltage and current/power curves of a 61 cm^2 single cell at 62 °C; Hydrogen pressure 1.4–1.5 bar_a (dead end); air near ambient pressure, stoich. 2.5–4.5. No gas humidification.

Upon cold start (T = 20 °C), 80% power is available in less than 30 s. Due to the elaborated control system the system exhibits excellent dynamics and automatically follows the external power requirement at rates of up to 10 kW/s. The PowerPac system has a maximum efficiency of 50% (at a stack efficiency of 60%). The characterization of the system net power output and system efficiency is shown in Fig. 7. The efficiency of the system is highest at mid-net power rates.

4. Light Mobility

The use of PEFC in applications for light mobility like scooters *etc*. allows the operation of these vehicles in a locally or even totally (dependent on the fuel generation) environmentally compatible manner and the noise emissions can be reduced significantly *versus* vehicles powered by internal combustion engines. This qualifies PEFC powered vehicles especially for the use in restricted locations such as congested urban areas or indoors. Compared with electric vehicles powered by batteries, fuel cell powered vehicles have an extended range and can be recharged quickly, therefore offering the user much more flexibility in the operation.

4.1. *Air-Cooled Systems*

Air-cooled PEFC systems for light mobility are being developed by MES-DEA. These systems are based on indirect air-cooled PEM fuel cell stacks and are characterized by their system simplicity. System simplicity in this case means:

- no humidification of the reactant gases (no complex humidifiers),
- close to ambient pressure on the cathode (no heavy air compressor),
- forced air cooling (no elaborate liquid cooling of the stack),
- modular layout (wide power range with an identical cell design).

To fulfill these requirements the main technical task to solve is the sufficient humidification of the polymer electrolyte membrane in the fuel cells under these conditions. Specially designed air flow fields combined with suitable gas diffusion layers and the optimized operating parameters (max. stack temperature 63 °C, stoichiometric air flow rate 2.5–4.5, hydrogen dead end with purge and periodic electric short circuits) of the fuel cell stack are employed to solve this problem.

The construction of a single 61 cm^2 active area cell is based on eight main components that are glued with silicone to form a single gas tight unit:

1. Anode bipolar plate (expanded graphite)
2. Anode parallel flow field (porous carbon paper)

CHIMIA **2004**, *58*, No. 12

3. Anode gas diffusion layer (porous carbon paper)
4. Polymer electrolyte membrane
5. Cathode gas diffusion layer (porous carbon paper)
6. Cathode bipolar plate (compression molded graphite)
7. Cooling layer (coated copper)
8. Gaskets (silicone)

The polarization and power output curves of a single cell used for the stacks manufactured by MES-DEA are given in Fig. 8. In single cells a current density of about 0.75 A/cm^2 at 0.6 V single cell voltage is reached (respective a power density of 0.45 W/cm^2 or 27.5 W per cell).

Based on this fuel cell stack technology, very compact and lightweight fuel cell systems with different nominal net power outputs from 0.5 kW up to 6 kW, which are ideal for light mobile applications (Table), have been realized. The current-based system efficiency (with respect to the lower heating value of hydrogen) of all systems at the maximum, nominal net power output is about 43%. Fig. 9 shows a 1.0 kW fuel cell system.

Fig. 10 schematically illustrates the process flows and their controls. The control electronics measure the stack current and voltage. Depending on these values the microcontroller calculates the set temperature of the fuel cell stack, the stoichiometric air flow rate, the hydrogen purging and periodic short circuit intervals and regulates the auxiliaries in order to operate the fuel cell stack continuously under optimal operating conditions. In the case of a malfunction (low voltage, high current or high temperature), security protocols are integrated in the software to protect the system from damage.

An Aprilia scooter Atlantic Zero equipped with a 6.0 kW fuel cell system (top speed 85 km/h, max range 125 km) is shown in Fig. 11. The fuel cell system is placed under the seat; three composite pressure bottles (300 bar) with a total volume of 20.4 Nl of hydrogen are integrated under the foot rest. The top case is fully available for the driver. Other examples of vehicles for light mobility with air-cooled fuel cell systems are an electric wheelchair with a 500 W fuel cell system as a range extender, a bicycle powered with a 1.0 kW fuel cell system (top speed 35 km/h, max. range 50 km) and a further Aprilia scooter SR 50 (3.0 kW, top speed 55 km/h, max range 75 km/h).

4.2. *Liquid-Cooled Systems*

4.2.1. *The Fuel Cell Hybrid Electric Vehicle SAM*

The University of Applied Sciences in Biel (CH) has developed in collaboration with different research institutes and industrial partners a fuel cell–battery hybrid sys-

Table. System characteristics of air-cooled systems for light transport

Net Power Output	Voltage Range/Cells	Overall Dimensions [mm]	Weight [kg]
500 W	12 V–19 V 20-cell stack	Stack 240 x 185 x 135 ECU[a] 185 x 160 x 60	Stack: 2.2 System: 3.1
1.0 kW	24 V–38 V 40-cell stack	Stack 300 x 230 x 155 ECU[a] 185 x 160 x 60 CBCU[b] 205 x 85 x 35	Stack: 3.4 System: 4.5
3.0 kW	72 V–114 V 120-cell stack	Stack 410 x 305 x 235 ECU[a] 295 x 155 x 95 CBCU[b] 205 x 85 x 35	Stack: 9.1 System: 11.2
6.0 kW	144 V–228 V 240-cell stack	Stack 455 x 410 x 310 ECU[a] 400 x 155 x 95 2 x CBCU[b] 205 x 85 x 35	Stack: 21.0 System: 24.9

[a] Electronic control unit; [b] Cooling blower control unit

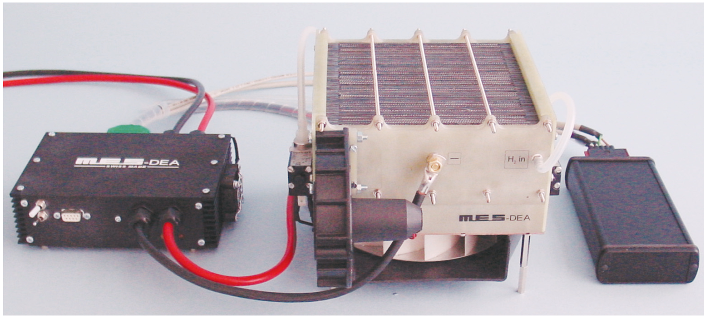

Fig. 9. 1.0 kW Fuel cell system with cooling blower control unit (right box) and electronic control unit (left box). Cooling blower below stack and process air blower on front end

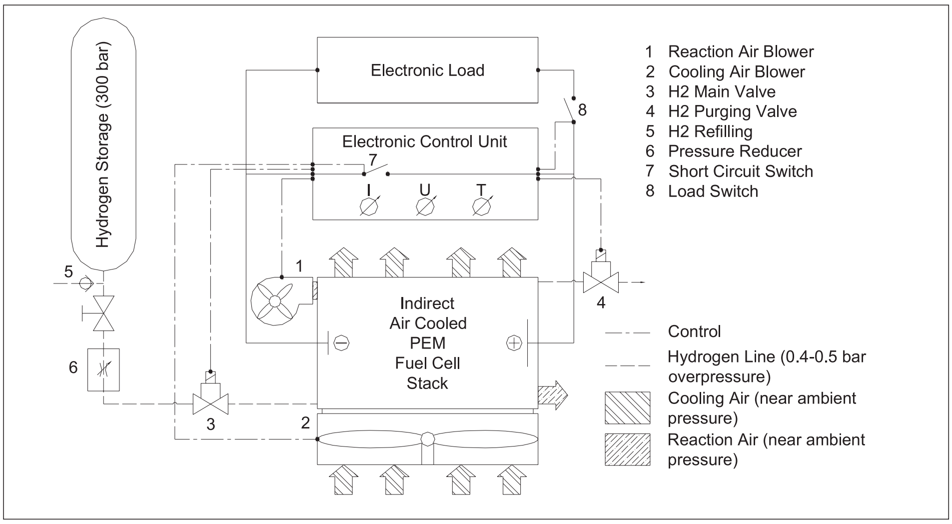

Fig. 10. Scheme of air-cooled fuel cell system for light mobile applications

Fig. 11. Aprilia Atlantic Zero Scooter equipped with MES-DEA 6.0 kW Fuel Cell System. Details see text

Fig. 12. Side view of the fuel cell vehicle SAM

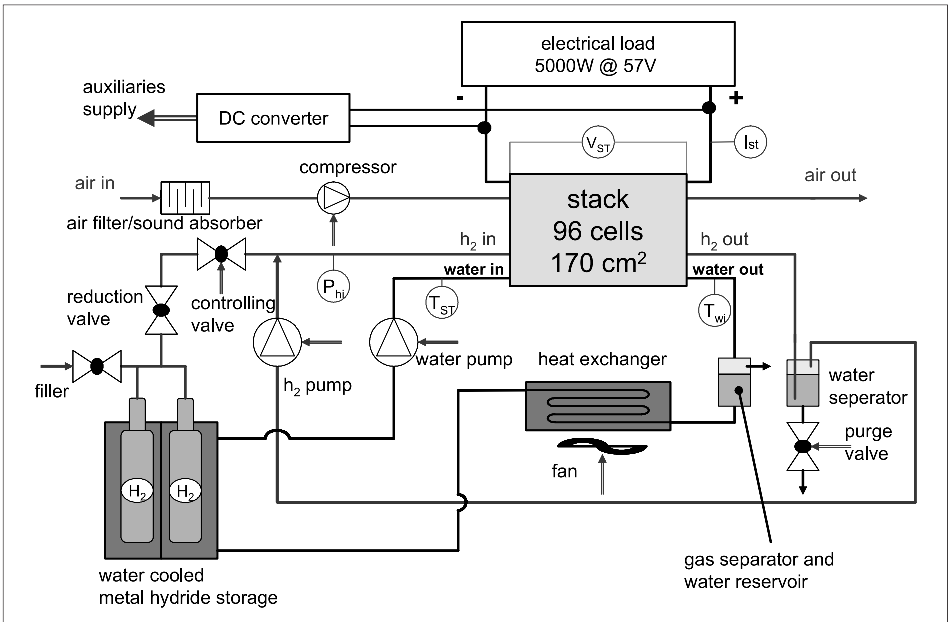

Fig. 13. Scheme of the SAM liquid-cooled fuel cell system

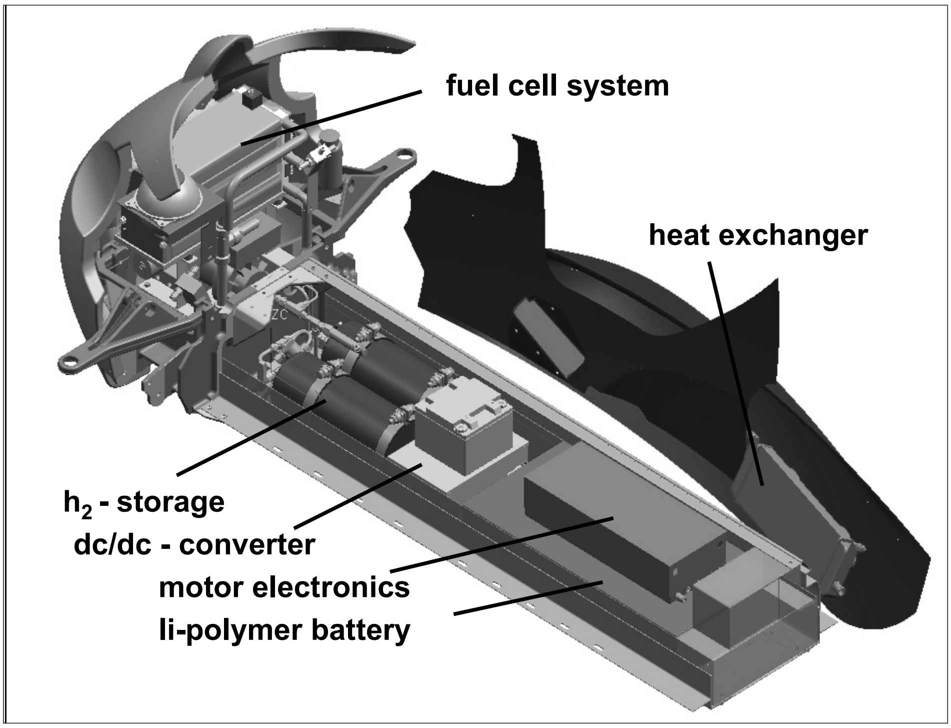

Fig. 14. CAD model showing the positioning of the system components in the SAM vehicle

tem and has integrated the system in the lightweight electric vehicle 'SAM', built by Cree AG (CH).

SAM is a three-wheel electric vehicle which offers two seats arranged in a row (Fig. 12). The vehicle has been developed for local traffic. The goals were a good driving performance, low energy consumption, low weight and low production costs. The car body is composed of four parts of polyurethane and a chassis structure made of aluminum which results in a curb weight of about 400 kg. The rear wheel is connected to the drive train by a synchronous belt drive. The electric motor has a maximum starting torque of 80 Nm and a peak power of 15 kW.

The fuel cell system layout is shown in Fig. 13. The PEM-stack is similar in design and construction to the one described in Section 3.2. It consists of 96 cells of 170 cm^2 active area and has a maximum power of 6 kW at a stack voltage of 57V. The gas input pressure is limited for both gases to 1.3 bar. The same cell-internal air humidification concept as described in Fig. 5 is employed. The stoichiometry on the air side, at full power, is $\lambda = 1.8$. On the hydrogen side the stoichiometry is at minimum $\lambda = 1.3$.

The hydrogen is stored onboard in two cylindrical bottles filled with powder of metal-hydride, storing approximately 400 g of hydrogen. As the metal-hydride cools down upon hydrogen discharge, the cylinders are integrated in the cooling system of the fuel cell stack. With two commercial heat exchangers for motorcycles the system temperature is held at a temperature of 65 °C. The hydrogen pressure is reduced by a pressure regulator at the inlet of the stack to 1.3 bar. The small amount of hydrogen coming out of the stack is recycled by a diaphragm pump, which reduces the losses of hydrogen to a minimum. The process air is pumped by a roots compressor into the system.

The arrangement of the complete drive train, including hydrogen tanks, is shown in Fig. 14. The power of the fuel cell stack is transferred to the battery circuit by a DC/DC converter. This boost-converter is an in-house development, with an efficiency of more than 96% over a wide range of power. The battery module contains powerful lithium–polymer batteries and a monitoring unit. With a total capacity of 35 Ah the batteries can cover temporarily the total power requirement of the SAM drive at a maximum discharge current of 2.5 C.

The fuel cell system is monitored and regulated by a central electronic unit. For the communication between the different components and the central electronic unit a CAN-bus is used. The gas concentration is measured by two hydrogen sensors; one in the nose and the other in the central longitudinal beam. Another security element is

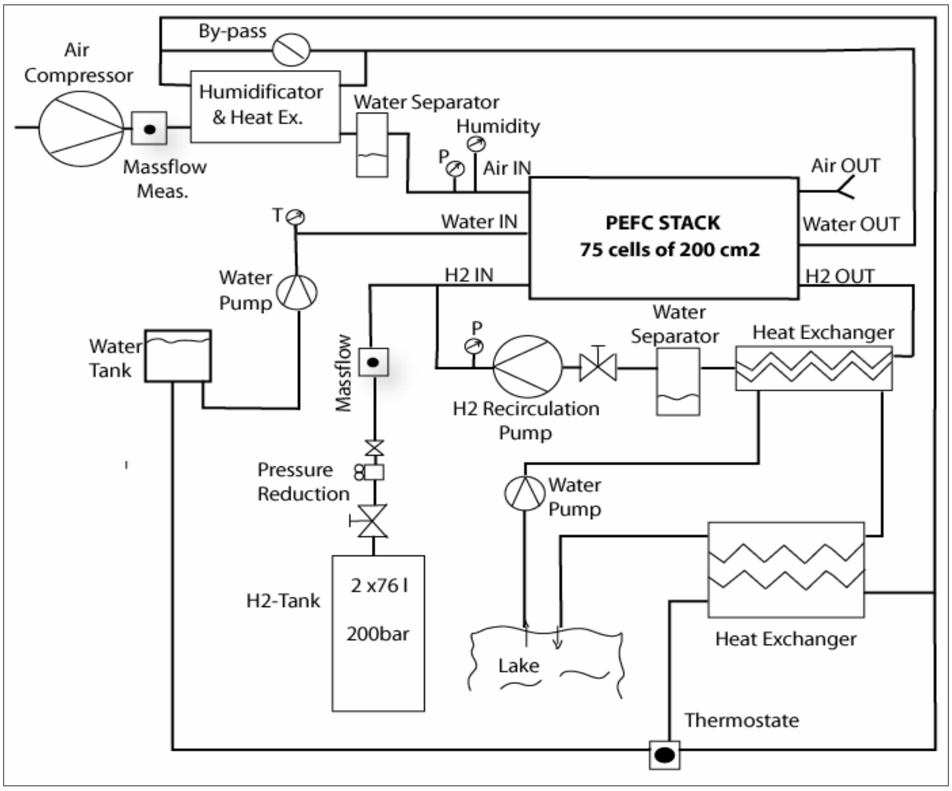

Fig. 15. Scheme of lake-water-cooled 3 kW fuel cell system

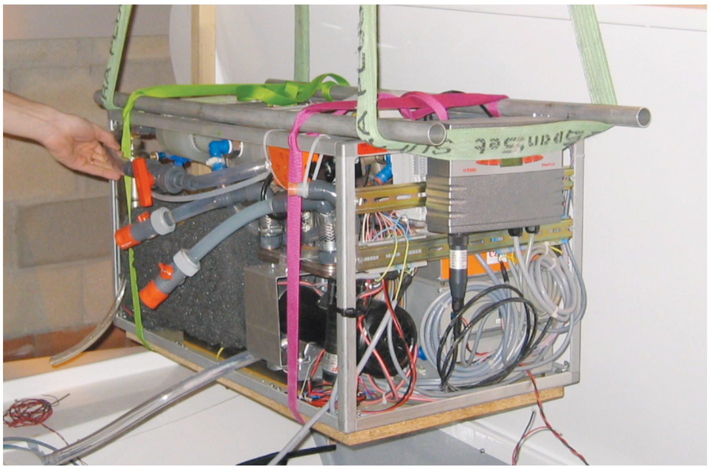

Fig. 16. 3 kW, water-cooled, fully automated fuel cell system is mounted to vessel. Volume 170 l, weight 70 kg.

Fig. 17. Electric boat Hydroxy3000 for six passengers, with 3 kW PEMFC/battery hybrid electric propulsion system, speed 12–18 km/h, size 7m x 2,5m, weight 1300 kg

the accident recognition system, which closes the valves in the hydrogen circuit. Additionally to this there is an automatic closing between hydrogen storage and the complete gas system.

With the homologation in Switzerland, the fuel cell powered vehicle will serve the University of Applied Sciences in Biel to accumulate field experience with their fuel cell technology.

4.2.2. *Demo Project Fuel Cell Boat Hydroxy3000*

Legislation for pollution is becoming more restrictive for lake and fresh water boating. A solution to replace the thermal motors, often based on gasoline for the small units, is PEFC technology [5][6]. With a better efficiency, zero emission and almost zero noise, PEFC-based boats are a perfect means to get a maximum pleasure on motorized navigation and to protect efficiently the drinkable fresh water resources.

Since 1997, the University of Applied Sciences of Western Switzerland in Yverdon (CH) has developed in collaboration with different research institutes and industrial partners fuel cell–battery hybrid boats, the 'Hydroxy' family. A world's first was realized with the crossing of the Atlantic of a sailing racing boat, equipped with a 300 W PEFC as auxiliary power unit, during the 'Course du Rhum 2002' [7].

For applications in boats, liquid cooling of the fuel cell system is obvious, as an infinitely big, cold reservoir is available, allowing for easy temperature control in the system. Further weight and volume restrictions, especially for the hydrogen tank, are generally less demanding in boats than in road transport applications. Therefore electric boats are a well-matched application for water-cooled fuel cell systems.

A 3 kW system, based on the stack technology initially developed for an automotive application (see Section 4.1.), was set up taking into account the special boundary conditions of the boat application (Fig. 15). The fuel cell system integrated into a rack is shown in Fig. 16.

Hydrogen is stored in two pressurized vessels containing 1.25 kg each at 200 bar, providing an autonomy of 12 to 40 h depending on average cruising power. Tests have shown a total efficiency of 33% from tank to propeller. With an ecological hydrogen production based on hydroelectricity, the well to propeller efficiency may be considered around 26%. This is an improvement compared to the practical efficiency of a gasoline engine (about 16%); not only in terms of efficiency, but mainly also in terms of pollution reduction (including noise and drinking water protection).

The demo-catamaran (Fig. 17) has been designed for minimum energy consump-

CHIMIA 2004, 58, No. 12

tion. It is propelled by two electric motors, powered by the hybrid electrical system of the 3 kW water-cooled PEMFC and a 9 kWh lead acid battery electric storage unit. The boat reaches a speed of 10 km/h at nominal power and 15 km/h with battery buffer. The prototype boat is intended for family leisure on lakes and channels.

5. Automotive

In the past the concern about local pollutants such as CO, NO_x, HC and PM as well as the influence of CO_2 on global warming has driven the development towards advanced powertrains in cars. It is possible that in some years also the concern about the resources of primary energy such as crude oil or natural gas will become a significant issue.

Based on the assumptions of the IPCC and UN, that the demand for individual mobility will rise by a factor of four between 1990 and 2050, for stabilization of the energy consumption for individual mobility near the actual levels, fuel efficiency has to improve by a factor of about four.

Mainly in part load driving in urban traffic fuel cell systems have the potential to increase the fuel efficiency by more than a factor of two. Therefore the potential of the technology is big but its degree of maturity is not yet as advanced as that of improved internal combustion engines or hybrid powertrains which can both already be bought on the market at reasonable costs.

The operation of passenger cars is characterized by a wide range of operation points, however, the share of low power demand is high. Further the dynamics of operation has a high priority [8][9]. As a consequence, a low vehicle mass is mandatory for efficient driving. This leads to the demand for a high power density of the propulsion unit, which can *i.e.* be achieved with high (> 2 bar_a) gas pressures in the fuel cell system.

Energy efficiency may also be improved by recovering the braking energy in stop and go traffic; the electric motor/generator in combination with an electric energy storage device can recuperate 20–30% of the energy which is normally transformed into heat in the brakes. Therefore hybrid electric powertrains, consisting of an efficient fuel cell energy converter and an electric storage unit offer advantages with respect to overall efficiency.

Since the fuel cell stack is the most expensive part of the drive train, in a hybrid concept the stack size can be dimensioned in order to satisfy the long-term power demand, offering the advantage of a smaller stack in combination with a less expensive electrical energy storage device which can be used to fulfill the short term acceleration performance.

Two system concepts, as described below, have recently been developed and realized in Switzerland.

5.1. *The HyPower Project*

In a collaboration between PSI, ETHZ, EPFL and the industrial partners Volkswagen, Montena SA and FEV Motorentechnik a fuel cell/super capacitor hybrid electric vehicle 'Hy.Power®' based on a Volkswagen Bora has been realized [10]. The power train layout is shown in Fig. 18. A 30 kW fuel cell system and a 50 kW super capacitor array as electric storage unit were combined [11].

The fuel cell system (Fig. 19) consists of six stacks with 6–8 kW nominal electric

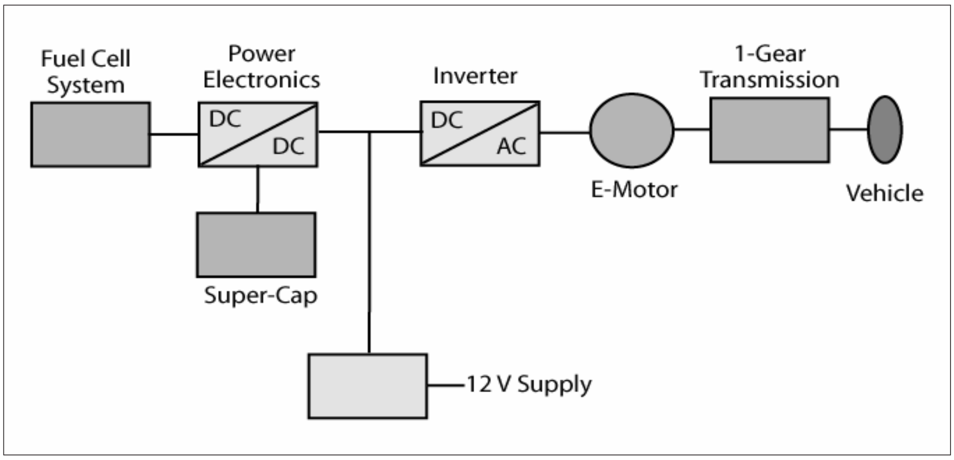

Fig. 18. Configuration of the powertrain of the Hy.Power PEFC-hybrid passenger car

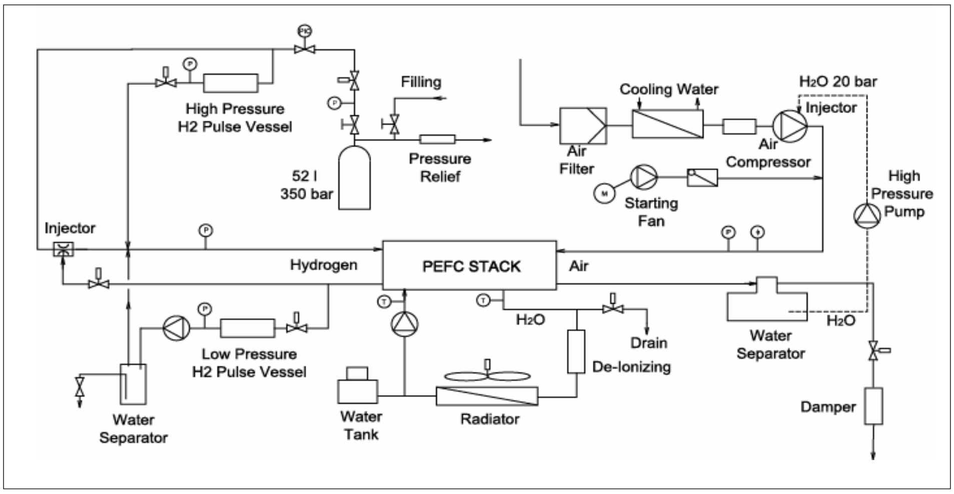

Fig. 19. Schematic of liquid-cooled fuel cell system, with air humidification through water injection into compressor

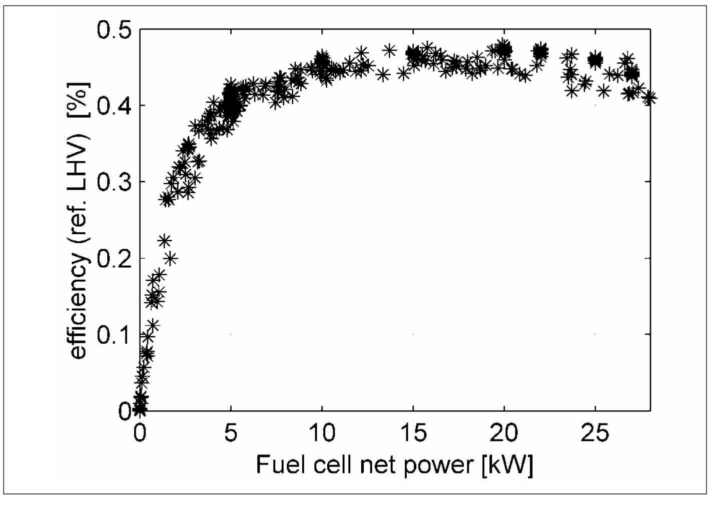

Fig. 20. Current-based system efficiency of the Hy.Power car during operation

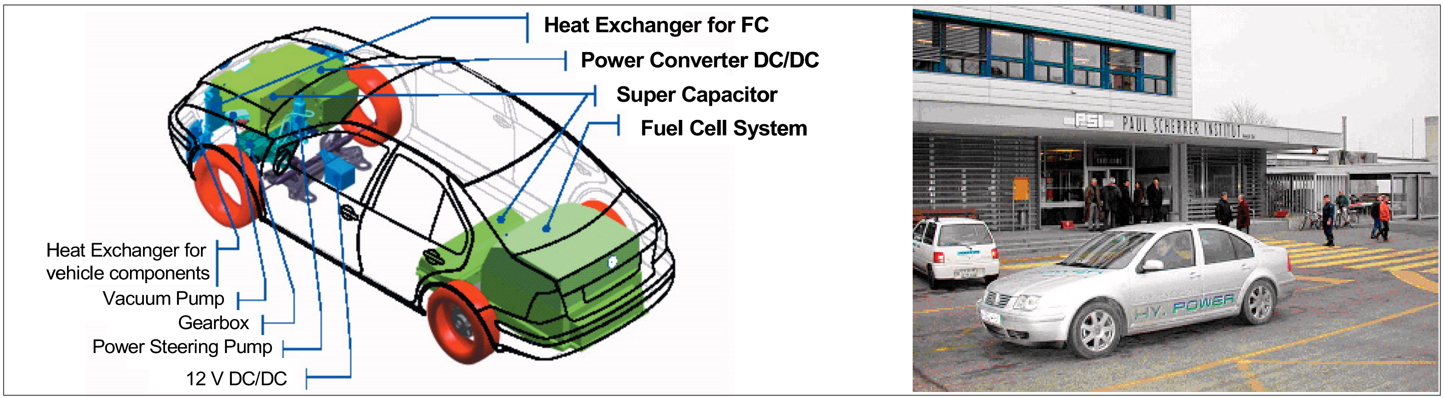

Fig. 21. Packaging of the adapted systems for the fuel cell power train in the VW Bora Hy.Power (left), and vehicle in operation (right)

Fig. 22. Left: the concept car HyCar; right: its visible fuel cell system

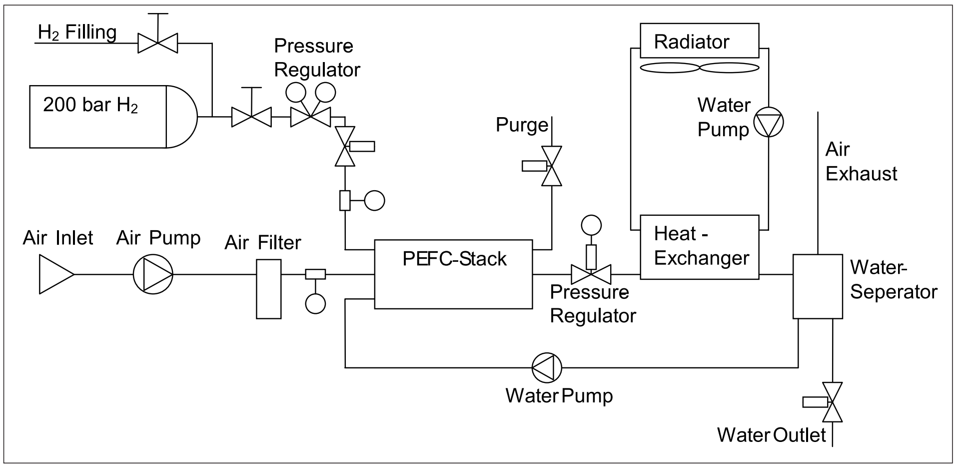

Fig. 23. HyCar's fuel cell system with Nuvera's direct injection cooling (combined cooling and humidification water circuit in the stack)

power output each [12][13]. The process air is delivered to the stacks by a twin screw compressor. For air humidification and cooling, water is injected directly into the compressor [14][15]. This is an energy efficient, low volume and low weight humidification method, as the waste heat of the compressor is used; however it requires an advanced control strategy to avoid liquid water input into the stacks. To improve operation stability, the pressure and flow in the hydrogen loop can be pulsed by high and low pressure pulses. This procedure supports water removal from the anode at low hydrogen mass flows [16]. The system can deliver up to 30 kW net power at current-based efficiencies mostly higher than 40% (Fig. 20).

In the Hy.Power® vehicle an electrical storage device based on a double-layer capacitor module has also been implemented. The 282 super-capacitor-cells can store an energy of 360 Wh and can deliver (or recover) a power of 50 kW for about 15 seconds [17][18]. The integration of the drive train components is shown in Fig. 21. This combination enabled a good dynamic performance of the vehicle. The car proved the state of the art of the technology by driving over a Swiss Alp pass in January 2002. The fuel consumption can be reduced by 15% using the recuperation function, storing the braking energy in the supercaps.

5.2. *The HyCar Project*

ESORO AG, a Swiss engineering company, has developed and realized the fuel cell powered concept vehicle HyCar with the objective to generate knowledge and the related software tools in the field of fuel cell systems. Further goals were to acquire practical experience with the fuel cell technology and its interactions with the 'real' world. HyCar features a hybrid drive train with a PEFC system and a ZEBRA high temperature battery (Na/NiCl type). A special packaging with a visible fuel cell system and a conventional power socket as an idea of an additional customer benefit of fuel cell vehicles are other characteristics of the vehicle (Fig. 22).

With regards to a future serial production of fuel cell powered vehicles, the entire fuel cell system has to be as simple as possible. Few and well-suited components generally reduce the weight, simplify the mounting and also reduce the costs of the system. The degree of simplification obviously depends on the specification of the application. During the system integration therefore it was an objective to realize a highly integrated system. However, since HyCar was mainly built for knowledge generation, its fuel cell system is not simplified to the minimum. Nevertheless some simplifications could be realized – also because of the direct injection cooling, featured by the Nuvera fuel cell stack. Cooling water is combined in the stack with the process air and thus also used for humidification (Fig. 23).

To enable high system integration, an accurate simulation of the entire system was needed. Therefore a real-time simulation environment was developed which enables a stepwise evolution from only software simulation to hardware in the loop and further to complete system control. Due to the use of the same software environment through the overall development process, the simulation could be improved by meas-

CHIMIA **2004**, *58*, No. 12

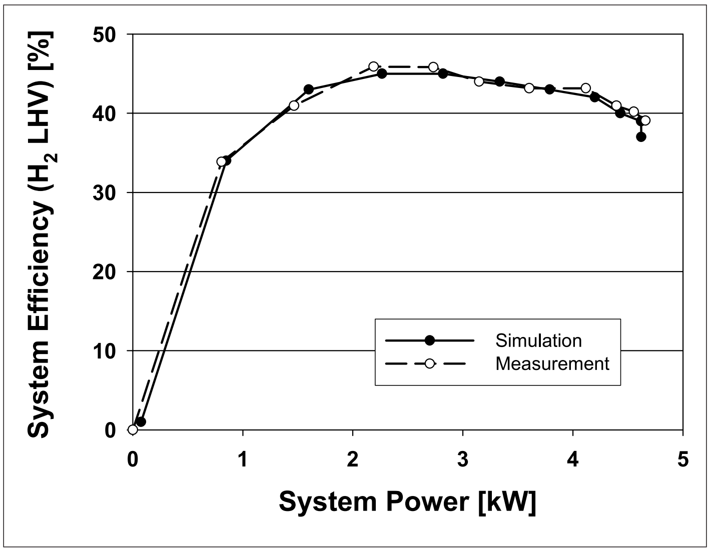

Fig. 24. Simulated and measured current based system efficiency of the HyCar fuel cell system

ured data and became a database for future developments. A simulated and a measured performance–efficiency curve with the same system parameters are shown in Fig. 24. For power ratings between 30 and 100% the current-based tank to wheel system efficiency based on the lower heating value of hydrogen is above 40%.

The process air pressure significantly influences system efficiency, since the power of the roots compressor is very much dependent on the pressure it has to deliver. A low operating pressure is therefore desirable as long the fuel cell stack can still be operated. This obviously depends on the point of operation and the required dynamics of the system. At least at low power points of operation – such as charging the battery while not operating the car – due to lowering of the air pressure, a higher overall efficiency and net power with the same stack current could be measured.

It can be concluded that system integration is a major task in the development of every fuel cell application. Efficiency and simplicity should be regarded as guidelines during the development.

6. Summary and Outlook

The article documents that in Switzerland innovative concepts for fuel cell stacks and systems are being developed. Depending on the application, portable or mobile, the stack and system concepts vary with respect to water management, cooling and system integration. However, all developments still are in the research phase, demonstration phase or prototype. For an application in commercial products further work is necessary. The stacks and systems still have room for improvement with respect to volumetric or gravimetric power density, new materials can be employed if they become available, *e.g.* membranes for higher temperature operation would reduce the size of the cooling sub-system. Catalysts with improved oxygen reduction kinetics could boost system efficiency. Research work is also needed to reduce cost by further reducing system complexity *i.e.* through function integration and developing stack concepts based on simpler, cheaper and fewer parts and by improving power density. In this field modeling will play an important role as discussed in the previous contribution on 'Modeling and Simulations'. Last but not least assessment and improvement of the lifetime of the systems in everyday use is an open question. Issues such as the freezing and cold start of fuel cell systems will have to be dealt with. Important research work will also be needed to understand and eliminate the degradation mechanisms of most of the employed components.

With respect to the complete system the fuel is an important component. Hydrogen is only an energy carrier and not a primary energy source. Therefore the efficiency of production of hydrogen is key in the assessment of hydrogen fuel cell applications. The total energy chain has to be considered. In the case of switching the energy supply to renewable sources, fuel cell power trains show best potentials. Hydrogen can be produced by electrolysis based on electricity produced by wind, solar or hydro. Renewable hydrogen can also be produced through solar chemistry pathways or based on biomass. A detailed analysis is given in the 'Fuels for Fuel Cells: Requirements and Fuel Processing' article in this issue.

Received: October 11, 2004

[1] D. Schmid, *Fortschritt-Berichte VDI*, Vol. 500, **2003**, ISBN 3-18-350006-X.
[2] M. Santis, D. Schmid, M. Ruge, S.A. Freunberger, F. N. Büchi, *Fuel Cells* **2004**, *128*, 208.
[3] M. Ruge, D. Schmid, F.N. Büchi, Swiss Patent Application, Nr. 1031/02, 17.06.**2002**.
[4] M. Ruge, D. Schmid, F.N. Büchi, PCT Patent Application, Nr. PCT/CH03/00014, **2002**.
[5] P. Favre, D. Cicio, J.F. Affolter, *Proceedings of the Portable Fuel Cells Conference*, Luzern, July 1999, **1999**, p. 85.
[6] J.F. Affolter, P. Mariotti, *Proceedings of the 5ème congrès Vel. Elec.*, Grenoble June 2002, Actes INRETS No 85, **2002**, p. 177.
[7] J.F. Affolter, *Proceedings of the Colloque Nouvelles Energies*, Le Havre, Nov. 2003, **2003**, p. 90.
[8] W. Josefowitz, S. Koehle, P. Lück, P*roceedings of the 8. Aachener Kolloquium Fahrzeug- und Motorentechnik*, Aachen, **1999**.
[9] W. Josefowitz, S. Koehle, P. Lück, *Proceedings of the Electric Vehicle Symposium 17*, Montreal,Canada, **2000**.
[10] P. Rodatz, O. Garcia, L. Guzzella, F.N. Büchi, M. Bärtschi, A. Tsukada, P. Dietrich, R. Kötz, G.G. Scherer, A. Wokaun, *Proceedings of the SAE Congress*, Detroit/Michigan, **2003**, SAE Paper 2003-01-0418.
[11] P. Dietrich, F. Büchi, A. Tsukada, M. Bärtschi, R. Kötz, G.G. Scherer, P. Rodatz, O. Garcia, M. Ruge, M. Wollenberg, P. Lück, A. Wiartalla, C. Schönfelder, A. Schneuwly, P. Barrade, *Proceedings of the International SATG-Symposium*, SAE-CH, FISITA; Wil, Switzerland, **2002**.
[12] M. Ruge, F.N. Büchi. *Proceedings of the 1st European PEFC Forum*, Luzern, 2001, **2001**, p. 299.
[13] F.N. Büchi, A. Tsukada, P. Rodatz, O. Garcia, M. Ruge, R. Kötz, M, Bärtschi, P. Dietrich, *Proceedings of the Fuel Cell World Conference*, Luzern, July 2002, **2002**, p. 218.
[14] S. Pischinger, C. Schönfelder, W. Bornscheuer, H. Kindl, A. Wiartalla, *Proceedings of the SAE Congress*, Detroit/Michigan, **2001**, SAE Paper 2001-01-0233.
[15] S. Pischinger, C. Schönfelder, O. Lang, H. Kindl, *Proceedings of the SAE Congress*, Detroit/Michigan, **2002**, SAE Paper 2002-01-0409.
[16] P. Rodatz, A. Tsukada, M. Mladek, L. Guzzella, *Proceedings of the XV IFAC World Congress*, Barcelona, **2002**.
[17] R. Kötz, M. Carlen, *Electrochim. Acta* **2000**, *45*, 2483.
[18] R. Kötz, S. Müller, M. Bärtschi, B. Schnyder, P. Dietrich, F.N. Büchi, A. Tsukada, G.G. Scherer, P. Rodatz, O. Garcia, P. Barrade, V. Hermann, R. Gallay, *Proceedings of the Advanced Batteries and Super Capacitors Symposium*, ECS Proceedings Volume PV 2001-21, The Electrochemical Society, Inc., Pennington, NJ **2002**.