Recording of characteristic curves of a PEM fuel cell stack

Aims of the experiment

- To produce electrical energy from hydrogen using PEM fuel cells
- To construct a fuel cell stack
- To compare parallel and series connections of fuel cells
- To record characteristic curves of voltage for a fuel cell stack
- To record characteristic curves of power for a fuel cell stack

Principles

A PEM fuel cell converts the chemical energy in hydrogen directly into electrical energy. In contrast to a battery, fuel is continuously supplied to it and reaction products continuously removed from it. Fuel cells are therefore suitable for applications in which more power is accessed over a longer period of time.

In the PEM fuel cell, hydrogen and oxygen react with the release of energy to produce water. The reaction takes place on a catalyst. The construction of such a fuel cell is illustrated in Fig. 1. PEM fuel cells have electrodes made from catalytically active noble metals. Here, the gases arriving as molecules are initially split into atoms. Each hydrogen atom releases one electron (e^-) that can flow through an external electrical circuit and provide electrical energy.

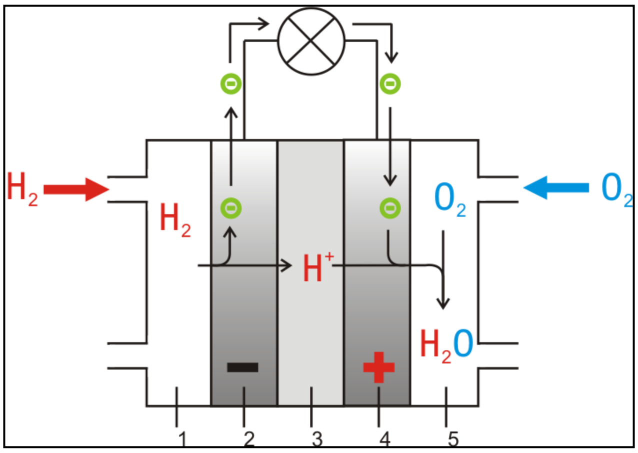

Fig. 1: Model of a fuel cell. 1 – H_2 chamber, 2 – Anode with catalyst, 3 – PEM (proton exchange membrane), 4 – Cathode with catalyst, 5 – O_2 chamber.

The resulting protons (H^+) travel through a membrane. For this, a proton exchange membrane (PEM) is used, which gives the fuel cell its name. It consists of Nafion, a sulfonated polymer similar to Teflon which in a wet condition is permeable only to protons. At the same time, this membrane serves as an electrolyte.

On the oxygen side, molecular oxygen is split into atomic oxygen on the same catalyst. The electrons moving though the electrical circuit together with the protons passing through the membrane produce water. The reaction equations are:

H_2 side (anode)	H_2	→	$2\ H^+ + 2\ e^-$
O_2 side (cathode)	$O_2 + 4\ H^+ + 4\ e^-$	→	H_2O
Overall reaction	$2\ H_2 + O_2$	→	$2\ H_2O$

The fuel cells used here are supplied with oxygen from the air. The small amounts of water produced evaporate on the surface. 1 L of hydrogen produces 0.75 mL of water.

The achievable voltage of a fuel cell can be calculated with the help of the standard potential. For the reaction of hydrogen with oxygen, this is about 1.23 V. However, real fuel cells rarely achieve a no-load voltage greater than 1.0 V. This is caused by the internal resistance or an inadequate supply of hydrogen to the electrodes. The voltage is independent of the size of the fuel cell, as it depends only on the hydrogen used as a fuel. However, the size of the fuel cell is decisive for the amount of current, i.e. the number of electrons that can be produced per unit of time.

If higher voltages are needed, then it is recommended to connect several fuel cells together. With the fuel cell stack used here, parallel and series connections can be tried out. Characteristic curves will be recorded in the investigation.

The characteristic curve of voltage indicates the voltage that the fuel cell can maintain when a defined amount of current is drawn. The defined current will be set using variable resistors. These convert the current into heat. The characteristic curve of power is also current-dependent. Here, the power of the fuel cell, that is the product of voltage and current, is plotted against the current. A fuel cell should be operated at close to its maximum power, if possible. To achieve this, the current drawn is regulated.

It is necessary to have a sufficient amount of hydrogen available when recording characteristic curves. Very little hydrogen is consumed at low current levels. The higher the current drawn, the more hydrogen is needed. At very high current levels it can happen that the voltage will fall owing insufficient hydrogen reaching the electrodes; the reaction is "starved". This would falsify the results of the characteristic curves.

In this experiment, the hydrogen is supplied from a metal hydride storage container. The hydrogen escapes from this at sufficient pressure to make measurements possible, even at very high current levels. However, even with this hydrogen source, measurement of the short-circuit current is possible only for a very short time.

In this experiment, the voltage and power characteristic curves of a fuel cell stack will be recorded. This will be connected in series and in parallel.

-2014-06

Risk assessment

When working with hydrogen, there is always the inherent risk of a detonating gas reaction. For this reason, only release hydrogen when there are no open flames in the vicinity. In the HydroStik PRO metal hydride storage container, there can only be a maximum of 10 L of hydrogen.

Hydrogen

Signal word: Hazard

Hazard statements

H220 Extremely flammable gas.

H280Contains gas under pressure; may explode if heated.

Precautionary statements

P210Keep away from heat/sparks/open flames/hot surfaces. No smoking.

P377Leaking gas fire: Do not extinguish unless the leak can be stopped safely.

P381Eliminate all ignition sources if safe to do so.

P403Store in a well-ventilated place.

Equipment and chemicals

1	PEM fuel cell stack, CPS	666 4812
1	HydroStik PRO, CPS	666 4795
1	Bubble counter, CPS	666 4794
1	Electric load, CPS	666 4831
1	HydroFill PRO	666 4798
1	Sensor-CASSY 2	524 013
1	CASSY Lab 2	524 220
	and 1 PC with Windows XP/Vista/7/8	
1	CASSY-Display USB	524 020USB
1	Connecting leads 19 A, 25 cm, pair	501 44
1	Connecting leads 19 A, 50 cm, pair	501 45
1	Panel frame C50, two-level, for CPS	666 425
1	Silicone tube 2 mm diam., 1 m	667 198
2	Blank panel 100 mm, CPS	666 464
1	Water, pure, 1L	675 3400

Set-up and preparation of the experiment

The hydrogen source

The hydrogen will be taken from a HydroStik PRO metal hydride storage cartridge. This will be filled from the HydroFill PRO electrolyser.

1. Open the cover of the water tank and carefully pour in distilled or deionised water up to the inner ridge. Close the cover.

2. Connect the AC-DC adaptor and plug it into an AC mains socket. The status indicator will now flash green.

3. Screw the HydroStik PRO into the HydroFill PRO. The status indicator changes from green to red to show that the connection has been made. Firmly screw in the HydroStik PRO.

4. The HydroStik PRO is filled automatically, which is shown by the red status indicator. Charging takes about 4 to 6 hours. An occasional hissing sound indicates that the system is rinsing. The oxygen produced can be seen in the form of bubbles.

5. When the status indicator changes to green, the HydroStik PRO is fully charged and can be removed. A brief hissing sound will occur at this time.

6. A further HydroStik PRO can now be charged. For this, repeat the instructions from step 3.

7. When charging is complete, disconnect the HydroFill PRO from the mains socket and empty the water tank.

The experimental set-up

1. Suspend the CPS module in the C50 panel frame as shown in Fig. 2.

2. Fill the bubble counters on the CPS module "Bubble Counter" with distilled or deionised water until about 5 mm of the inner tube is under water.

3. Connect the regulating valve of the CPS module "HydroStik PRO" to the upper bubble counter using a piece of tubing. Ensure that the HydroStik PRO is connected to the inner tube.

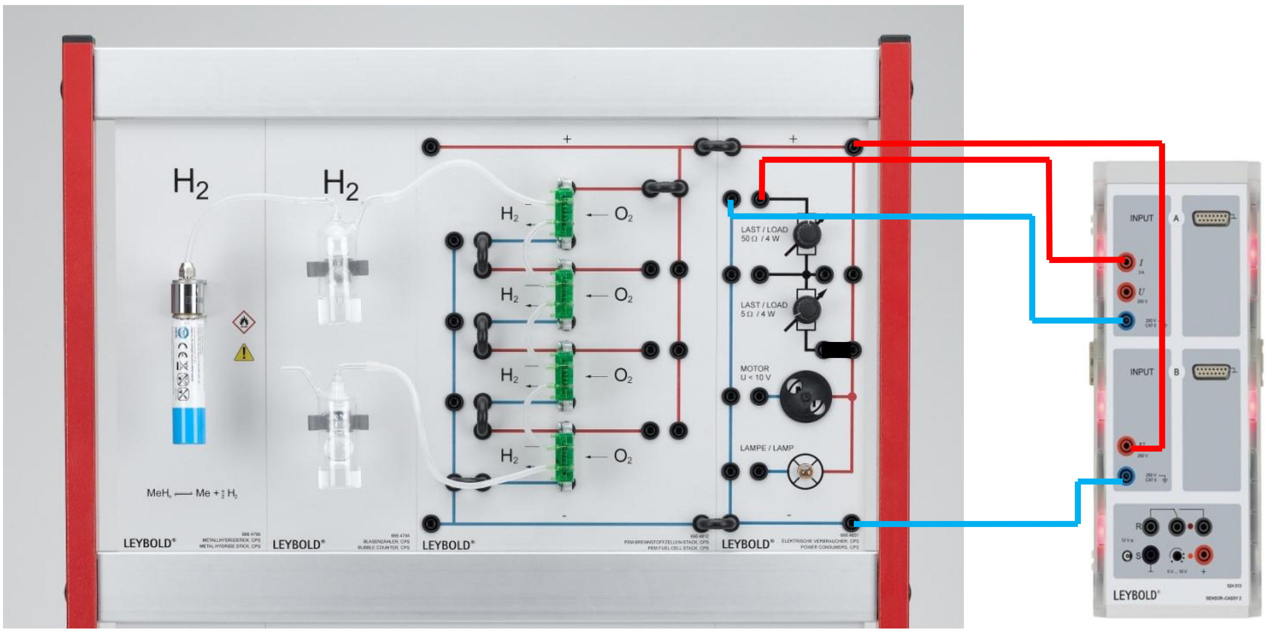

Fig. 2: Experimental set-up for investigation of the fuel cell stack. The fuel cells are connected in series. Blue and red lines: Connections from the CPS module "Electric Load" to the Sensor-CASSY 2 using connecting leads. In this example, the variable load is connected.

4. Construct the CPS module "PEM fuel cell stack" as described in the instructions for use. For this:

   a. Insert the fuel cells into the CPS board. Connect the individual fuel cells with one another using short pieces of tubing. All tubes, and therefore the hydrogen side, are located on the left.

   b. Wet the fuel cells with distilled water. To do this, connect a further piece of tubing to the lower fuel cell. Using a syringe, inject water into the fuel cells until it drips out of the uppermost fuel cell. Remove the syringe and allow the water to run out again.

5. Now connect the lowermost fuel cell with the lower bubble counter. Also here, ensure that the tubing is connected to the inner tube.

6. Connect the fuel cell stack with the CPS module "Electric Load" using bridge connectors.

7. On the CPS module "Electric Load", connect the variable load (resistors, potentiometer) into the circuit. As shown in Fig.2, connect the positive lead (red) to the lower output of the potentiometers using a bridge connector.

8. Connect the whole construction to a Sensor-CASSY 2 or another measuring instrument.

   a. To measure voltage, connect the electric load with Input B of the Sensor-CASSY 2 using connecting leads, as shown in Fig. 2.

   b. To measure current, connect the variable resistor to Input A of the Sensor-CASSY 2, as shown in Fig. 2.

Note: The Sensor-CASSY 2 can now be connected via a USB cable to a computer running the Software CASSY Lab 2. Alternatively, a CASSY-Display can be used, which makes it possible to work without a computer and Sensor-CASSY 2.

Performing the experiment

In Experiment C4.4.7.2, characteristic curves of a fuel cell stack will be recorded. For this, the individual fuel cells will first be connected in series and then in parallel.

1. Connect the individual fuel cells of the fuel cell stack in series (see Fig. 3, left).

2. Screw the charged HydroStik PRO into the regulating valve of the CPS module "HydroStik PRO" until bubbles of hydrogen can be distinctly seen in the bubble counter.

3. First measure and note the no-load voltage. The load must not be connected for this.

4. Set the variable resistor to maximum resistance (smallest current) by turning the control knobs in a clockwise direction as far as the end stop.

5. Connect the load and note the current and voltage values.

6. Now reduce the resistance with the upper control knob until a current of 100 mA flows. Note the values.

Note: Make sure that there is a continuous supply of hydrogen. This can be recognised by the fact that bubbles are also visible in the second bubble counter.

7. Increase the current further and record the values every 100 mA.

8. Measurement of the short-circuit voltage is made without the resistors. For this, join the middle connector sockets using bridge connectors. Alternatively, insert the red and the blue cables into one another.

The short circuit will damage the fuel cells over a longer period, therefore run them in short-circuit operation only briefly.

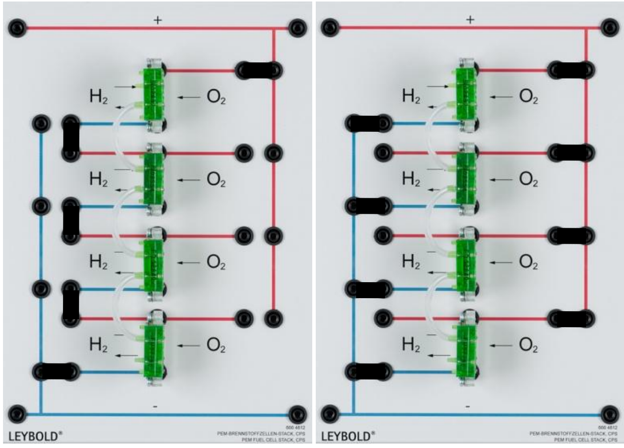

Fig. 3: Left: series connection, right: parallel connection.

9. Repeat the experiment. This time, connect the fuel cells in parallel (see Fig. 3, right).

10. For the voltage characteristic curve, plot the voltage against the current.

11. For the power characteristic curve, calculate the power P from the voltage U and the current I using

$$P = U \cdot I$$

and also plot it against the current.

Result of the experiment

Measured values for the experiment with series connection

Current [A]	Voltage [V]	Power [W]
0	3.62	0
0.04	2.85	0.11
0.10	2.72	0.27
0.21	2.18	0.45
0.30	1.66	0.50
0.41	1.29	0.52
0.50	0.94	0.47
0.61	0.59	0.36
0.70	0.36	0.25
0.75	0.16	0.12

Measured values for the experiment with parallel connection

Current [A]	Voltage [V]	Power [W]
0	0.86	0
0.02	0.81	0.01
0.10	0.74	0.07
0.20	0.70	0.14
0.30	0.68	0.20
0.40	0.66	0.27
0.50	0.64	0.32
0.61	0.62	0.37
0.70	0.60	0.42
0.80	0.58	0.46
0.90	0.56	0.50
1.01	0.54	0.54
1.10	0.51	0.56
1.21	0.51	0.61
1.30	0.5	0.64
1.43	0.47	0.66
1.51	0.45	0.68
1.79	0.38	0.67

Evaluation of the experiment

If no load is connected (no-load voltage), the fuel cell stack will achieve considerably higher voltages when connected in series than when connected in parallel. When connected in series the voltages are added, but not when connected in parallel.

Voltage characteristic curves

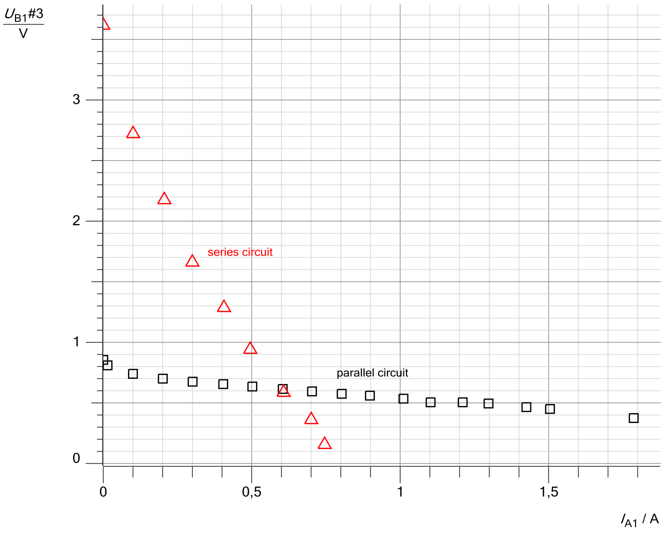

Fig. 4: Voltage characteristic curves for the fuel cell stack connected in series (red) and in parallel (black).

The higher the current, the more the voltage falls. This can be observed with both connections. However, the voltage with the series connection falls considerably quicker and the maximum achievable current is 0.75 A. With the parallel connection, the voltage remains relatively constant over a wide range. Current values of up to 1.8 A are achieved.

Power characteristic curves

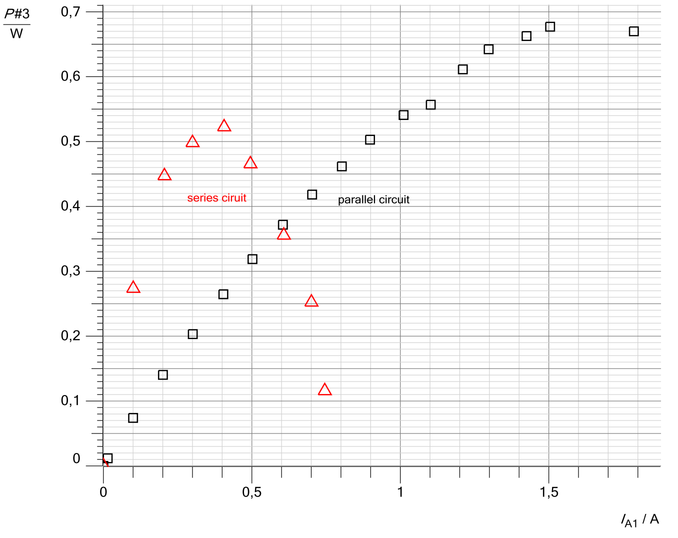

Fig. 5: Power characteristic curves for the fuel cell stack connected in series (red) and in parallel (black).

The power characteristic curves increase with increasing current and pass through a maximum. After this, a considerable fall in power occurs. The power maximum with the series connection is 0.52 W (at 0.41 A). With the parallel connection, the power maximum is 0.86 W (1.51 A).

Comparison of series and parallel connections

The series connection shows a high no-load voltage. However, there is no power behind this. With the parallel connection, however, considerably more power can be extracted, although at a lower voltage.

In applications using fuel cells, a combination of both connection versions is usually chosen. In this way, high voltages and high power levels can be achieved. However, one problem that remains is the supply of hydrogen. This is solved in professional fuel cell stacks using channels rather than tubes.

Cleaning and disposal

Once used, the fuel cells should be stored in a moist condition if possible. For this, connect both hydrogen inputs together using a short piece of tubing and store all fuel cells in a water-tight bag.

Unscrew the HydroStik PRO from the valve for storage. It is then sealed and no hydrogen can escape.

Remarks

If the fuel cells lose their power, there can be two reasons for this:

If the cells are too wet, the hydrogen can no longer reach the catalytically active electrode in sufficient quantities. Therefore the power falls drastically. In this case blow out the cells with air (from a syringe) or with hydrogen from the HydroStik PRO.

If the cells are too dry, the PEM will not function perfectly. The proton-conducting property is only present when the membrane is wet. It can help in this case to wet the cells again.