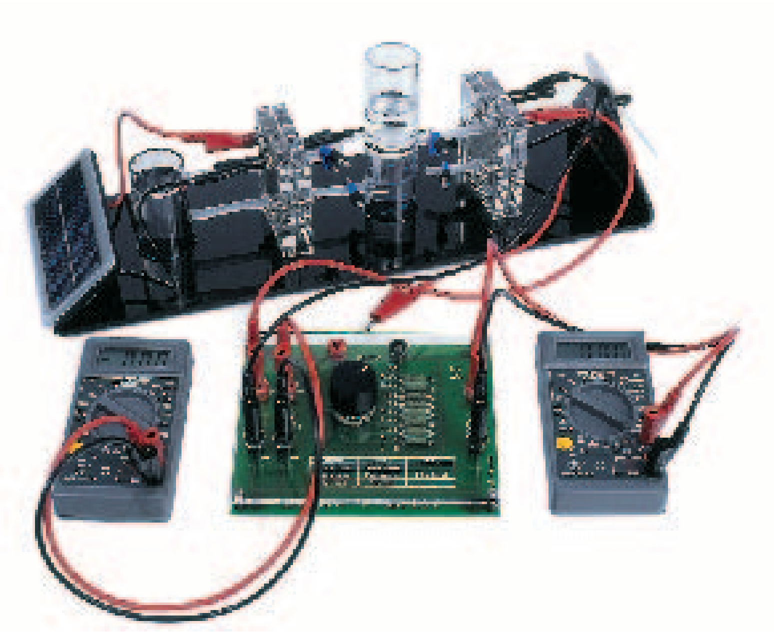
h-tec

Experiments



Fuel Cell

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1. Student Experiments

1.1. Experiments with solar modules

Several solar cells are interconnected to form modules capable of providing voltages and power outputs suitable for the different applications. Series connection produces a higher voltage and parallel a higher current.

1.1.1. Current-voltage characteristic, power curve and efficiency of solar module

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Background:

The current-voltage characteristic tells you about the power characteristic of the solar module. Together with the power curve the characteristic gives you the maximum power point (MPP).

The efficiency of the solar module indicates the proportion of incident radiant energy converted into electrical energy.

$$\text{Efficiency } \eta = \frac{Electrical\ power}{Incident\ radiant\ power} = \frac{P_{out}}{P_{in}}$$

Apparatus:

- Solar module
- A light if necessary to operate the solar module
- 2 multimeters
- Decade resistor, set with different resistors or potentiometer
- Instrument for determining the radiant power of the light:
  - **a)** An instrument for measuring this directly, e.g. a solarimeter
  - **b)** Alternative: The short-circuit current of the solar module is used to determine the radiant power.

Setup:

Connect the apparatus as shown in the following circuit diagram.

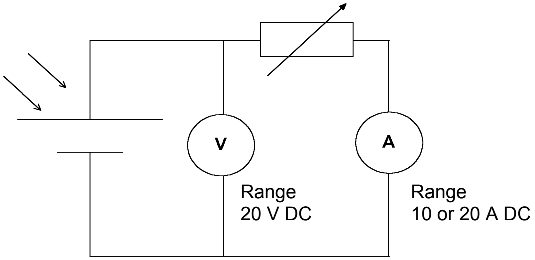

Figure 1.1.1.a: Setup for determining characteristics of a solar module

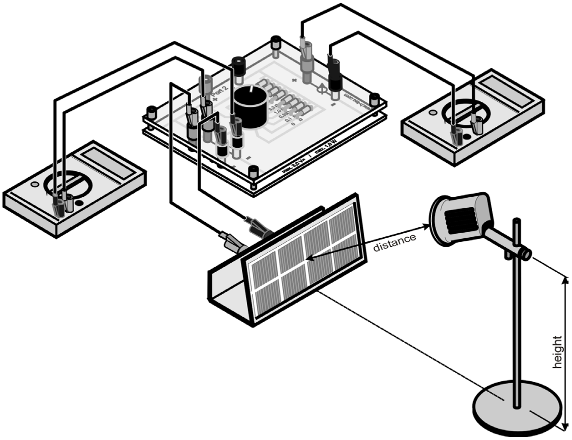

Figure 1.1.1.b: Typical setup for determining characteristics of a solar module

Method:

Set the experiment up as shown above (Figure 1.1.1.a). Direct the light straight at the solar module (angle of 90°). Then wait for 1 minute to avoid errors due to temperature fluctuations. Start recording the current-voltage characteristic with the open circuit voltage ($R = \infty$), then switch the decade resistor to smaller values. Measure voltage and current for each resistance and record them in a table. Allow about 20 seconds to elapse between each pair of measurements.

Example:

R [Ω]	V [volts]	I [A]	P [W] calculated: P=V·I
∞	***1.95***	***0.00***	***0.000***
330	***1.94***	***0.01***	***0.019***
100	***1.93***	***0.02***	***0.039***
33	***1.91***	***0.05***	***0.096***
10	***1.83***	***0.17***	***0.311***
3.3	***0.71***	***0.18***	***0.128***
1	***0.22***	***0.18***	***0.040***
0.33	***0.17***	***0.18***	***0.031***
0.1	***0.04***	***0.18***	***0.007***
0	***0.02***	***0.18***	***0.004***

Figure 1.1.1.c: Table of measurements
Voltage and current measured for each value of resistance (using the h-tec Junior (polycrystalline silicon) Solar Module and 75 W light 50 cm away)

Evaluation:

Plot a graph of the measurements in the table to show how the photoelectric current depends on the photoelectric voltage.

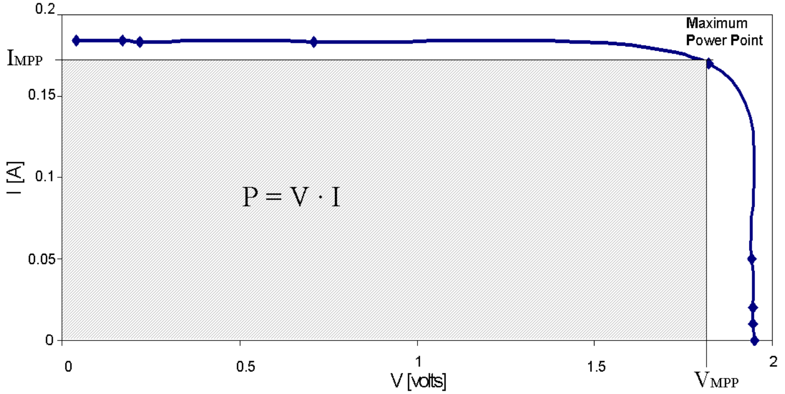

Figure 1.1.1.d: Current-voltage characteristic of the solar module

Plot a graph of power as a function of voltage.

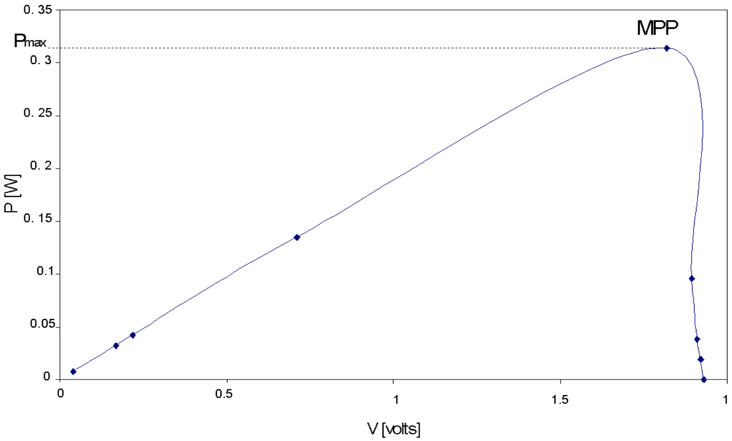

Figure 1.1.1.e: Power curve of the solar module

The maximum power point (MPP) is the maximum of the power curve. It occurs where the product of voltage and current is greatest (at 1.83 V x 0.17 A = 0.311 W in this example).

The MPP can also be determined from the current-voltage characteristic by forming the rectangles (products) of voltage and associated current. The rectangle with the greatest area indicates the point at which the maximum power arises.

Efficiency of solar module

To determine the efficiency you need the value of the incident radiant power P_{in} and the value of the electrical power P_{out} output by the solar cell. The cell outputs the maximum electrical power at the maximum power point. The value of P_{out} is therefore known in advance (0.311 W in this example).

a) Use the instrument described above to measure the radiant power of the light incident per unit area ('irradiance'). This value has to be multiplied by the effective area of the solar module to determine the power (P_{in}).

You can then calculate the efficiency with $\eta = \frac{P_{out}}{P_{in}}$.

b) If no such instrument is available, the multimeter can be used to estimate the incident radiant power of the light. This method makes use of the fact that the short-circuit current (maximum photoelectric current) is proportional to the photons (radiation) striking the solar cell. The short-circuit current is therefore proportional to the incident radiant power of the light.

The open circuit voltage is characteristic of the semiconductor of which the solar cell is made. It is not proportional to the incident radiant power and therefore cannot be used for this measurement.

To allow the multimeter to be used to measure the power of the light, the short-circuit current indicated on the multimeter must be multiplied by a certain factor F to obtain a quantitative indication. This factor is dependent upon the maximum value of the short-circuit current of the solar module.

The maximum irradiance in summer sunshine is approx.1000 W/m^2. The maximum value of the short-circuit current specified by the manufacturer is achieved at this value. (The parameters of the solar module relate to the standard test conditions of insolation of 1000 W/m² and cell temperature of 25 °C.)

In this example the maximum short-circuit current is 350 mA. The factor F is easily calculated using the following formula.

Example: $$F = \frac{1000\,\frac{W}{m^2}}{350\,mA} = 2.86\,\frac{W}{m^2\,mA}$$

Multiplying the short-circuit current indicated on the multimeter by the factor F = $2.86\frac{W}{m^2\,mA}$ now gives an approximation of the radiant power per unit area (irradiance) striking the solar module.

To calculate the radiant power incident on the solar module, measure its effective area and multiply this by the irradiance.

Example:
Area of solar cells: A = $6 \cdot 10^{-3}$ m² (four 30 mm x 50 mm cells)
Short-circuit current: I_s = 180 mA

$$P_{in} = F \cdot I_s \cdot A = 2.86 \frac{W}{m^2\ mA} \cdot 180\ \text{mA} \cdot 6 \cdot 10^{-3}\ \text{m}^2 = 3.089\ \text{W}$$

The electrical power of the solar module at the maximum power point is 0.311 W; this is the maximum value of the electrical power P_{out} output by the solar module (with an incident radiant power of 3.089 W).

Now calculate the efficiency from $\eta = \frac{P_{out}}{P_{in}}$.

$$\eta = \frac{0.311}{3.089} = 0.101 = \underline{\underline{10.1\ \%}}$$

Discussion:

The 'maximum power point' (MPP) can be read off the power curve extremely easily. On the current-voltage characteristic the MPP describes the greatest possible rectangular area that can be fitted between the coordinate axes (V and I) and the envelope of the characteristic. The resistance, R_{MPP}, at which the output power is a maximum can be calculated using the following formula: $R_{MPP} = \frac{V_{MPP}}{I_{MPP}}$

The efficiencies of polycrystalline solar cells lie between 12 and 14 %. At 10.1 % the determined value is slightly less. This is due to measuring errors and inaccuracies in determining the incident radiant power. Furthermore, the efficiency of solar modules is less than that of their separate constituent cells. This is caused by losses that arise in matching solar cells that do not all have exactly the same properties. If the solar cells are connected in series to form a module, they do not all have the same maximum power point.

Where do the solar cell losses arise? Not all photons striking the cell can be converted into charge carriers. Part of the light is reflected as soon as it hits the surface and the metal contacts cast shadows. Since the photon energy does not correspond to the energy gap, more than half of the incident energy is not used. Recombination of charge carriers (atomic rebinding of electrons) and electrical losses caused by internal resistances (ohmic losses in the semiconductor) of the solar cell and its contacts also arise.

1.2. Experiments with PEM electrolyzer

1.2.1. Current-voltage characteristic of PEM electrolyzer

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Background:

The PEM electrolyzer splits water into hydrogen and oxygen.

The voltage applied to the electrolyzer has to exceed a certain value, the 'decomposition voltage' of the water, for this to be achieved. Below this voltage no splitting takes place. The aim of the following experiment is to determine the magnitude of this voltage.

Apparatus:

- PEM electrolyzer
- 2 multimeters
- Power source
  - **a)** Variable power source, e.g. laboratory power supply
  - **b)** Alternatively: Non-variable power source, e.g. solar module, in which case the following are also needed:
    - A light if necessary to operate the solar module
    - Decade resistor, set with different resistors or potentiometer

Setup:

a) Connect the electrolyzer directly to the variable power source. This source should be set to 0 V initially and then increased to a maximum of 2.0 V.

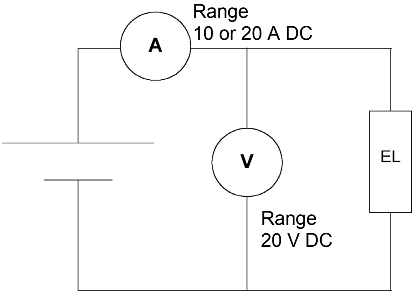

Figure 1.2.1.a: Setup for determining current-voltage characteristic of electrolyzer, with a variable power source

b) Connect the apparatus as shown in the following circuit diagram:

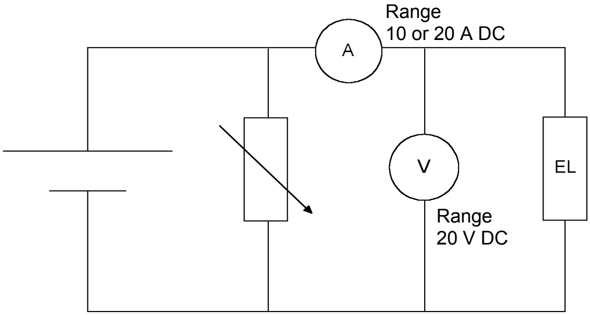

Figure 1.2.1.b: Setup for determining current-voltage characteristic of electrolyzer, with non-variable power source

Method:

Bring the apparatus into operation as described in the relevant Operating Instructions.

a) Continually increase the voltages on the power source in 0.1 V increments from 0 to 2 V, recording each voltage and the corresponding current in a table. Wait 20 seconds between each pair of measurements to obtain representative values. Take note of the start of gas production and mark the corresponding voltage in the table accordingly.

b) Switch the measurement decade step by step from small to large resistances, recording each voltage and the corresponding current in a table. Wait 20 seconds between measurements to obtain representative values. Take note of the start of gas production and mark the corresponding voltage in the table accordingly.

Example (using the h-tec Premium Electrolyzer):

R [Ω]	V [volts]	I [A]
0	0.04	0.00
0.1	0.14	0.00
0.33	0.37	0.01
1.0	1.09	0.01
3.3	1.59	0.57
10	1.64	0.89
33	1.66	1.01
100	1.66	1.01
330	1.66	1.01
∞	1.66	1.01

Figure 1.2.1.c: Table of measurements
The PEM electrolyzer will not start producing hydrogen and oxygen continuously until a certain DC voltage is exceeded. From this point onwards the current values start increasing. This table shows the currents for the different applied voltages.

Evaluation:

Plot the recorded pairs of values on a graph. The resultant curve is the current-voltage characteristic of the electrolyzer, which approximates to two intersecting straight lines (see example). Draw these lines through the data points and mark the point of intersection of the steep line with the V-axis.

Example (using the h-tec Premium Electrolyzer):

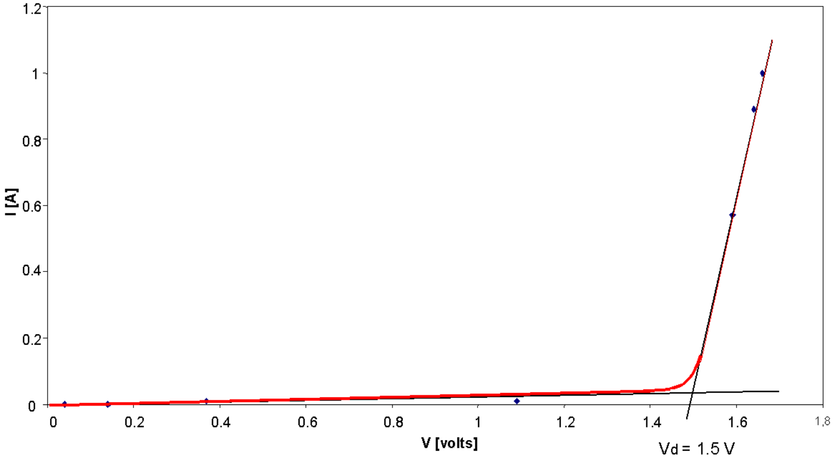

Figure 1.2.1.d: Current-voltage characteristic of electrolyzer

Discussion:

The relationship between current and applied voltage is plotted in Figure 1.2.1.d.

It is clearly evident from the shape of the curve that the current does not start flowing until a certain voltage is reached.

Only when a readily measurable current flows, has the water started to split into hydrogen and oxygen. In our example this occurs at 1.59 V (see table of Figure 1.2.1.c).

However, the decomposition voltage is lower. It is given by the point of intersection of the steeper line and the abscissa (V-axis).

The theoretical decomposition voltage is 1.23 V. Below this no splitting takes place. In practice, however, this voltage is higher as a result of 'overvoltages'. The difference between the theoretical and actual value of this voltage depends on several parameters, e.g. the type and composition of the electrode material, the electrolyte and the temperature.

1.2.2. Energy efficiency and Faraday efficiency of PEM electrolyzer

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Apparatus:

- PEM electrolyzer
- Graduated hydrogen storage tanks for experimental purposes
- 2 multimeters
- Stopwatch
- Power source
  - **a)** Variable power source, e.g. laboratory power supply
  - **b)** Alternatively: Non-variable power source, e.g. solar module; in which case the following are also needed:
    - A light if necessary to operate the solar module
    - Decade resistor, set with different resistors or potentiometer

Setup:

a) Connect the electrolyzer directly to the variable power source. Set a voltage of, for example, 1.8 V (greater than 1.5 V and less than 2 V).

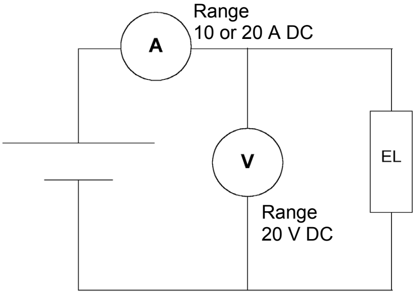

Figure 1.2.2.a: Setup for determining the energy and Faraday efficiency of the electrolyzer with variable power source

b) Connect the apparatus as shown in the following circuit diagram.

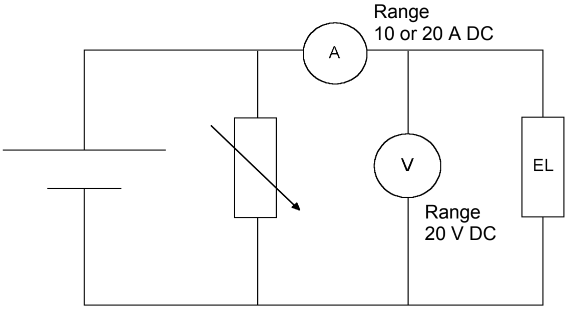

Figure 1.2.2.b: Setup for determining energy and Faraday efficiency of electrolyzer with non-variable power source

Method:

Bring the apparatus into operation as described in the relevant Operating Instructions.

Allow several minutes of gas production before starting the experiment, then interrupt the supply of power to the electrolyzer. Open the outlet valves of the gas storage tanks to completely release the gases produced. When the gases have been entirely removed, fill the storage tanks right up with distilled water. In other words the water level must coincide with the 0 cm^3 graduation when viewed vertically. Now close the outlet valves of the gas storage tanks.

Start measuring the time from the moment you connect the electrolyzer to the power source. Record the voltage applied to the electrolyzer and the current flowing through it. Record time, voltage and current when the main graduations are reached. Take the final measurements when the hydrogen storage tank is completely full of gas (20 cm^3 in our example).

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

V_{H2} [cm³]	t [s]	V [volts]	I [A]	P [W] calculated: P=V·I
0	***0***	***1.62***	***0.23***	***0.37***
5	***184***	***1.62***	***0.23***	***0.37***
10	***377***	***1.62***	***0.23***	***0.37***
15	***562***	***1.62***	***0.23***	***0.37***
20	***768***	***1.62***	***0.23***	***0.37***

Figure 1.2.2.c: Table of measurements
A PEM electrolyzer produces hydrogen and oxygen continuously if the applied DC voltage exceeds a certain value. The time, voltage and current values have been recorded in this table for certain volumes (in 5 cm³ increments) of hydrogen gas produced.

Energy efficiency

Background:

Energy efficiency η_{energy} states the amount of the input energy E_{input} which leaves the system, in this case the electrolyzer, in the form of actually useful energy E_{useful}.

$$\eta_{energy} = \frac{E_{useful}}{E_{input}} = \frac{E_{hydrogen}}{E_{electric}}$$

Evaluation (Part 1):

Plot the produced volume of gas as a function of time on a graph.

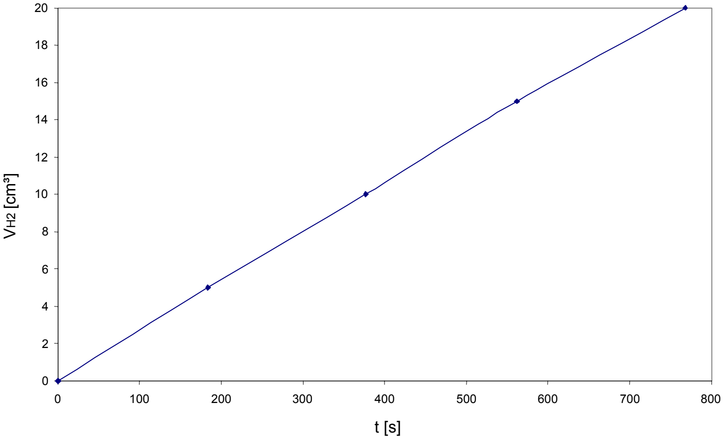

Figure 1.2.2.d: Electrolyzer gas volume against time (at $\overline{P}$ = 0.37 W)

Evaluation (Part 2):

Calculate the energy efficiency of the electrolyzer.

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

$$\eta_{energy} = \frac{E_{hydrogen}}{E_{electric}} = \frac{V_{H_2} \cdot H_0}{\overline{V} \cdot \overline{I} \cdot t}$$

$$\eta_{energy} = \frac{2 \cdot 10^{-5}\, m^3 \cdot 12.745 \cdot 10^6\, \frac{J}{m^3}}{1.62\ V \cdot 0.23\ A \cdot 768\ s} = 0.89 = \underline{\underline{89\ \%}}$$

H_u = Gross calorific value of hydrogen[1] = $12.745 \cdot 10^6 \frac{J}{m^3}$ (also called 'upper heating value')

V_{H_2} = Produced volume of hydrogen in m³

V = Voltage in volts

I = Current in A

T = Time in s

[1] 'Gross calorific value' is defined as the energy released during the combustion (oxidation) of a substance. It also includes the energy the water vapour from the fuel contains as condensation heat. This energy cannot be used in conventional firing systems. A value that neglects the condensation heat is therefore also formulated. This is called the heating value. The heating value is used in physics and engineering calculations, whereas the gross calorific value is used in chemistry.

Discussion:

It is evident from the table that the electrical power consumption of the electrolyzer is constant with time. The hydrogen production is also constant, since, as can be seen from the graph of gas volume against time, the volume of gas produced is a linear function of time. In other words the gas volume is proportional to time.

The energy efficiency of the electrolyzer in our example is 89 %. This means that 89 % of the electrical energy with which we operate the electrolyzer is stored in the hydrogen gas. Losses arise as the combined result of the overvoltages due to the particular electrodes (the overvoltage is generally defined as the deviation of the theoretical from the actual (experimentally determined) decomposition voltage), the internal resistance of the electrolytic cell and the diffusion losses of the gases within the cell.

Faraday efficiency of PEM electrolyzer

Background:

Faraday's First Law of Electrolysis describes the relationship between the magnitude of the current flowing and the volume of gas produced. It follows from the fact that one atom of hydrogen produced has one electron that had previously contributed to the current flowing. The relationship between current and electrons is I = Q/t (I: current, Q: charge, t: time). The Faraday efficiency of the electrolyzer is obtained from the ratio of the produced volume of gas, to that calculated for the electrical power.

Evaluation:

Faraday's First Law of Electrolysis states:

$$\boxed{V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}}$$

V= Theoretically produced volume of gas in m³

R= Universal gas constant = 8.314 $\frac{J}{mol \cdot K}$

p = Ambient pressure in Pa ($1\ Pa = 1\frac{N}{m^2}$)

F = Faraday's constant = 96485 $\frac{C}{mol}$ (1C = 1As)

T = Ambient temperature in K

I = Current in A

t = Time in s

z = Number of electrons to release one molecule:

z (H_2) = 2, i.e. 2 mols of electrons are required to release 1 mol of hydrogen.

z (O_2) = 4

$$V_{calculated} = \frac{R \cdot \bar{I} \cdot T \cdot t}{F \cdot p \cdot z} = \frac{8.314\ \frac{J}{mol \cdot K} \cdot 0.23A \cdot 293K \cdot 768s}{96485\ \frac{C}{mol} \cdot 1.013 \cdot 10^{5} Pa \cdot 2}$$

$V_{calculated}$ = $2.20 \cdot 10^{-5}$ m³ = 22 cm³

The Faraday efficiency is obtained from the following formula:

$$\eta_{Faraday} = \frac{V_{H_2}(produced)}{V_{H_2}(calculated)}$$

The volume of hydrogen produced in the experiment is:

V_{H_2} (produced) = 20 cm³.

The Faraday efficiency is therefore:

$$n_{Faraday} = \frac{20\ cm^3}{22\ cm^3} = 0.91 = \underline{\underline{91\ \%}}$$

Discussion:

The difference between theory ($\eta = 100\ \%$) and practice ($\eta_{Faraday} = 91\ \%$) is 9 %. It consists of measuring errors and diffusion losses of the gases within the cell. The diffusion losses arise from the fact that a proportion of the gases diffuses through the membrane of the electrolyzer and reacts in contact with the catalyst to form water. A small proportion of the gases produced is therefore immediately reconverted without being allowed to escape from the cell.

1.3. Experiments with PEM fuel cell

1.3.1. Current-voltage characteristic and power curve of PEM fuel cell

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Background:

The fuel cell converts chemical energy stored as hydrogen and oxygen directly into electrical energy. Hydrogen and oxygen are fed in and react to water, giving off electricity and heat in the process.

The power output of the cell depends on the load resistance. The aim of the following experiment is to determine the resistance and hence current for optimum power yield.

Apparatus:

- PEM fuel cell
- 2 multimeters
- Decade resistor, set with different resistors or potentiometer
- Hydrogen source
    - **a)** Hydrogen storage tank, e.g. pressure gas can, metal hydride storage tank
    - **b)** Alternatively: electrolyzer, in this case you also need:
        - A power source, such as a solar module or laboratory power supply
        - A light if necessary to operate the solar module

Setup:

Connect the apparatus as shown in the following circuit diagram.

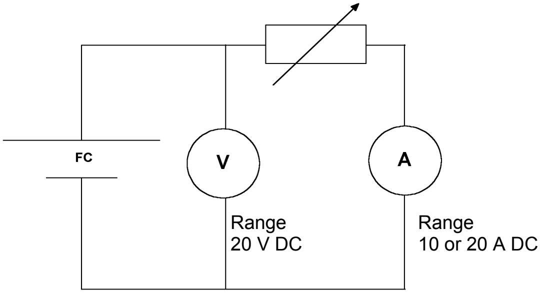

Figure 1.3.1.a: Setup for determining current-voltage characteristic of fuel cell (FC = Fuel Cell)

Method:

Bring the apparatus into operation as described in the relevant Operating Instructions.

a) Close the outlet valves of the fuel cell. Connect the outlets of the source of hydrogen to the inlets of the fuel cell (see Operating Instructions). Open the outlet valves of the fuel cell, purge the cell briefly with hydrogen, then close the valves again. This removes gas residues that lead to measuring errors. To prevent the fuel cell using any hydrogen before the measurements are taken, it must be switched to open circuit (clamps open, no current flow).

When recording the current-voltage characteristics start with the open-circuit voltage. Switch the decade resistor from larger to smaller values and record the voltage and current for each resistance. To obtain representative results allow 20 seconds to elapse between each pair of measurements.

b) Connect the electrolyzer to the power source to produce hydrogen and oxygen. Connect the outlets of the electrolyzer (ideally in conjunction with small graduated hydrogen storage tank for experimental purposes) to the inlets of the fuel cell. Close the outlet values of the fuel cell. After producing at least 5 cm^3 of hydrogen, open the outlet valves of the fuel cell, purge with gases then close the valves again. This removes gas residues that lead to measuring errors. To prevent the fuel cell using any hydrogen before the measurements are taken, it must be switched to open circuit (clamps open, no current flow).

Now produce the hydrogen. Start recording the current-voltage characteristic with the open-circuit voltage (R = ∞), then switch the decade resistor from larger to smaller values. Measure and record voltage and current for each resistance. To obtain representative results allow about 20 seconds to elapse between each pair of measurements.

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

R [Ω]	U [V]	I [A]	P [W] calculated: P=V·I
∞	***0.99***	***0.00***	***0.000***
330	***0.97***	***0.01***	***0.001***
100	***0.94***	***0.01***	***0.001***
33	***0.90***	***0.03***	***0.027***
10	***0.84***	***0.08***	***0.075***
3.3	***0.76***	***0.22***	***0.167***
1	***0.62***	***0.56***	***0.347***
0.33	***0.47***	***1.05***	***0.494***
0.1	***0.32***	***1.43***	***0.458***
0	***0.24***	***1.61***	***0.386***

Figure 1.3.1.b: Table of measurements
Measurement of the voltage and current values of the fuel cell with different load resistances.

Evaluation:

Plot the recorded values as current-voltage characteristic on a graph.

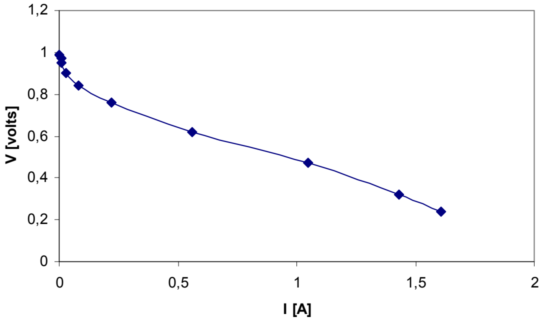

Figure 1.3.1.c: Voltage-current characteristic of fuel cell

Plot the power as a function of current on a graph.

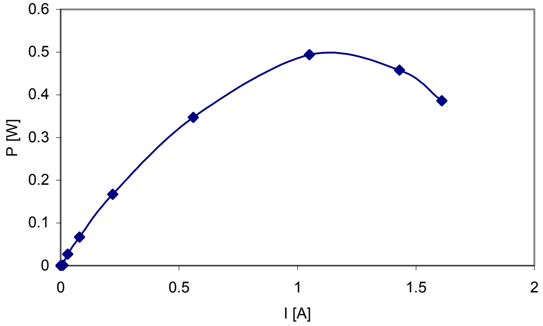

Figure 1.3.1.d: Power curve of fuel cell

Discussion:

The current at which the fuel cell gives the greatest power output is clearly evident from the power curve. Maximum power arises at about 1.05 A, which corresponds to a load resistance of 0.33 Ω (see Table 1.3.1.b). The load resistance must therefore be 0.33 Ω if the greatest possible output is to be achieved.

1.3.2. Energy efficiency and Faraday efficiency of PEM fuel cell

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Apparatus**:**

- PEM fuel cell
- Hydrogen source, e.g. PEM electrolyzer, with graduated storage tank for experimental purposes
- Power source, when an electrolyzer is being used, such as solar module or laboratory power supply
- A light if necessary to operate the solar module
- 2 multimeters
- Decade resistor, set with different resistors or potentiometer
- Stopwatch

Setup:

Connect the apparatus as shown in the following circuit diagram.

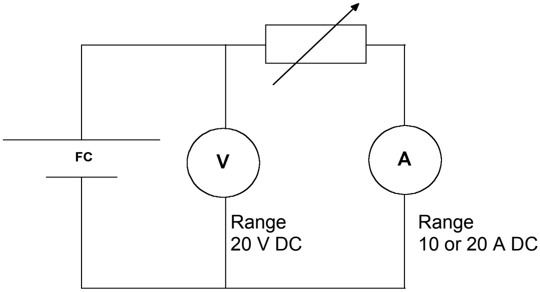

Figure 1.3.2.a: Setup for determining energy and Faraday efficiency of fuel cell (FC = fuel cell)

Method:

Bring the apparatus into operation as described in the relevant Operating Instructions.

Connect the outlets of the hydrogen storage tank of the electrolyzer to the inlets of the fuel cell. Close the outlet values of the fuel cell. Produce about 20 cm³ of hydrogen then briefly open the clamps on the outlet of the fuel cell to vent the system. Produce the maximum volume of hydrogen (20 cm³ in the example) possible with the system. Interrupt the supply of power to the electrolyzer. Disconnect the electrical connection between the fuel cell and the decade resistor. Switch the decade to the resistance at which you want to determine the energy efficiency (e.g 3.3 Ω). Reconnect the circuit between fuel cell and decade resistor and start measuring the time from this moment.

Record the measured time, voltage and current after constant volume increments (e.g. 5 cm³) with an unchanged resistance. Ensure that the values of current do not fluctuate too much. Any substantial reduction in the current in the course of measurement will probably be due to gas residues that impair the operation of the fuel cell remaining in the storage tanks. This problem is only slight as it only arises when there is a small volume of hydrogen remaining in the storage tank (e.g. just 5 cm³).

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

V_{H2} [cm³]	t [s]	V [volts]	I [A]	P [W] calculated: P=V·I
20	**0**	**0.813**	**0.128**	**0.104**
15	**281**	**0.770**	**0.120**	**0.092**
10	**605**	**0.678**	**0.106**	**0.072**
Mean		$\overline{V} = \mathbf{0.754}$	$\overline{I} = \mathbf{0.118}$	$\overline{P} = \mathbf{0.089}$

Figure 1.3.2.b: Table of measurements
A fuel cell continuously converts hydrogen gas introduced as fuel into electrical energy. The values of time, voltage and current for certain hydrogen consumptions (5 cm³ increments) have been recorded in this table.

Energy efficiency of PEM fuel cell

Background:

Energy efficiency η_{energy} states the amount of the input energy E_{input} which leaves the system, in this case the fuel cell, in the form of actually useful energy E_{useful}.

$$\eta_{energy} = \frac{E_{useful}}{E_{input}} = \frac{E_{electric}}{E_{hydrogen}}$$

Evaluation (Part 1):

Plot the consumed volume of gas as a function of time on a graph.

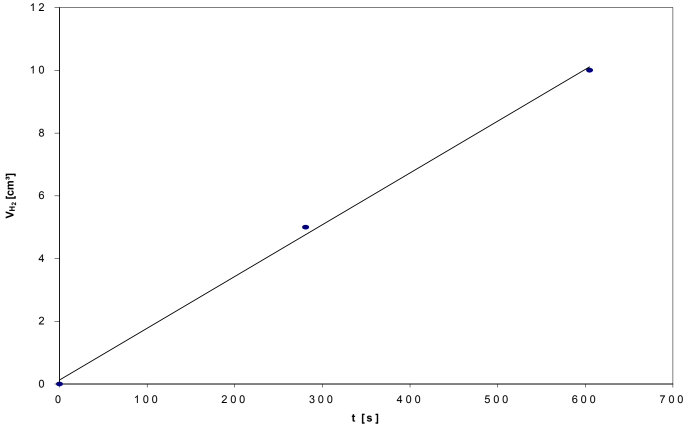

Figure 1.3.2.c: Graph of hydrogen consumption of fuel cell as a function of time (at $\overline{P}$ =0.089 W)

Evaluation (Part 2):

Calculate the energy efficiency of the fuel cell.

Example (using h-tec JuniorBasic Hydrogen Experimentation System):

$$\eta_{energy} = \frac{E_{electric}}{E_{hydrogen}} = \frac{\overline{V} \cdot \overline{I} \cdot t}{V_{H_2} \cdot H_l}$$

$$\eta_{energy} = \frac{0.754V \cdot 0.118A \cdot 605s}{10 \cdot 10^{-6} m^3 \cdot 10.8 \cdot 10^6 \frac{J}{m^3}} = 0.498 \approx \underline{\underline{50\ \%}}$$

H_l = Heating value of the hydrogen[1] = $10.8 \cdot 10^6 \frac{J}{m^3}$ (also called lower heating value)

V_{H_2} = Volume of hydrogen consumed in m³

V = Voltage in volts

I = Current in A

t = Time in s

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[1] 'Heating value' is defined as the energy released during the combustion (oxidation) of a substance. It also includes the energy the water vapour from the fuel contains as condensation heat. This energy cannot be used in conventional firing systems. A value that neglects the condensation heat is therefore also formulated. This is called the heating value. The heating value is used in physics and engineering calculations, whereas the calorific value is used in chemistry.

Discussion:

It is evident from the table that the electrical power output of the fuel cell is approximately constant with time. The hydrogen consumption is also constant, since, as can be seen from the graph of hydrogen consumption against time, the consumed volume of gas is proportional to time.

The energy efficiency of the fuel cell in our example is 50 %. This means that 50 % of the energy stored in the hydrogen with which we operate the fuel cell is output as electrical energy. The fuel cell also outputs heat. If not used this heat is to be regarded as lost energy. This limits the efficiency from the outset. To take account of this an ideal efficiency η_{id} is defined as the ratio of the free reaction enthalpy ΔG (the work released during the reaction, e.g. in the form of electrical energy) and the reaction enthalpy ΔH (the energy released during the reaction).

$$\eta_{id} = \frac{\Delta G}{\Delta H}$$

The difference between free reaction enthalpy ΔG and the reaction enthalpy ΔH is the heat released Q = T·ΔS.

$$\Delta H = \Delta G + T \cdot \Delta S$$

$$\eta_{id} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T \cdot \Delta S}{\Delta H} = 1 - \frac{T \cdot \Delta S}{\Delta H} = 1 - \frac{298\,K \cdot (-162.985\,\frac{J}{K\ mol})}{-285840\,\frac{J}{mol}}$$

$$\eta_{id} = 0.83 = \underline{\underline{83\ \%}}$$

$T = Temperature = 298\,K$

$\Delta S = Reaction\ \ entropy = -162.985\,\frac{J}{K\ mol}$

$\Delta H = Reaction\ \ enthalpy = -285840\,\frac{J}{mol}$

Voltage losses, which are also manifested as heat, further reduce the efficiency. As a result of the overvoltages due to the particular electrodes, the internal resistance of the fuel cell and diffusion losses with the fuel cell, the achievable terminal voltage will never reach the ideal value of 1.23 volts.

In a similar manner to the electrolyzer, the efficiency of the fuel cell is heavily dependent on the power level. If the load has a high electrical resistance, although the efficiency of the cell is high it only operates under part load. The power extracted is therefore less than it can produce.

To ascertain the load resistance at which the energy efficiency of the fuel cell is greatest, this experiment can be repeated with difference resistances (10 to 0.1 Ω recommended).

Faraday efficiency of PEM fuel cell

Background:

Faraday's First Law of Electrolysis relates the magnitude of the current flowing to the consumed volume of gas. It follows from the fact that one consumed atom of hydrogen has one electron that subsequently contributes to the current flowing. The relationship between current and electrons is I= Q/t (I: current, Q: charge, t: time). The Faraday efficiency of the fuel cell is obtained from the ratio of the volume of gas calculated for the electrical power, to the consumed volume.

Evaluation:

Faraday's First Law of Electrolysis states:

$$\boxed{V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}}$$

V= Theoretical volume of gas in m³

R= Universal gas constant = $8.314 \frac{J}{mol \cdot K}$

p = Ambient pressure in Pa ($1\,Pa = 1 \frac{N}{m^2}$)

F= Faraday's constant = $96485 \frac{C}{mol}$ (1C = 1As)

T= Ambient temperature in K

I = Current in A

t = Time in s

z = Number of electrons to release one molecule:

z (H_2) = 2, i.e. 2 mols of electrons are required to release 1 mol of hydrogen.

z (O_2) = 4

The Faraday efficiency is obtained from the following formula:

$$\eta_{Faraday} = \frac{V_{H_2}(calculated)}{V_{H_2}(consumed)}$$

Example (using the h-tec JuniorBasic Hydrogen Experimentation System):

$$V_{H_2}(consumed) = 10\,cm^3$$

$$V_{H_2}(calculated) = \frac{R \cdot \bar{I} \cdot T \cdot t}{F \cdot p \cdot z} = \frac{8.314 \frac{J}{mol \cdot K} \cdot 0.118\ A \cdot 293\ K \cdot 605\ s}{96485 \frac{C}{mol} \cdot 1.013 \cdot 10^5\ Pa \cdot 2}$$

$$= 8.89 \cdot 10^{-6} m^3 = 8.89\ cm^3$$

$$\eta_{Faraday} = \frac{8.89\ cm^3}{10\ cm^3} = 0.889 \approx \underline{\underline{89\ \%}}$$

Discussion:

The volume of gas actually consumed is slightly greater than that calculated, since diffusion losses similar to those in the electrolyzer arise in the fuel cell.
However, according to the experimental results the Faraday efficiency of the fuel cell is slightly poorer than that of the electrolyzer. This is due to a smaller current flowing. According to Faraday the result is that it takes more time to form a given volume of water than to split it. Over a longer time period more hydrogen diffuses through the membrane and is then no longer available for producing electricity.

1.4. Experiments with direct-methanol fuel cell (DMFC)

1.4.1 Current-voltage characteristic of direct-methanol fuel cell

Before starting the experiment please read the Safety Precautions in the Operating Instructions!

Background:

The power output produced by a DMFC depends on the load resistance connected. The resistance for optimum power yield has to be determined.

Apparatus:

- Direct-methanol fuel cell
- 2 multimeters
- Decade resistor, set with different resistors or potentiometer

DANGER!

Methanol is poisonous.

Setup:

Connect the apparatus as shown in the following circuit diagram.

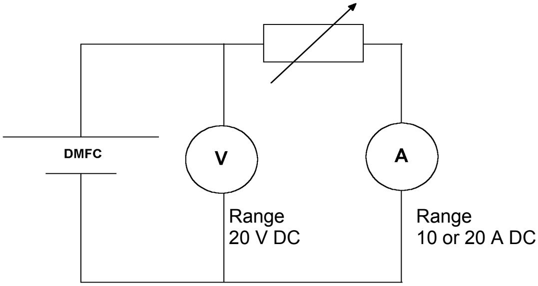

Figure 1.4.1.a: Setup for determining current-voltage characteristic of direct-methanol fuel cell (DMFC)

Method:

Connect the DMFC, the voltmeter and the ammeter to the Decade resistor as shown on the circuit diagram. Before starting the measurements the DMFC must be allowed to stand for a few minutes with the methanol solution in order to ensure it yields representative values.
Start recording the current-voltage characteristic with the open-circuit voltage (R=∞), then switch the decade resistor to smaller values. Measure voltage and current for each resistance and record them in a table. Allow about 20 seconds to elapse between each pair of measurements.

Example (using h-tec Premium DMFC Direct-methanol Fuel Cell):

R [Ω]	V [volts]	I [A]	P [mW] calculated: P=V·I
∞	***0.60***	***0.00***	***0.0***
330	***0.60***	***0.00***	***0.0***
100	***0.59***	***0.01***	***5.9***
33	***0.57***	***0.02***	***11.4***
10	***0.50***	***0.05***	***25.0***
3.3	***0.41***	***0.12***	***49.2***
1	***0.28***	***0.26***	***72.8***
0.33	***0.18***	***0.38***	***68.4***
0.1	***0.10***	***0.50***	***50.0***
0	***0.06***	***0.54***	***32.4***

Figure 1.4.1.b: Table of measurements
Measurement of the voltage and current values of the direct-methanol fuel cell with different load resistance.

Evaluation:

Use the tabulated values to plot the voltage as a function of current on a graph.

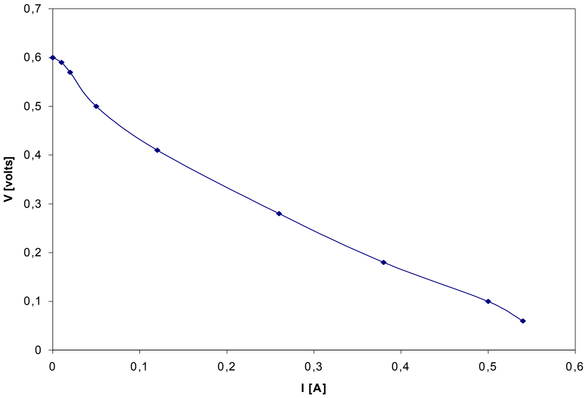

Figure 1.4.1.c: Current-voltage characteristic of direct-methanol fuel cell

Plot the power as a function of current on a graph.

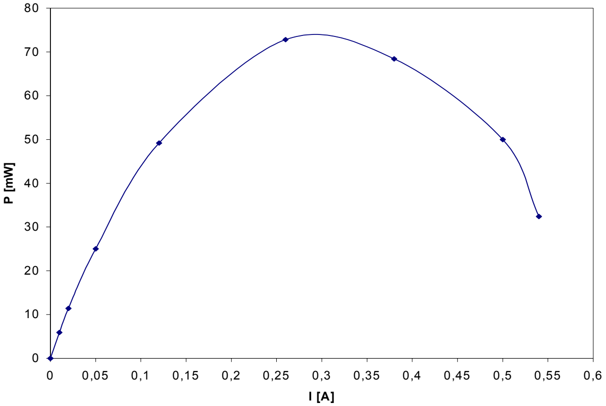

Figure 1.4.1.d: Power curve of direct-methanol fuel cell

Discussion:

It is evident from the graphs that the power output by a direct-methanol fuel cell depends on the load resistance (cell voltage, current).

The current at which this fuel cell gives the greatest power output is readily determined from the power curve. Maximum power occurs at about 0.29 A, which corresponds to a load resistance of approximately 1 Ω. The load resistance must therefore be 1 Ω if the greatest possible output is to be achieved.