Keywords
Electrolysis, proton exchange membrane, separation of charge, hydrogen, efficiency, Faraday's laws, and universal gas constant.

Principle
Degrees of efficiency describe the efficiency of a process under certain aspects. The first part of the experiment describes the determination of the energetic efficiency. It is the ratio between the real gas quantity that is produced and the theoretical value that is calculated.

Equipment
*2 Connector, angled, module DB 09401-02
*2 Junction, module DB 09401-10
1 Double PEM electrolyser, DB 09488-00
2 Gas storage with a magnetic pad, including tube and plug, DB 09489-00
2 Building block with a magnetic pad, DB 09490-00
2 Metal angle for the building block with a magnetic pad 09491-00

Additional equipment
1 Demo physics board with a stand 02150-00
1 Power supply, universal 13500-93
**1 Cobra4 Wireless-Manager 12600-00
**2 Cobra4 Wireless-Link 12601-00
***1 Cobra4 Sensor-Unit Energy 12656-00
***1 Cobra4 Sensor-Unit 2x Temp., NiCr-Ni 12641-00
**2 Holder for Cobra4, magnetic 02161-10

Fig. 1: Experiment set-up
**1** Immersion probe, NiCr-Ni, stainless steel, -13615-03

50...400°C

**1** measure software for Cobra4 14550-61

1 Connecting cable, 250 mm, blue 07360-04

1 Connecting cable, 250 mm, yellow 07360-02

1 Connecting cable, 750 mm, red 07362-01

1 Connecting cable, 750 mm, blue 07362-04

Distilled water 31246-81

1 Protective glasses 39316-00

* Included in the ENT 1 set 09492-88

** Included in the Cobra4 extension set 12608-88

**Note**

Use only distilled (deionised) water for filling the gas storage.

The maximum operating voltage of the electrolyser is 4 V and its maximum current intensity is 2 A.

At 4.0 V, the double PEM electrolyser has a current intensity of 0.6 A minimum (nominal values). If the current intensity of the electrolyser is lower, it usually increases during the operation. If this is not the case, the two connectors of the electrolyser must be short-circuited for one minute or longer.

Prior to the experiment, the electrolyser should be in the idle state for approximately 2 minutes in order to allow the membranes to become moist.

**Safety information**

*Oxygen*

H: 270 – 280

P: 220 – 244 – 370+376 – 403

Oxygen is a colourless, odourless, and flavourless oxidising gas. There is a fire hazard when it comes into contact with flammable substances.

*Hydrogen*

H: 220 – 280

P: 210 – 377 – 381 - 403

Hydrogen is a colourless, odourless, and flavourless flammable gas that readily forms explosive mixtures with air. This is why good ventilation must be ensured for experiments involving hydrogen. Any ignition sources must be removed prior to the experiments.

Wear protective glasses.

**Set-up**

- Set the circuit for the electrolyser up as shown in Fig. 1.
- The power supply unit is switched off.
- Ensure the correct polarity of the PEM electrolyser.
- Ensure that the red cable of the power supply unit is connected to the **A** socket of the Cobra4 Sensor-Unit Energy.
- Position the two gas storages on the left and on the right of the circuit and connect them to the PEM electrolyser by way of the silicone tubes (Fig. 2).
- Connect an additional silicone tube to each of the free ends of the two gas storages and seal it with the aid of a hose clamp.
- Fill the gas storage right below the **upper** mark with distilled water (Fig. 3).
- Hold the tubes upward and open the hose clamps so that the water flows into the lower part of the gas tanks.
- Close the hose clamps.
1. **Energetic efficiency**

**Procedure**
- Start the PC and Windows.
- Connect the Cobra4 Wireless Manager to the USB port of the PC.
- Start the "measure" software package on the PC.
- Connect the Cobra4 Wireless-Links to the Cobra4 Sensor-Units one by one. After the Wireless-Links have been switched on, the Sensor-Units will be automatically detected and assigned an ID number that will be displayed on the displays of the two Cobra4 Wireless-Links. The communication between the Cobra4 Wireless-Manager and the Cobra4 Wireless-Links is indicated by way of the respective data LED.
- Switch the Cobra4 Wireless-Link with the connected Cobra4 Sensor-Unit on. The Sensor-Unit and the electrical quantities $U$, $I$, $P$, and $W$ are displayed as the measuring channels.
- Load the experiment "ENT 4.2 Part 1" (Experiment > Open experiment > …). The program will now open all of the required presettings for the measurement data recording process (Fig. 4).
- Prior to the start of the experiment, read the gas quantities in the two gas storages and note them down.
- Adjust the voltage to 0 V and the current limitation to 2 A on the power supply unit.
- Switch the power supply unit on.
- Start the measurement data recording process in "measure".
- Quickly adjust to a voltage of 4 V.
- When the hydrogen storage on the negative side of the electrolyser reaches the 30 cm$^3$ mark, reset the voltage to 0 V.

![Fig. 4: Measurement data recording for the energetic efficiency](image-url)
Stop the measurement data recording process in "measure".
- Switch the power supply unit off.
- Open the hose clamps so that the water flows back into the gas storages.
- Close the hose clamps again.
- Transfer the measurement values to the "measure" main program.

Observation
The voltage and current remain constant. The electric work increases linearly.

Evaluation
In Fig. 5, the function "Survey" shows that electric work of 466.5 Ws is performed in order to produce 30 cm$^3$ of hydrogen in 69.5 s.

The energetic efficiency is the ratio between the useful output of energy and the energy input. The useful output of energy is calculated with the aid of the calorific value of hydrogen.

$$\eta_{\text{energy}} = \frac{E_{\text{useful}}}{E_{\text{input}}} = \frac{E_{\text{hydrogen}}}{E_{\text{electric}}} = \frac{V_H \cdot H_0}{W}$$

With:
$E$ = energy
$\eta$ = efficiency
$V_H$ = produced hydrogen gas volume
$H_0$ = calorific value of hydrogen = 12.745 $\cdot$ 10$^6$ J/m$^3$

This leads to an efficiency of 82%.

Fig 5: Measurement data evaluation for the energetic efficiency
2. Faraday efficiency

Procedure
- Connect the immersion probe to the Cobra4 Sensor Unit 2x Temperature.
- Switch the Cobra4 Wireless-Link with the connected Cobra4 Sensor-Unit 2x Temperature on. The Sensor-Unit and the electrical quantities $T_1$ and $T_2$ are displayed as the measuring channels.
- Load the experiment "ENT 4.2 Part 2" (Experiment > Open experiment > …). The program will now open all of the required presets for the measurement data recording process (Fig. 6).
- Position the immersion probe away from any sources of heat or cold so that the room temperature can be determined.
- Adjust the voltage to 0 V and the current limitation to 2 A on the power supply unit.
- Switch the power supply unit on.
- Start the measurement data recording process in "measure" ●.
- Quickly adjust to a voltage of 4 V.
- When the hydrogen storage on the negative side of the electrolyser reaches the 30 cm³ mark, stop the measurement data recording process in "measure" ■.
- Set the voltage quickly to 0 V on the power supply unit.
- Switch the power supply unit off.
- Open the hose clamps so that the water flows back into the gas storages.
- Close the hose clamps again.
- Transfer the measurement values to the "measure" main program.

Fig. 6: Measurement data recording for the Faraday efficiency
**Observation**

In this case, the voltage and current also remain constant. The room temperature is 295.1 K.

**Evaluation**

By way of the function "Average Value", the average value of the current intensity can be determined. It is 1.658 A. At this current intensity, it takes 73 s to fill the hydrogen gas storage with 30 cm\(^3\) of gas.

The Faraday efficiency describes the ratio between the produced quantity of gas and the theoretically possible gas quantity that could be produced based on the energy input. Based on Faraday's second law \(Q = I \cdot t = n \cdot z \cdot F\), and based on the general equation of the state of gases \(p \cdot V = n \cdot R \cdot T\), the following can be concluded:

\[
V_{H_2}\text{(calculated)} = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}
\]

It must be taken into consideration that the PEM double electrolyser consists of two electrolysis cells that are connected in series, which means that the current is identical in each of the cells and that the calculated gas volume is also produced in each of the cells. As a consequence, the result must be multiplied by two. In addition, the following applies:

- \(Q\) = electric charge
- \(V\) = gas volume
- \(I\) = mean current intensity
- \(T\) = ambient temperature
- \(t\) = time
- \(R\) = universal gas constant = 8.314 J/(mol \cdot K)
- \(F\) = Faraday constant = 96485 (A \cdot s)/mol
- \(p\) = ambient pressure in Pa. The following applies: 1 Pa = 1 N/m\(^2\) (normal pressure 1.013 \cdot 10\(^5\) Pa)*
- \(z\) = number of electrons required for separating a molecule (\(z(H_2)=2\))

![Figure 7: Measurement data evaluation for the Faraday efficiency](image-url)
Faraday efficiency and energetic efficiency of a PEM electrolyser

With the formula:

\[ \eta_{\text{Faraday}} = \frac{V_{\text{H}_2} \text{(produced)}}{V_{\text{H}_2} \text{(calculated)}} \times 2 \]

a Faraday efficiency of 99% results.

The Faraday efficiency is considerably higher than the energetic efficiency, since it takes only losses during the direct conversion, e.g. by diffusion, into consideration. For the energetic efficiency, additional losses, e.g. due to the internal resistance of the electrolyser, also play a role.

* For more accurate results, the ambient pressure can also be determined with the Cobra4 Sensor-Unit Pressure.

Application
Apart from the PEM electrolyser, there are also various other types of electrolysis. Two common methods for the decomposition of water are the alkaline electrolysis and the high-temperature electrolysis. The latter, in particular, enables considerably higher efficiencies than the PEM electrolyser. However, it requires temperatures of more than 800°C. The alkaline electrolysis reaches similar efficiency values as the PEM electrolyser, but it requires a solution of caustic potash. Despite the costs and conditions that are required for the electrolysis, the three mentioned variants are used in most cases, since the chemical or biological production of hydrogen is much more difficult and expensive and cannot provide hydrogen with the level of pureness that can be achieved by electrolysis.

Notes

Corresponding student experiments TESS EN
4.6 Faraday efficiency and energetic efficiency of a PEM electrolyser (P9516600)

For the execution of the experiment without a PC, the items on the list (page 1) that are marked with (***) must be replaced with the following items:

**Experiment P9504263**
1. Cobra4 Mobile-Link 12620-00
2. Cobra4 Sensor-Unit Energy 12656-00
3. Cobra4 Sensor-Unit 2x Temperature, NiCr-Ni 12641-00
4. Cobra4 Display-Connect, transmitter and receiver set 12623-88
5. Holder for hand-held meters 02161-00
6. Immersion probe, NiCr-Ni, stainless steel, -50...400°C 13615-03
7. Large-scale display 07157-93

**Experiment P9504200**
1. Analog demonstration multimeter ADM 2 13820-00
2. Laboratory thermometer, -10...+50°C, without Hg 47039-00
3. Precision barometer, \(d=100\) mm 87998-00
Faraday efficiency and energetic efficiency of a PEM electrolyser

Room for notes