POLITECHNIKA GDAŃSKA
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RENEWABLE ENERGY SOURCES LABORATORY

Department of Chemical Apparatus and Theory of Machines

Faculty of Chemistry, Gdańsk University of Technology

LABORATORY INSTRUCTION NO. 2-OP

ELECTROLYSER AND FUEL CELLS STUDY

Purpose & range of the exercise

The exercise aims to familiarize students with the following topics:

- Measuring current-voltage characteristic of an electrolyser.
- Faraday's first and second law for an electrolyser.
- Measuring current-voltage characteristic of a fuel cell.
- Faraday's first law for a fuel cell.
- Assessing Faraday's efficiency and energy efficiency for an electrolyser and a fuel cell.
- Assessing working parameters for fuel cells in series and parallel connection.

1. Scope of exercise

Fuel cell consists of two electrodes – anode and cathode, bisected by the thin layer of electrolyte. Fuel cell type is defined by the kind of electrolyte used. According to the information presented in Table 1, various types of fuel cells significantly differ from each other in terms of temperature, working conditions and efficiency.

Table 1. Fuel cell types and their parameters [on the basis of: 1, 2]

Fuel cell type	**Proton exchange membrane fuel cell (PEMFC)**	**Alkaline fuel cell (AFC)**	**Phosphoric acid fuel cell (PAFC)**	**Molten carbonate fuell cell (MCFC)**	**Solid oxide fuel cell (SOFC)**
Electrolyte	Polymer electrolyte	Potassium hydroxide solution (KOH)	Concentrated phosphoric acid (H_3PO_4)	Mixture of alkali metal carbonates (Li, K, Na)	Non-porous solid metal oxide, usually yttrium stabilized (Y_2O_3) zirconium oxide (ZrO_2)
Charge carrier	Oxygen ions	Carbonate ions	Hydrogen ions	Hydroxide ions	Hydrogen ions
Fuel	Hydrogen	Hydrogen, hydrazine N_2H_4, methane	Pure hydrogen, natural gas, methanol, biogas, fuel subjected to external reforming	Natural gas, methanol, biogas, fuel subjected to internal or external reforming	Natural gas, biogas, fuel subjected to internal or external reforming
Catalyst	Platinum	Platinum	Platinum	Nickel	Non-noble metals
Operating temperature	Room temperature to 80°C	Room temperature to 90°C	160 – 220°C	620 – 660°C	800 – 1000°C
Efficiency	40 – 60 %	60 – 70 %	55 %	65 %	60 – 65 %
Existing installations power	do 250 kW	5 – 100 kW	do 10 MW	50 kW – 3 MW	1 – 250 kW
Application	Transport, UPS, portable power supplies	Portable power supplies, transport, cosmic and military installations	Distributed generation, co-generation	Distributed generation, co-generation	Distributed generation, co-generation
Advantages	Low operating temperature, short start-up time, high energy density, no corrosive materials	High energy density	High efficiency in co-generation	High temperature enabling operating in co-generation	High temperature enabling operating in co-generation
Disadvantages	Expensive catalyst	Expensive catalyst, sensitive to CO and CO_2	Expensive catalyst, highly corrosive electrolyte	Highly corrosive electrolyte	Long start-up time

Figure 1 presents main components of a fuel cell and depending on its type – gases appearing on anode and cathode. Gases are transported from electrodes through the channels mounted on a fuel board. Once gasses are combined (for example hydrogen with oxygen in PEMFC), electric energy, heat and water are generated.

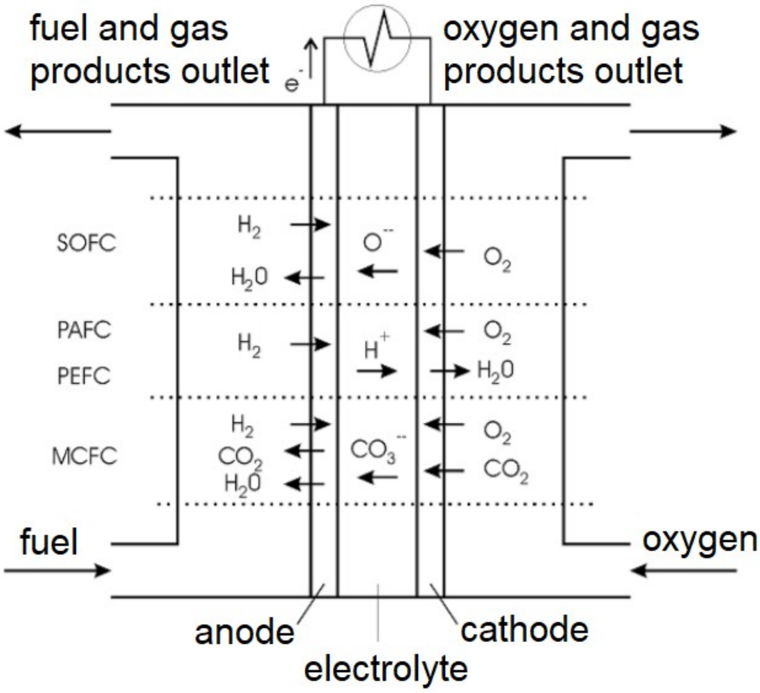

Fig. 1. Fuel cell and its reaction gases [3]

The general principle of fuel cell operation is described following the example of PEMFC, whose products are hydrogen and oxygen.

Hydrogen necessary to power fuel cell is obtained as a product of water electrolysis. At the moment of applying external voltage water molecules oxidase on the anode to oxygen particles and protons, and electrons are released. Next protons pass through polymer membrane in the cathode direction, whereas electrons flow in the power source. Hydrogen ions bond with electrons on the cathode surface, which produces hydrogen.

Reaction occurring on the anode are described by (1) equation and on the cathode – equation (2) [2].

$$2H_2(g) \rightarrow 4H^+ + 4e^+ \quad (1)$$

$$O_2(g) + 4H^+ + 4e^+ \rightarrow 2H_2O \quad (2)$$

As can be deduced from above mentioned reactions, gaseous oxygen is produced on the anode, and gaseous hydrogen on the cathode.

The overview of each reaction and ion transport in electrolyte is presented In the Figure 2. It is worth noting the hydrogen ions are not the only charge carriers, as for high temperature fuel cells, namely SOFC and MCFC, they are oxygen and carbonate ions respectively.

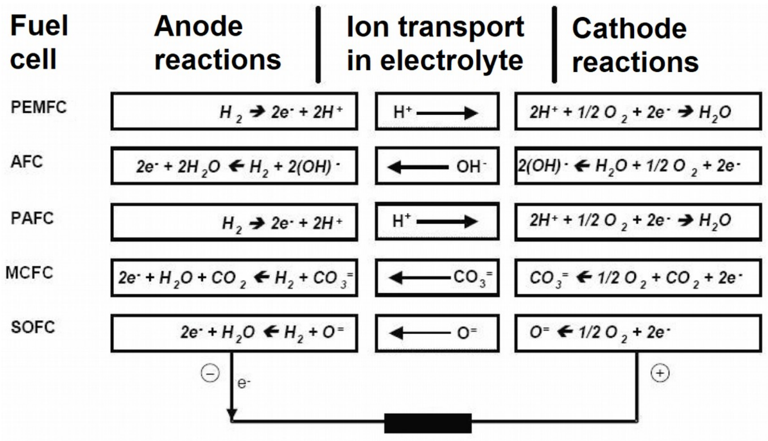

Fig. 2. Electric scheme of a fuel cell, reactions occurring on it's electrodes and ion transport in electrolyte [1]

Direct Carbon Fuel Cells

The basic structure of fuel cells directly supplied by carbon is identical to other fuel cell types described in this chapter. The only difference is such, that instead of using gas stream or liquid fuel, anode is powered by solid fuel, which reacts and creates gaseous product. In order for this fuel cell to work at maximum efficiency the reaction has to happen according to equation:

$$C + O_2 \rightarrow CO_2 \tag{3}$$

where half reactions are as follows:
on the cathode:

$$C + O_2 \rightarrow CO_2 \tag{4}$$

on the anode:

$$2O^{2-} + C \rightarrow CO_2 + 4e^- \tag{5}$$

The key DCFC features, in contrast to other fuel cells and energy generation technologies, are:
– working in high temperatures (500 – 900°C) and converting chemical energy from solid carbon directly to electric energy by the means of a direct electrochemical oxidation,

– fuel consumption may reach almost 100%, since supplying gas and gas products are distinct phases, and as such can be easily separated,

– theoretical efficiency is high, almost 100%,

– pure CO_2 is a byproduct and it can be directly sequenced, avoiding fines related to emissions,

– solid fuel power system may be more complex in comparison to gas or liquid fueled power systems.

Faraday's first law of electrolysis

The mass of substance deposited on the electrode during electrolysis is proportional to the quantity of electricity, which flows though electrolyte in accordance to the formula:

$$m = k \cdot I \cdot t \tag{6}$$

where chemical equivalent is:

$$k = \frac{M}{n \cdot F} \tag{7}$$

m – mass deposited on the electrode [g],
I – current flow during electrolysis [A],
t – electrolysis time [s],
M – molar mass of released ion [g/mole],
n – number of electrons exchanged during electrolysis,
F – Faraday's constant [C/mole].

2. Description of the experimental station

Laboratory station consists of following elements (Figure 3): two fuel cells (1, 2), electrolyser (3), ammeter (4), voltmeter (5), 120 W incandescent light (6), solar module (7), serial resistor with adjusting know (8), small light bulb (9), electric engine with propeller (10), laboratory cables (11), plastic wash bottle with distilled water (12), timer (13), connecting hose with clamps (14). Technical data for solar module, electrolyser, fuel cell and resistor are given in Table 2.

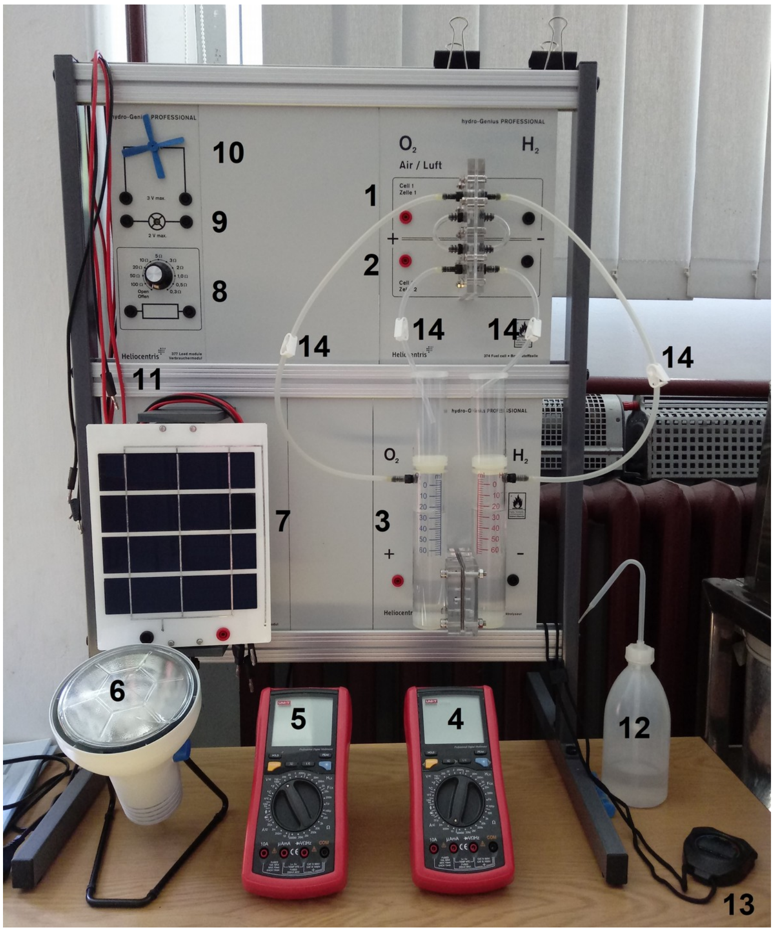

Fig. 3. Laboratory station for fuel cell measurements

Table 2. Technical data of each laboratory station element

Solar module (STC)	
Width x height x depth	200 mm x 297 mm x 100 mm
Open circuit voltage	2,2 V
Short circuit current	1200 mA
Maximum power point voltage	1,8 V
Maximum power point current	1000 mA
Maximum power point power	1,8 W
Electrolyser	
Width x height x depth	200 mm x 310 mm x 110 mm
Membrane area	25 cm^2
Hydrogen peroxide usage	1 ml/3 h for electrolysis current 1000 mA
Water quantity transported from oxygen part to hydrogen part	2 ml/3 h for electrolysis current 1000 mA

Electrolyser	
Continuous work voltage	1,4 – 1,8 V
Short-term peak load voltage	2,0 V
Current	0 – 400 mA
Hydrogen production	Maximum 28 ml/min
Fuel cell	
Width x height x depth	200 mm x 297 mm x 90 mm
Membrane area	2 x 10 cm^2
Voltage in series connection	0,8 – 2,0 V
Voltage in parallel connection	0,4 – 1,0 V
Current in parallel connection	Maximum 4000 mA
Hydrogen usage	Maksimum 28 ml/min at current 4000 mA
Resistor	
Width x height x depth	200 mm x 297 mm x 100 mm
Engine operation voltage	0,2 – 3 V
Engine current	10 – 50 mA
Incandescent lamp voltage	1,5 – 3 V
Possible resistance settings	0,3 / 0,5 / 1 / 2 / 3 / 5 / 10 / 20 / 50 / 100 Ω
Maximum load for the resistor	0,3 Ω: 4 W 0,5 – 1 Ω: 2,5 W 2 – 5 Ω: 1 W 10 – 20 Ω: 0,5 W 50 – 100 Ω: 0,2 W

Attention: electrolyser current should not exceed 4 A, and voltage 2 V DC. Otherwise electrolyser could be damaged.

The correct current source connection should be noted, meaning linking a positive current source connection to a positive electrolyser connection, as well as negative current source connection to a negative electrolyser connection. A fuel cell should work with its maximum power around 10 minutes after launching electrolyser.

Attention: hydrogen and oxygen form an explosive mixture, so each exercise ought to be carried out step by step, according to this instruction.
In case of doubts consult the teacher.

Set of experiments for the study:

A. Plotting current-voltage characteristic, calculating Faraday's first and second law and comparing energy efficiency to Faraday's efficiency for an electrolyser.

B. Plotting current-voltage characteristic, calculating Faraday's first law and comparing energy efficiency to Faraday's efficiency for a single fuel cell.

C. Plotting current-voltage characteristic, calculating Faraday's first law and comparing energy efficiency to Faraday's efficiency for two fuel cells connected in series.

D. Plotting current-voltage characteristic, calculating Faraday's first law and comparing energy efficiency to Faraday's efficiency for two fuel cells connected in parallel.

3. The course of exercise

A. Plotting current-voltage characteristic, calculating Faraday's first and second law and comparing energy efficiency to Faraday's efficiency for an electrolyser

Electrolyser current-voltage characteristic

For the small voltage range the exercise should be carried out for the measuring system assembled according to the scheme presented in Figure 4. Distilled water level is around 0 – 20 ml on the O_2 site and 20 – 40 ml on the H_2 site. 120 W incandescent lamp may be turned on after checking all of the connections by the teacher.

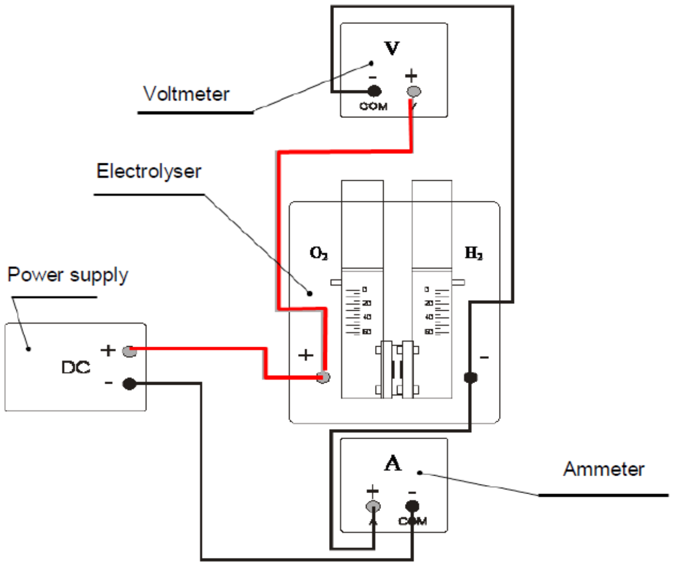

Fig. 4. Connection scheme for current-voltage measurement of electrolyser

Irradiance can be adjusted by differentiating incandescent lamp distance from solar module. Measurement should be done for different current values, starting from around 30 mA and steadily increasing to around 500 mA. Gather 10 voltage and current pairs of data for this range.

In the next step incandescent lamp and solar module are replaced by the power supply, allowing to generate higher currents. 10 voltage and current pairs of data are to be noted, for current values above 500 mA and below 3 A. Afterwards, the measuring unit should be turned off.

Ultimately, at least 20 current and voltage measurements should be obtained in this experiment part (Table 3). Plot current-voltage characteristic for an electrolyser and comment on the results. Specify what is the starting point of electrolysis.

Tab. 3. Data necessary for obtaining electrolyser current-voltage characteristic

Measurement	**Current [A]**	**Voltage [V]**	**Measurement**	**Current [A]**	**Voltage [V]**
1			11		
2			12		
3			13		
4			14		
5			15		
6			16		
7			17		
8			18		
9			19		
10			20		

Faraday's laws

Connect measuring system according to Figure 5. Distilled water level should reach 0 ml in both cylinders. Before experiment start secure clamp on connecting hose at the hydrogen tank site. 120 W incandescent lamp should be turned on only after checking all of the connections by the teacher.

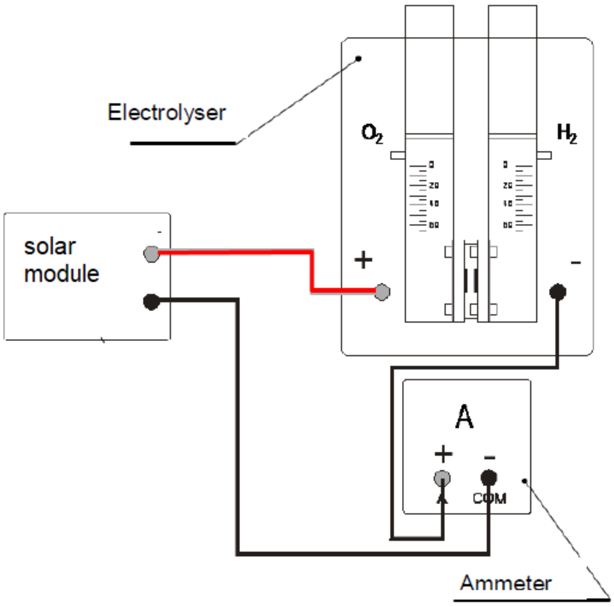

Fig. 5. Connection scheme for hydrogen generation measurement

Table 4. Measurement table for obtaining the generated hydrogen volume V_{H2} in a function of time at a constant current value

Time [s]	**Voltage [V]**	**V_{H2} [ml]**
60		
90		
120		
150		

Place solar module in such a way that it generates steady current, I=850 mA, and write down the amount of generated hydrogen for different time intervals, from 60 s to 150 s, every 30 s (Table 4). Repeat this exercise for two other current values.

Present obtained values on a graph describing relationship between generated hydrogen volume and time for constant current (Figure 6) and relationship between generated hydrogen volume and current for constant time (Figure 7). Comment on both graphs. Based on Faraday's first law study the relation between the amount of generated hydrogen and exchanged charge. Analyze Faraday's second law.

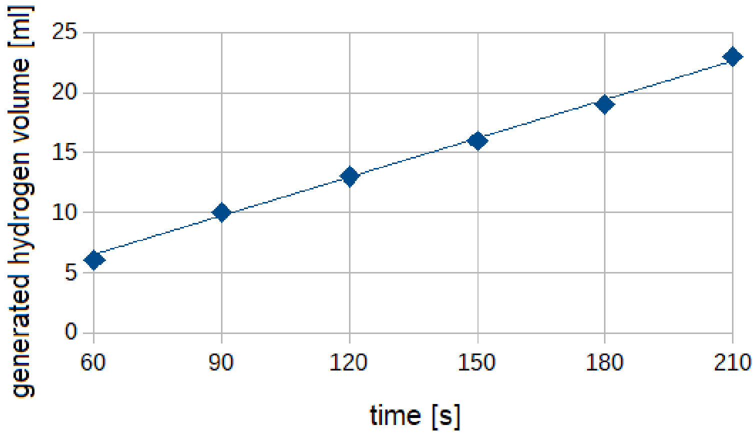

Fig. 6. Relationship between generated hydrogen and time for constant current value at 850 mA

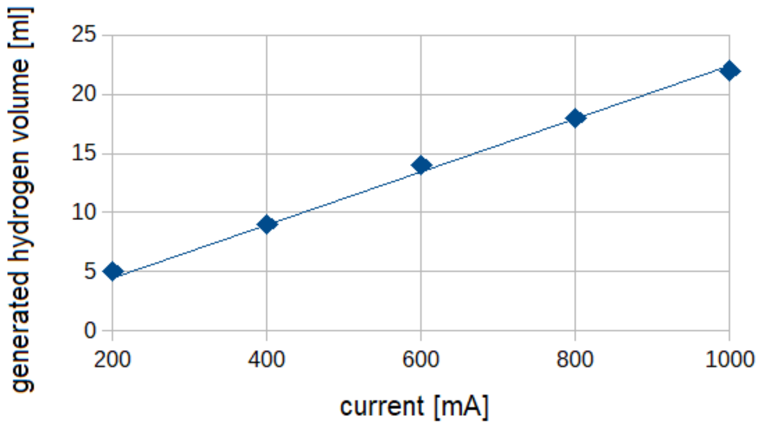

Fig. 7. Relationship between generated hydrogen and current for constant time value at 180 s

$V_{H2}(t)$ graph indicated that there is a proportional correlation between the amount of generated hydrogen and elapsed time. Additionally, $V_{H2}(I)$ graph illustrates proportional relation between the quantity of generated hydrogen and current. Therefore, the volume of produced hydrogen is proportional to the product of time and current.

On the basis of Faraday's law calculate the amount of gas that should be generated during electrolysis for each value of current and time. Compare results to volumes obtained during the experiment.

B. Plotting current-voltage characteristic, calculating Faraday's first law and comparing energy efficiency to Faraday's efficiency for two fuel cells connected in series and parallel.

Series connection

Connect measuring system according to Figure 8. Distilled water level should reach 0 ml in both cylinders. Power supply should be turned on only after checking all of the connections by the teacher.

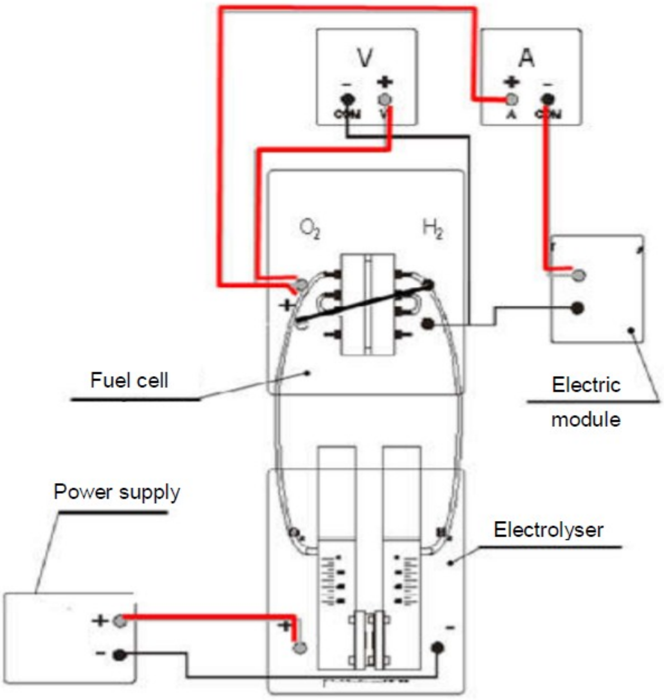

Fig. 8. Connection scheme for two fuel cells connected in series

By changing the resistance in the range from 0 Ω to 100 Ω, gather 20 current and voltage measurements (Table 5). Afterwards, the measuring unit should be turned off. Plot a current-voltage characteristic of two fuel cells connected in series and comment on it.

Table 5. Data necessary for obtaining current-voltage characteristic of two fuel cells connected in series

Measurement	**Current [A]**	**Voltage [V]**	**Measurement**	**Current [A]**	**Voltage [V]**
1			11		
2			12		
3			13		
4			14		
5			15		
6			16		
7			17		
8			18		
9			19		
10			20		

Parallel connection

Connect measuring system according to Figure 9. Distilled water level should reach 0 ml in both cylinders. Power supply should be turned on only after checking all of the connections by the teacher.

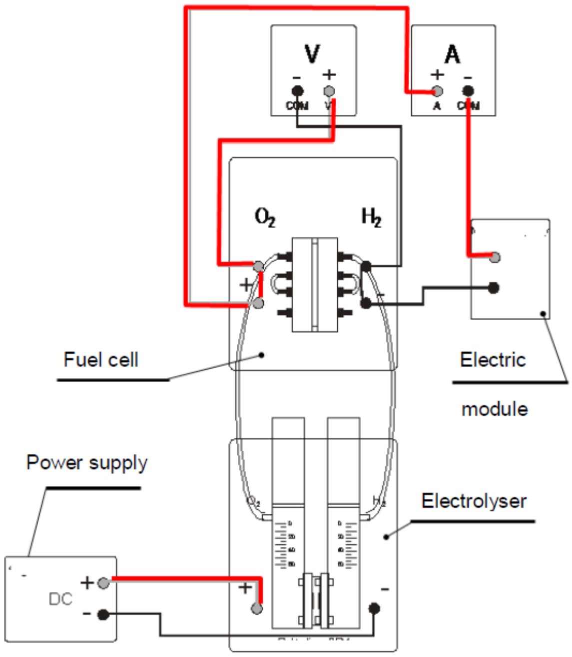

Fig. 9. Connection scheme for two fuel cells connected in parallel

By changing the resistance in the range from 0 Ω to 100 Ω, gather 20 current and voltage measurements (Table 5). Afterwards, the measuring unit should be turned off. Plot a current-voltage characteristic of two fuel cells connected in parallel and comment on it. Add additional analysis concerning differences in results for series and parallel connection.

Table 5. Data necessary for obtaining current-voltage characteristic of two fuel cells connected in parallel

Measurement	**Current [A]**	**Voltage [V]**	**Measurement**	**Current [A]**	**Voltage [V]**
1			11		
2			12		
3			13		
4			14		
5			15		
6			16		
7			17		
8			18		
9			19		
10			20		

4. Literature

[1] Józef Paska. Mariusz Kłos, Ogniwa paliwowe przyszłością wytwarzania energii elektrycznej i ciepła?, Przegląd Elektrochemiczny (Electrical Review), R. 86, Nr 8, (2010), s. 93-99.

[2] Piotr Grygiel, Henryk Sodolski, Laboratorium Konwersji Energii, Wydział Fizyki Technicznej i Matematyki Stosowanej, Politechnika Gdańska, 2014, s. 113-140.

[3] Małek A., Wendeker, Ogniwa paliwowe typu PEM. Teoria i praktyka, Wydawnictwo-Drukarnia „Liber Duo", Lublin 2010.

[4] S. Giddy et al., A comprehensive review of direct carbon fuel cell technology, Progress in Energy and Combustion Science, 38, (2012), s. 360-399.