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HYDROGEN/OXYGEN FUEL CELL SYSTEM DEMONSTRATING HIGH POWER DENSITY AND EFFICIENCY

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Abstract

Commonly polymer electrolyte fuel cell systems (PEFC) in transport applications use oxygen from air as the oxidant. However, in a renewable energy system when hydrogen is obtained from the splitting of water by electrolysis or other water splitting processes then oxygen is obtained as energetically cheap by-product. The use of pure oxygen allows the development of mobile fuel cell systems with interesting properties.

The oxygen reduction reaction is the main limiting process in PEFC. Operating PE fuel cells with pure oxygen enables for operation with oxygen partial pressures of up to several bar, which is about an order of magnitude higher than oxygen partial pressures achievable in pressurized hydrogen/air systems. Thus the main advantage of pure oxygen PEFC systems is the high specific power. At gas pressures below 4 bar abs. and a stack efficiency of 0.5 (LHV), a power density of 1.4 W/cm^2 has been obtained on the short stack level. This is about a factor of two higher than what is obtained in today's state of the art H2/air technology stacks.

Using high oxygen partial pressures is under suspicion of triggering higher degradation of membrane and/or catalyst. Long-term degradation experiments were performed, using cycling protocols, showing that stack life times, useful for the automotive application can be achieved with high oxygen partial pressures and high specific power densities.

A compact 7 kW prototype system based on a 24 cell stack was realized. Current densities of 2.1 A/cm^2 were obtained using a very compact system with all system components (valves, gas recirculation, coolant pump asf.) except gas tanks and heat exchanger included into the stack endplates.

Keywords: fuel cell, power density, efficiency

1 Introduction

Belenos Clean Power is developing a complete clean energy chain, where electrical energy is gained decentralized from photovoltaic electricity. The electric energy not immediately consumed is used to split water in an electrolyser to produce hydrogen and pure oxygen that can be stored and recombined to water in a fuel cell.
Belenos Clean Power and Paul Scherrer Institut, have developed compact fuel cell system prototypes between 3 and 30 kW fulfilling automotive needs. These prototypes are designed for pure oxygen and hydrogen operation. Beside automotive use, the systems can also be used for several other applications like UPS, back-up Power and electric boats. Belenos integrated a complete 7kW H_2/O_2 Fuel cell system (Fuel cell system, H_2 and O_2 storage vessels, piping, etc…) in an electrically powered boat which is now navigating for tests on lake Neuchâtel, Switzerland (Figure 1).

Figure 1: Catamaran with series hybrid FC/Battery power train propelled by 7 kW H_2/O_2 fuel cell system.

When hydrogen is obtained from the splitting of water by electrolysis or thermal splitting (i.e. through solar thermal processes [1]) then oxygen is obtained as energetically cheap by-product.
Pure oxygen enables operation with oxygen partial pressures about an order of magnitude higher than oxygen partial pressures achievable in pressurized hydrogen/air systems. Thus the main advantage of pure oxygen PEFC systems is the high specific power.

Further advantages of H_2/O_2- Systems compared to H_2/Air-Systems are [2]:

- Higher efficiency
- High power dynamics
- Easier humidification on cathode side
- Lower dependence on environmental conditions (pollution; elevation)

The above advantages are obtained at the expense of an O_2-tank that has to be carried on board.
Still, up to a certain stored energy, depending on the O_2-tank and system characteristics, the H_2/O_2 system is superior to comparable H_2/air systems due to high specific power density, gravimetric power and energy density [3].

Specific power and efficiency of a 7 kW system at high current densities is explored with oxygen partial pressures up to 4 bar_{abs}.
Using high oxygen partial pressures is under suspicion of triggering higher degradation of membrane and/or catalyst. To analyse this, long-term degradation experiments were performed using cycling protocols, showing that stack life times useful for automotive application can be achieved with high oxygen partial pressures and high specific power densities.

2 Materials and methods

2.1 Fuel cell system

Table 1 shows the main properties of the fuel cell system.

Table 1: Fuel cell system data

Fuel	H_2/O_2
Cell active area [cm^2]	230
Cells in stack	24
Cooling	liquid
Power [kW]	7

In Figure 2 the 7 kW fuel cell system prototype developed between Belenos and PSI is shown. On either side of the stack (orange/black) are system plates (white), containing all balance of plant components for the gas supply, gas recirculation and cooling. Only the gas storage, heat exchanger and coolant reservoir are external to the compact system.

The system is operated in gas recirculation mode on anode and cathode. This leads to a very compact and efficient humidification by recirculation water vapour. The recirculation also lowers the gas consumption.
On the back side of the system rack are the DC/DC converter and the control electronics developed by Belenos for the electricity supply of the propulsion system and the auxiliaries of the boat.

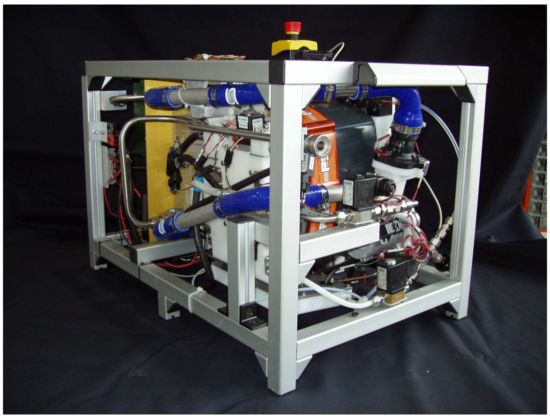

Figure 2: Fuel cell system containing stack, balance of plant, DC/DC and control electronics.

The system in the end-plates was originally designed for a 25kW-System. Only some of the components were adapted for a smaller stack. The majority of the components are therefore over sized such as the coolant pump. It thus allows the exploration of very high specific power densities.

2.2 Stack for analytic experiments

For durability measurements short stacks with the same cell geometry as in the system were used. These short-stacks were operated on a test bench where all important operation parameters such as dew point, cell temperature and gas purity were controlled and analytical measurements done (product water sampling and analysis; cell high frequency resistance; membrane permeability).
To examine long term degradation using high oxygen partial pressure at the cathode, short stacks were cycled using cycling protocols with two different current densities. The respective load cycles are shown in Figure 3.

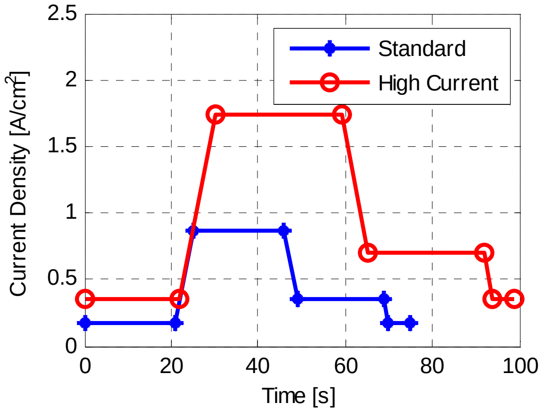

Figure 3: Load cycles used for degradation measurements by load cycling.

3 Results

3.1 Stack and system performances

Short stacks on the bench (Figure 4) and a 24 cell stack in the system (Figure 5) were tested for high specific power and current densities.

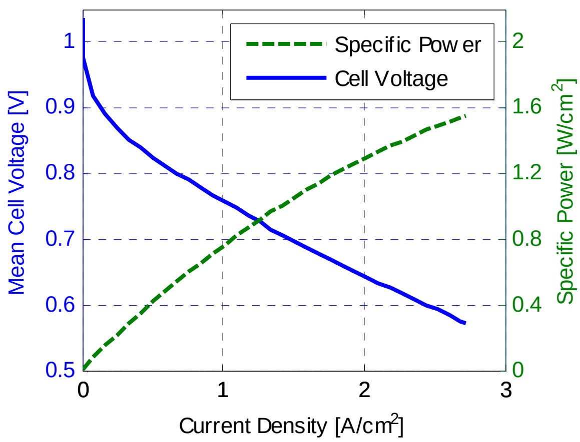

Figure 4: Polarization curve and power characteristics of small stack on test bench.

With short stacks tested on the bench, using gas pressures below 4 bar_{abs} and gas flow through mode, a current density of 2.2 A/cm^2 is obtained at a stack efficiency of 0.5_{LHV} (0.62 V/cell). This corresponds to a power density of 1.4 W/cm^2 (see Figure 4). This is about a factor of two higher than what is obtained in today's state of the art H_2/air technology stacks at the same efficiency.
In the system, using gas recirculation on anode and cathode, inert gases contained in the feed gases accumulate in the gas loops. The gas purity depends on the purge strategy which in turn defines the gas utilization.

In this configuration a current density of 2.0 A/cm^2 and a specific power of 1.3W/cm^2 is obtained at a stack efficiency of 0.5_{LHV} (0.62 V/cell) as shown in Figure 5.
The slightly lower performance in the system is also due to further different boundary conditions in the system, such as the humidity of the inlet gases which is controlled only passively through gas recirculation and the pressure control (constant p at stack outlet for the bench and constant p at stack inlet for the system) resulting in a higher mean pressure for the short stack in the bench at same nominal pressure. These differences in operating conditions are responsible for the slightly lower stack performance in the system environment as compared to the test bench.

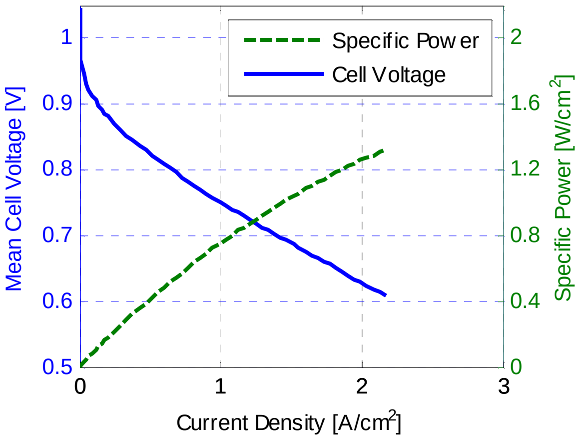

Figure 5: Polarization curve and power characteristics of stack in system.

3.2 System efficiency

The use of pure oxygen allows not only for high specific power densities, it also enables high system efficiencies because in the absence of a compressor or blower the parasitic power consumption of the balance of plant components is very moderate. The system efficiency is calculated as "hydrogen reacted to DC power" considering the parasitic power of all auxiliaries in the system.
Although some system components are over-sized, efficiencies of up to 62% are obtained as shown in Figure 6. At a system power density of 1.2W/cm^2 which corresponds to 6.6 kW system power, a system efficiency of 0.5_{LHV} is obtained.

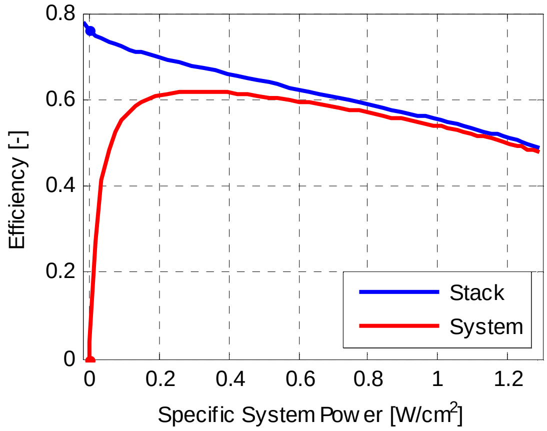

Figure 6: Stack and System efficiency of 7kW system with 24 cell stack.

3.3 Degradation

Degradation was assessed in short stack experiments (6 – 9 cells) in flow through mode in the test bench. The long term experiments were performed with two different protocols (see Figure 4) one with a maximum current density of 0.87 A/cm^2 and one with a current density maximum of 1.74 A/cm^2. Table 2 shows the degradation values obtained in these experiments over durations between 1200 and 2700 hours. Degradation is compared at the 80A (0.35 A/cm^2) current level, which is used in both protocols.

Table 2: Temporal degradation at 80 A (0.35 A/cm^2) in load cycling protocol.

Current cycle	Exp.1	Exp.2	Exp.3	Mean	
High			11	**11**	**[µV/h]**
Standard	8.6	13.4		**11**	**[µV/h]**
Duration [h]	2700	1400	1200		

4 Discussion

The data shows that current densities of up to 2.5A/cm^2 can be reached at cell voltages of 0.6 V. Cycling cells to high current densities is not affecting the degradation in cyclic operation protocols. The degradation rates observed with the protocols up to almost 2 A/cm^2 are similar the ones in protocols that are restricted to current densities below 1 A/cm^2.

Due to the advantage of high oxygen partial pressure in pure oxygen operation, the polarization losses on the cathode are smaller in H_2/O_2 stacks, and thus the efficiency is higher at the same current densities. In turn higher current densities can be reached at the same efficiency.

In addition the auxiliaries in H_2/O_2 systems require less power than the ones in air systems (no blower/compressor required), which further contributes to higher system efficiencies and/or system power gains.

These power density advantages lead to a cost advantage as compared to air systems since at the same efficiency only about half of the active area is required.

The fuel cell system advantages of the H_2/O_2 technology are obtained at the expense of an additional O_2-tank that has to be carried on board. The advantage of the power and energy densities of H_2/O_2 systems vs. H_2 /air systems including tanks depends on the energy carried [3].

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