15th Triennial World Congress, Barcelona, Spain

EFFICIENCY IMPROVEMENTS BY PULSED HYDROGEN SUPPLY IN PEM FUEL CELL SYSTEMS

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Abstract: The membrane electrode assembly of a PEM fuel cell has to be wet for the fuel cell to work efficiently. However too much water impedes the delivery of reactants and impairs the electrochemical reaction. In this paper, an arrangement is presented which uses pressure waves to remove water droplets and inert gas blankets from the fuel cell. Experiments showed good short and long term performance of the proposed configuration. *Copyright © 2002 IFAC*

Keywords: Fuel cell, Systems Design

1. INTRODUCTION

The ever continuing rise in energy consumption and the ongoing discussion about carbon dioxide emissions has generated interest in alternative energy propulsion systems. Fuel cells are widely assumed to play a major role in the future. Depending on the hydrogen source, fuel cells can be operated totally free from any emissions, including carbon dioxide.

Proton Exchange Membrane (PEM) fuel cells work only efficiently if the membrane electrode assembly (MEA) is wet. The membrane not only acts as the electrolyte but also separates the reactant fluids (hydrogen and air). If the membrane dries out, the electrochemical reaction stops in that area. However, if the membrane is too wet, the delivery of the reactants is impeded. Therefore good humidification is necessary and excess product water and/or excess humidification water has to be removed from the fuel cell. Although many studies have been done to optimize the fuel cell system performance there is still little agreement for mobile solutions. Carlstrom and Maynard (2000) have described the usage of a pulsator to remove blankets of inert gas and excess humidification fluid from the fuel cell. This idea is also found in Schott et.al. (2000). In both papers scant attention has been given to the practical realization.

This study focuses on the hydrogen supply. Several system configurations were investigated and compared. A feasible solution that produced good results was found. The voltage levels are similar to static test bench experiments where the fuel cell is operated under optimal conditions (favorable humidification, favorable temperature level, excess reactants flow on anode and cathode side).

After a short introduction and the description of the system the latest results will be discussed. First various arrangements of the hydrogen supply are described and compared. Next the most favorable solution is discussed in detail. Finally measurement results will be given to show the advantage of the solution found. The paper will end with a brief conclusion.

2. PROJECT AND SYSTEM DESCRIPTION

This work is part of an ongoing collaboration between the Paul Scherrer Institute (PSI), the Swiss Federal Institute of Technology (ETH) and industrial partners. The target of this project is the development and construction of a fuel cell powered electric vehicle with supercapacitor storage. The described experiments were conducted on a test bench which was built within the framework of this project.

The test bench comprises a PEM fuel cell stack which was developed at the Paul Scherrer Institut. It consists of 100 cells, each with an active area of approximately 200 cm^2. The nominal power output is 6.5 kW. The stack is supplied with pure hydrogen and air. It is operated at 2 bar_a and at temperatures below 70°C. The fuel cell is described in more details in Ruge and

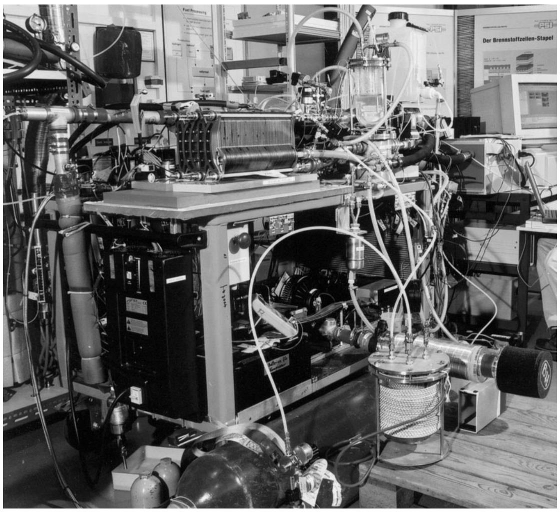

Fig. 1: View of test bench

Büchi (2001).

For the air supply a Opcon^{TM} twin-screw charger OA 1040 was used. The air was humidified using a Lechler^{TM} supersonic atomizer. Because of the break down of the humidity sensor during the tests, no data on the actual humidity are available. Nevertheless, with rough estimations of the amount of water that was consumed by the humidification device, that was produced by the fuel cell reaction and that was recollected, it is assumed that the humidification was well below satisfactory levels. The cathode was supplied with 100% excess air.

The hydrogen is supplied from a high pressure tank at pressures up to 200 bar. The hydrogen is humidified by passing it through a vessel filled with liquid water. As the hydrogen supply is the main part of this paper, it will be discussed in detail below.

The control algorithms are centrally managed by a dSpace^{TM} MicroAutoBox (MABX) 1401/1504. It has a Motorola^{TM} PowerPC 603e running at 200MHz with a slave processor to handle the digital I/O units. Matlab/Simulink^{TM} is used to program the control algorithms. Logical sequences were programmed with the help of the Matlab toolbox Stateflow^{TM}. Euler's method was chosen as solver with a fixed step size of 5ms.

The MABX has only a limited number of I/O units. Therefore, the communication between the sensors and the MABX, as well as the communication to the actuators is handled by a CAN-Bus. For this purpose the highly flexible WAGO^{TM} 750 CANopen series is installed, which is a modular I/O-system. Modules are available for almost every type of sensor signal or actuator output and the configuration can be expanded easily by adding additional elements.

3. RESULTS AND DISCUSSION

This section is divided into three parts. First, an evaluation of different hydrogen supply systems is performed. In the second part, the most favorable supply arrangement is described. Finally, measurement results are presented.

3.1 Comparison of different hydrogen supply systems

The most simple arrangement to supply the fuel cell with hydrogen is a dead-end system (arrangement A in Figure 2). In this arrangement only the amount of hydrogen which is needed to sustain the reaction is fed to the entrance of the fuel cell. The exit is sealed off by a valve which is only opened sporadically to remove inert gases which may have accumulated inside the fuel cell.

Since only the amount of hydrogen which is consumed by the fuel cell enters the stack, the dynamics that can be achieved are very limited. This disadvantage can be overcome if excess hydrogen is available. In this case a flow larger then required is passed through the fuel cell by opening the exit valve. If the excess hydrogen is released to the surrounding, the overall system efficiency will drop to very low levels. The hydrogen released to the environment not only leads to a deterioration of the efficiency, but is also a potential safety hazard, since it may react uncontrolled with air oxygen. A possible solution is the recirculation of the excess hydrogen to the stack entrance by means of a pump which compensates the pressure drop across the fuel cell (arrangement B). Although the pump is a parasitic power consumer, the system efficiency increases substantially when compared to the arrangement where the excess hydrogen is not circulated.

The hydrogen can also be recirculated using an ejector (arrangement C). In this device hydrogen is fed at high pressure and relative low velocity into a nozzle where it changes to a low pressure and high velocity stream. The relative low pressure attracts hydrogen to be pumped from the exit of the fuel cell stack. Momentum is exchanged between the fluids raising the pressure of the hydrogen being pumped. The mixture is then discharges and released to the entrance of the fuel cell stack. The ejector is a static device, therefore it works well only at one point of the flow spectrum.

In arrangement A the fuel cell voltage dropped slowly but continously during two purging events when the exit valve remained closed. Whereas the voltage regenerated with each purging cycle. When the frequency of the purging events was increased the mean

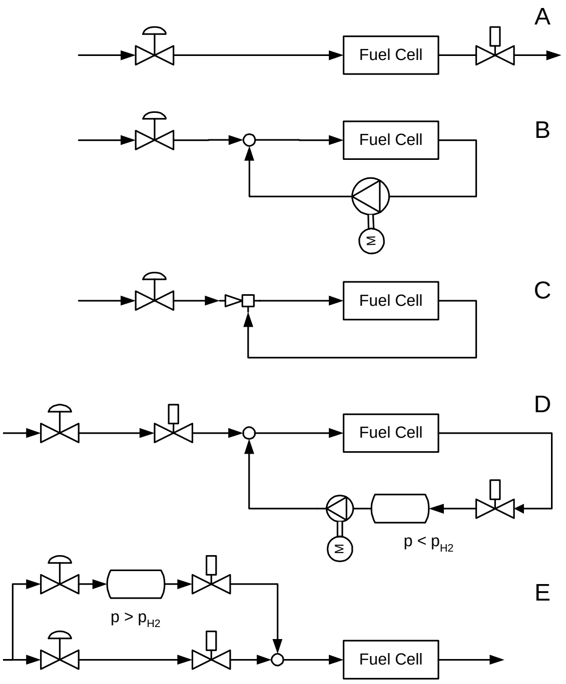

Fig. 2: Schematics of different hydrogen supply systems

voltage also increased. At high frequencies the voltage could almost be stabilized at levels similar to arrangement B where the fuel cell was operated with excess hydrogen. Of course the increase of the purging frequency resulted in an increase of the amount of hydrogen that was wasted to the environment.

The positive effect of the purging cannot be explained solely by the removal of inert gases from the system. Because of the pressure difference between both sides of the valve and because of the fast opening of the valve a shock wave is generated. This wave moves through the service channel and the fuel cell flow field at high speed. Thereby any water droplets that may have formed inside the fuel cell are dispersed. The wave is followed by a temporary increase in flow velocity. Consequently, the liquid water particles are blown out from the fuel cell, allowing for the delivery of additional hydrogen and thus preventing the reactant starvation of part of the fuel cell.

Further the diffusion layer which situated between the flow channel and the membrane electrode assembly is dynamically inflected by the pressure wave. These recurring expansions and contractions support the removal of unwanted liquid fluid from the membrane electrode assembly and the supply of hydrogen to the same. Also, blankets of inert gases (such as accumulated nitrogen) that may have formed in the flow field and/ or the diffusion layer and thus impeding the supply of hydrogen to the membrane electrode assembly are carried away.

Arrangement D shows a system that is able to generate these pressure waves without wasting any hydrogen to the environment. Using a small pump low pressure (relative to the operating pressure of the fuel cell) is created inside a vessel. Between the fuel cell stack and the low pressure vessel a magnetic valve is installed. The pressure drop across this valve is similar to the pressure drop across the purging valve. Therefore, using the pump near-atmospheric conditions are created inside the vessel and the same effect as purging to the environment is achieved. The parasitic power loss by the pump is 5 to 10 times lower than the pump used in arrangement B.

The idea to use pressure waves to clear the flow field from any water-droplets can be enhanced even further. In arrangement D the pressure waves resulted in a difference in pressure between the fuel cell and the vessel, whereas the operating pressure of the fuel cell is higher than the one inside the vessel. Another possibility is to have a vessel where the pressure is higher than the operating pressure of the fuel cell (arrangement E). As the relative pressure difference is the same, the effect of the pressure wave is approximately the same as well. When using a high pressure hydrogen storage the pressure elevation is of course easily achieved.

With the pressure wave originating from the low pressure vessel water-droplets are pulled out, whereas the arrangement with the high pressure vessel the droplets are pushed out. A logical next step is the combination of both systems to maximizes the effect.

3.2 Analysis of final arrangement

Figure 3 shows the arrangement of the hydrogen supply that was realized on the test bench. Hydrogen is fed to the fuel cell using a variety of different paths. These paths will be discussed below.

The hydrogen is stored in two high pressure tanks, each with a volume of 50 liters. The tanks are separated from the rest of the system by a safety valve. A pressure reduction valve follows, where the pressure is reduced from a maximum value of 200 bar_a to 8 bar_a. This relative high pressure at the exit of the reduction valve is needed to guarantee a proper functioning of the subsequent ejector. Ahead of the ejector the control valve A is installed in the main hydrogen stream. This valve controls the pressure at the entrance to the fuel cell stack using the signal from the pressure sensor 4. In the ejector the main stream is mixed with the excess hydrogen flow, which was not consumed in the fuel cell reaction.

Between the pressure reduction valve and the control valve A part of the hydrogen flow is branched off and fed to the high pressure vessel. The pressure inside this vessel is controlled by means of control valve B using the signal from pressure sensor 5. With the help

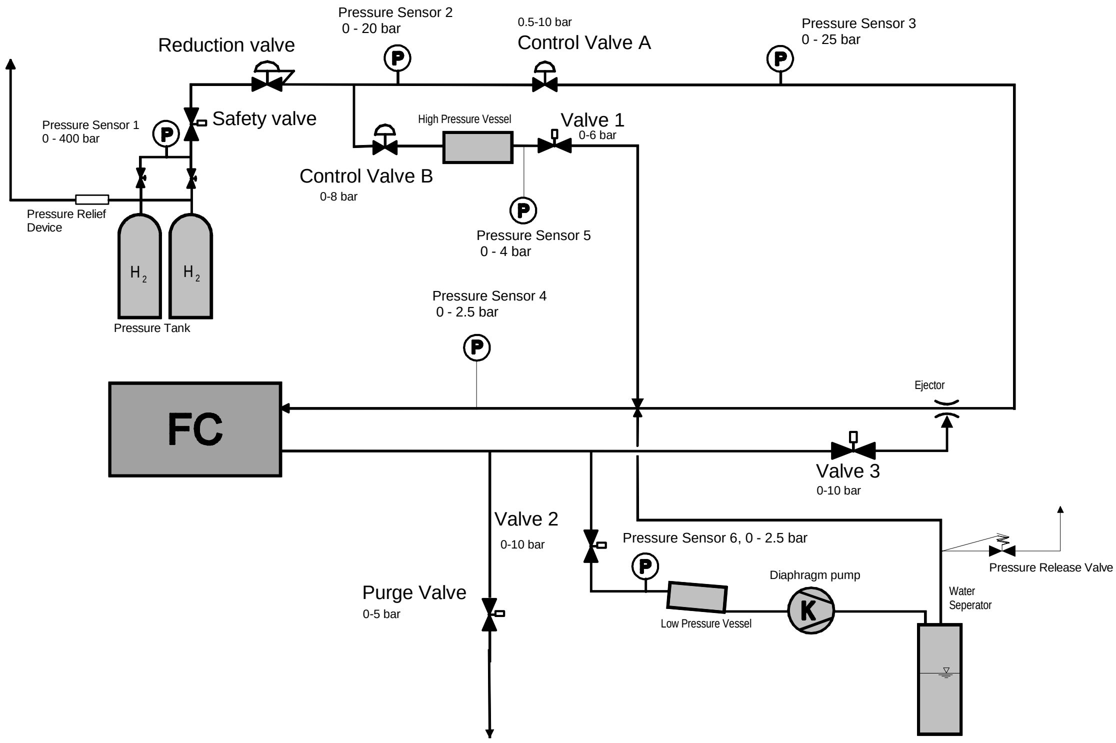

Fig. 3: Schema of hydrogen supply as realized on the test bench

from the magnetic valve 1 pressure waves are generated which are routed to the entrance of the fuel cell. This secondary hydrogen flow is combined with the main stream between the ejector and the fuel cell. Precaution has to be taken to avoid a migration of the pressure wave through the ejector. Because of the high pressure at the entrance of the ejector there is no risk that the pressure wave will migrate in that direction. Whereas the pressure wave is likely to take the recirculation path and enter the fuel cell from the exit. Since the pressure waves would collide inside the flow field and thereby jeopardize the scavenging effect, the magnetic valve 3 was installed in the recirculation path. This valve is closed (with a proper time delay) every time valve 1 is opened to block the pressure wave from travelling in the wrong direction. Otherwise valve 3 remains open.

The hydrogen flow that leaves the fuel cell at the exit of the stack is branched into three paths. The main flow being recirculated to the ejector, where the pressure is raised again to the level of the fuel cell entrance. In the second branch hydrogen is released periodically to the low pressure vessel. A diaphragm pump is used to create a low pressure inside this vessel. The pump discharges to the hydrogen feed between the ejector and the stack entrance. Similar to the high pressure vessel branch, the magnetic valve 2 is used to generate pressure waves. In this case the pressure waves are routed to the exit of the fuel cell as the pressure wave values are lower than the operating pressure of the fuel cell. Again valve 3 is used to prevent the migration of the pressure waves in the wrong direction. Further, a third branch with a purging valve is installed allowing the removal of inert gases which inevitable accumulate inside the system. The operation of this purging valve is managed by open-loop control every 30 minutes.

Consequently the hydrogen system described above consists of five different “supply routes”. The straightforward path from the pressurized storage tanks is assisted by a recirculation path using an ejector. Further, two pressure wave generators are installed, which differ in the sign of the pressure difference. Finally a purge valve enables the removal of inert gases.

Figure 4 shows measurements conducted on the test bench. The upper plot illustrates the progression of the hydrogen system pressure. The dashed line indicates the setpoint, the solid line the measurement. The fuel cell voltage is given in the lower plot, normalized with the initial value. The pressure setpoint is programmed to follow the instantaneous value of the pressure on the air side. As a consequence the setpoint is not a fixed value but an image of the oscillating air pressure. The actual pressure is characterized by a repeating sequence of two spikes. The first spike with a positive value is closely followed by a second spike with a negative value. After the second spike the pressure slowly climbs again to the vicinity of the setpoint. These two spikes represent the pressure waves mentioned above. The timing of the pressure waves

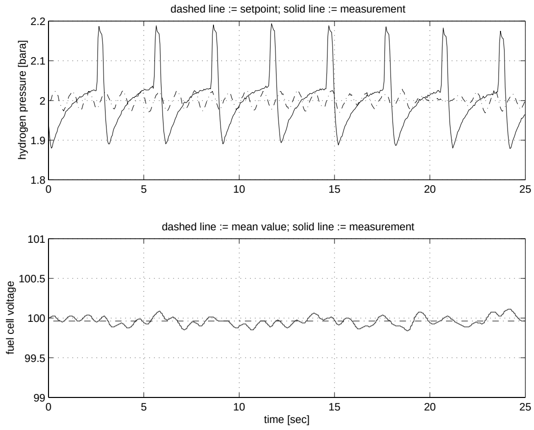

Fig. 4: Measurements of hydrogen system pressure and fuel cell voltage

was chosen to maximizes the scavenging effect. First a wall of fresh hydrogen is pushed into the fuel cell by the first pressure wave and than is subsequently pulled out at the other side by the second wave, thereby removing any water droplets and/ or inert gas pockets. The voltage plots demonstrates that a stable operation with only very small deviation from the mean value is achieved. Measurements over a longer time period verify this.

3.3 Measurements

Polarization curves in Figure 5 show the performance of different arrangements. The measuring points denote the mean value taken from a time span of 15 sec after the system had settled down. Both the current as well as the voltage are normalized by the respective maximum value. As a reference the fuel cell stack was run on a static test bench where the fuel cell was operated under optimal conditions. The operating temperature was 70°C, the humidity at the anode (hydrogen-side) 50%, respectively 70% at the cathode (air-side), the excess flow was 100% on both sides and the system pressure was 2 bar_a. The results are shown in Figure 5 by the solid line.

The crosses denote measurements done with arrangement A. As can be seen clearly the performance is very poor. The polarization curve has a stepper gradient and the maximum power falls short 50% of the result from the static test. Measurements with arrangement B are represented by diamonds. The results have increased substantially from arrangement A but are still well below the static test bench. In contrast, with arrangement E (denoted by the circles) very good performance was achieved. At some point even the results from the static test bench could be topped. Unfortunately due to the limitations of the electric load the whole power range of the fuel cell could not be measured, but there are no indication of a drop off in power at higher currents.

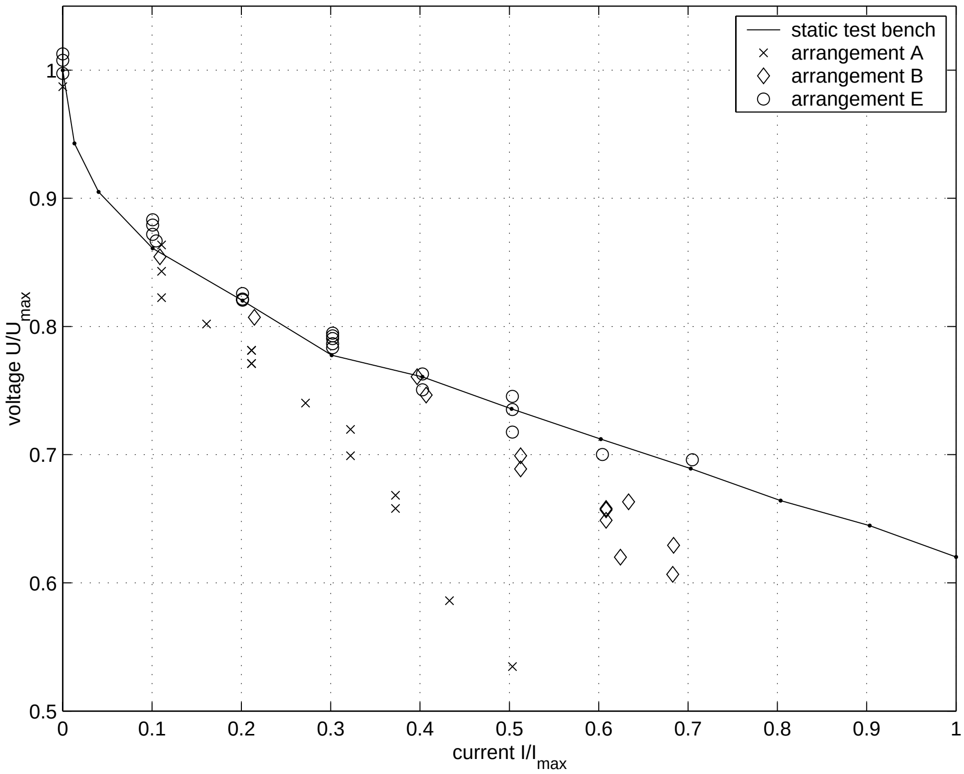

Fig. 5: Polarization curves of the different arrangements

4. CONCLUSION

In contrast to static fuel cell systems, fuel cells in mobile application are operated under transient conditions. Therefore, it is very difficult to obtain a satisfactory humidification of the membrane. Under these circumstances, a device by which excess water is removed from the fuel cell is highly desirable. Two pressure waves are used to clear the hydrogen side of the fuel cell from water droplets. Compared to conventional dead-end systems a substantial increase in system efficiency is achieved with the described hydrogen supply arrangement. In addition experiments show good long-term stability of the arrangement.

Water droplets that are formed on the air side are more easily removed from the fuel cell because of the much larger mass flow. Therefore the need for additional devices is less urgent. However, it is assumed that pulses will assist the removal of water droplets and/or nitrogen blankets. Hence further research will focus on the expected gains of the scavenging effect on the air side of the fuel cell.

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