Internship Energy Technology

Fuel cells

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1 Introduction

Fuel cells are electrochemical energy converters that convert chemical energy directly into electrical energy. In contrast to heat engines, the lossy intermediate step via thermal energy (or mechanical energy) is omitted. For this purpose, gaseous fuels and oxygen or air are continuously supplied to a fuel cell. Since the fuel is stored separately from the power unit in a fuel cell system, the capacity (Ah) and power (W) of the system are decoupled. The range of applications for fuel cells ranges from stationary applications in power plant technology to decentralised power and heat generation, electric drives and battery replacement. Compared to conventional systems for power generation, fuel cells have many positive properties. The most important advantages include:

- high efficiencies (regardless of size),
- low pollutant emissions (only water when operated with hydrogen),
- low noise emissions,
- Good part-load behavior (increasing efficiencies in the part-load range),
- Modular design (suitable for centralized and decentralized applications),
- high flexibility (performance) and dynamics (load change),
- Combined heat and power generation possible (especially in the high-temperature range),
- no mechanical wear and no moving parts.

In addition to these general properties, all fuel cell types have specific properties and are accordingly suitable for different areas of application. The functional principle is always based on the spatial separation of the reaction partners by an electrolyte. In this way, the chemical reaction is controlled in such a way that the electron exchange that takes place during the chemical reaction does not take place locally, but via an external circuit. The fuel cell is part of this circuit. In principle, all redox reactions, i.e. reactions in which electron exchange takes place, are suitable for electrochemical power generation. The use of hydrogen as fuel gas, or natural gas that is processed in an upstream reformer, has become established due to its good reactivity. The reaction equation of the entire redox reaction adds up to the following for all fuel cell types:

$$H_2 + 0{,}5\ O_2 \rightarrow H_2O. \qquad \textbf{1.1}$$

The classification of the various fuel cells is usually based on the electrolytes used and the operating temperature. The electrolyte used determines whether either positively charged ions diffuse in the direction of the cathode (reduction electrode) or negatively charged ions in the direction of the anode (oxidation electrode) (see Fig. 1.1). Depending on the direction of diffusion, the product water is produced accordingly on the anode or cathode side.

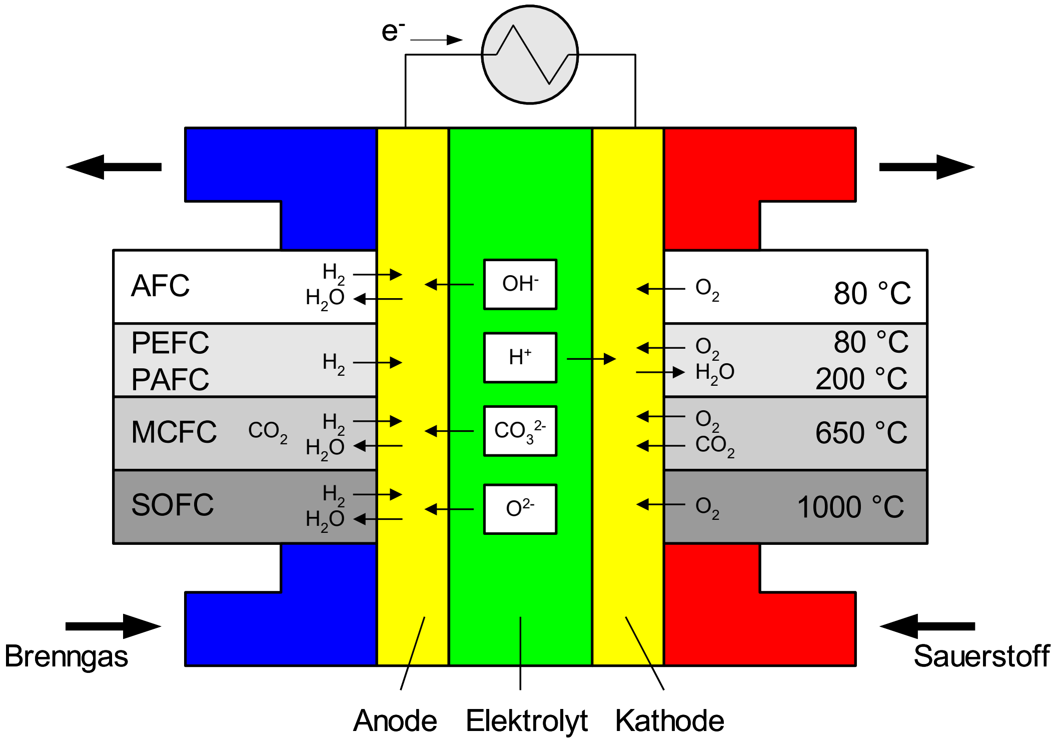

Fig. 1.1: Properties of different fuel cell types

2 PEM fuel cells

In the following, the functionality and structure will be presented using the example of the polymer electrolyte membrane fuel cell (PEMFC) used in the practical course.

2.1 Functional principle PEMFC

The electrochemical process of energy conversion takes place in fuel cells in two reaction steps. At the anode, the fuel (hydrogen) is supplied and oxidized (electron release). The positively charged hydrogen ions () diffuse through an electron-impermeable, proton-conducting membrane (electrolyte) towards the cathode. The emitted electrons (), on the other hand, are conducted to the cathode via an external electrical circuit. The flow of electrons causes a technical current in the opposite direction. The reaction equation of oxidation at the anode is:$H^+ e^-$

$$H_2 \rightarrow 2\,H^+ + 2\,e^-. \qquad \textbf{2.1}$$

At the cathode, the oxidation agent (oxygen) supplied is reduced by the electrons. Subsequently, the negatively charged oxygen ions () and the positively charged hydrogen ions form the end product water (). The reaction equation at the cathode is thus as follows:$O^{2-} H_2O$

$$2\,H^+ + 0{,}5\,O_2 + 2\,e^- \rightarrow H_2O. \qquad \textbf{2.2}$$

The reaction equation of the total redox reaction adds up to:

$$H_2 + 0{,}5\,O_2 \rightarrow H_2O. \qquad \textbf{2.3}$$

The potential difference between the negative electrode (anode) and the positive electrode (cathode) is the so-called clamping voltage. The electrical power () can be tapped via a consumer as a product of the clamping voltage () and the current ():$P_{el}U_{bz}I_{bz}$

$$P_{el} = U_{bz} * I_{bz}. \qquad \textbf{2.4}$$

2.2 Structure PEMFC

The basic structure of a PEM fuel cell consists of an anode and a cathode, which are separated from each other by an electrolyte (PE membrane) (see Fig. 2.1). The electrolyte is coated on both sides (anode and cathode side) with catalyst material (e.g. platinum, palladium). This arrangement is also known as MEA (Membrane Electrode Assembly). The two catalyst layers are followed by a gas diffusion layer (GDL = gas diffusion layer). The fuel cell is completed by two bipolar plates.

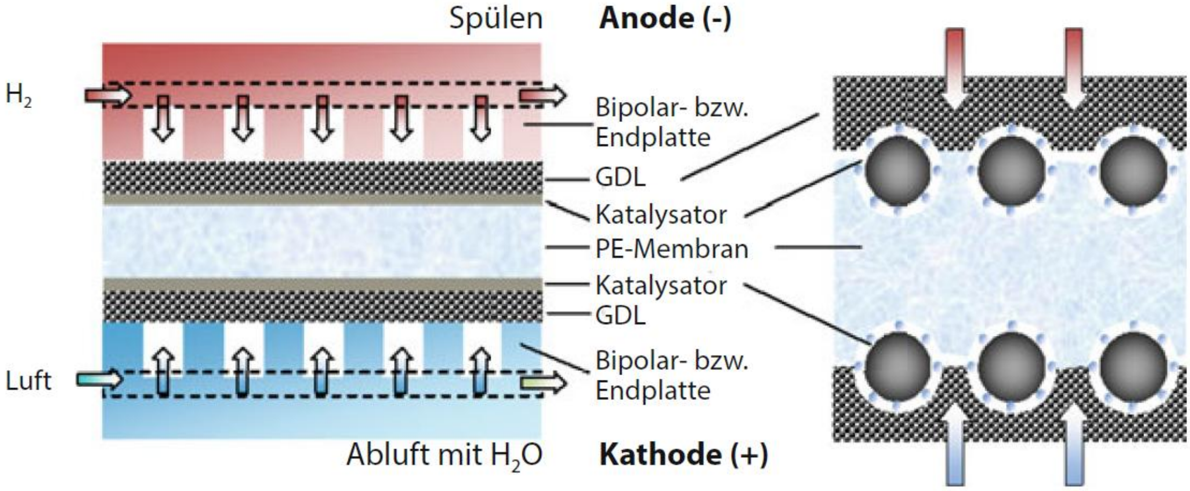

Fig. 2.1: Schematic structure of a PEM fuel cell[1]

The electrolyte separates the two reaction spaces with the corresponding reactants from each other, but at the same time is permeable to H+ ions. The catalyst layer on the anode and cathode sides is used to reduce the activation energy of the electrochemical reactions. The gas diffusion layer ensures both electrical and thermal contact with the outer bipolar plates, but at the same time also serves the uniform distribution of the incoming gases (e.g. hydrogen at the anode and oxygen at the cathode) as well as the supply and removal of water for membrane humidification (water management). Together with the bipolar plates, the GDL form so-called gas distribution structures, which are intended to enable optimal distribution of gases. The gas distribution structures not only ensure the transport of the gases to the gas diffusion electrodes, but also ensure electrical contact between the individual cells and must therefore have a high electrical conductivity. An additional function is the removal of heat through appropriate cooling channels.

The bipolar plates are usually made of a metallic material (e.g. titanium) or of graphite or carbon composite materials. Channels are milled into the bipolar plates (flow fields), which are supposed to distribute the gas evenly over the entire surface. The GDL, on the other hand, are mostly made of carbon fiber substrate, which is reinforced with carbonized plastic Hartz. In order to consume electricity, the largest possible contact area must be created between the electrode and the entire gas distribu-

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[1] J. Lehmann, T. Luschtinetz: Hydrogen and Fuel Cells, Springer-Verlag, 2014

tion structure, because gas diffusion electrodes usually have poor transverse conductivity due to their porous structure and low thickness. The complicated structure and functioning of the gas diffusion electrode, which makes fuel cell operation possible in the first place, but at the same time also entails difficult handling, is explained in the following section.

2.3 The Gas Diffusion Electrode

Fuel cell operation requires a large active surface area at both electrodes in order to minimize overvoltages and thus voltage losses (see Chapter 4). In principle, such a large active surface corresponds to an extended three-phase zone (solid, liquid, gaseous) inside the electrode. Fig. 2.2:Figure 2 shows the idealized structure of a gas diffusion electrode with an extended three-phase zone. This requires a high specific surface area of the catalyst material used. Furthermore, the entire surface of the catalyst material must be electrically contacted and in contact with the electrolyte and gas.

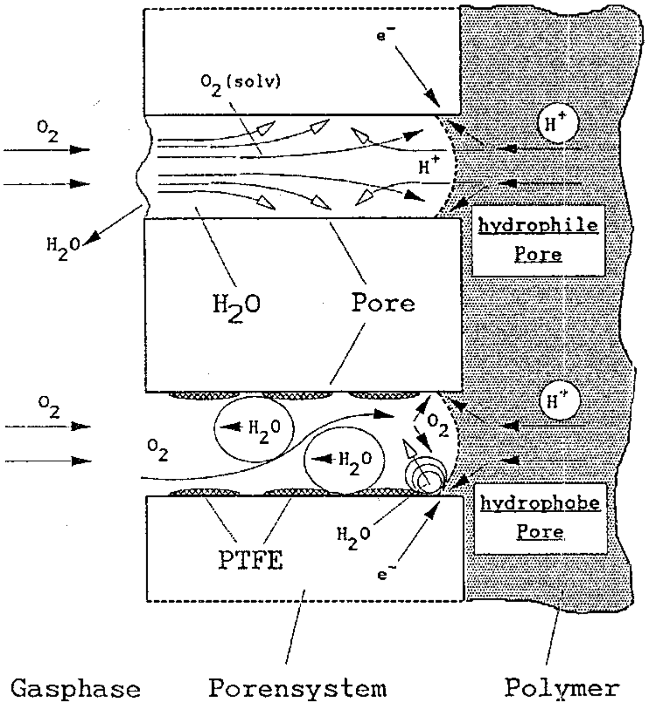

Fig. 2.2: Idealized structure of a gas diffusion electrode (PEMFC)

The electrode must have a porous structure inside to ensure sufficient gas supply and water removal. In this porous structure, the transport of substances to and from the three-phase zones must be able to proceed as uninhibited as possible. A three-phase zone thus contains the catalyst and the electrolyte (both solid), the gaseous reactants and water (liquid). In addition to the catalytic activity, electrical and ionic contact as well as gas contact are required to operate an electrode. The processes within the complicated structure of the gas diffusion electrode are so complicated that no complete model to describe them exists to date. One is dependent on empirical correlations, among other things.

2.4 The Cell Stack

The fuel cells are interconnected to form a cell stack by layering the individual cells on top of each other in a sandwich design and e.g. by bipolar plates (see Fig. 2.3). The outer metal housing compresses the array to ensure sufficient electrical contact between the electrolyte matrix and the electrodes.

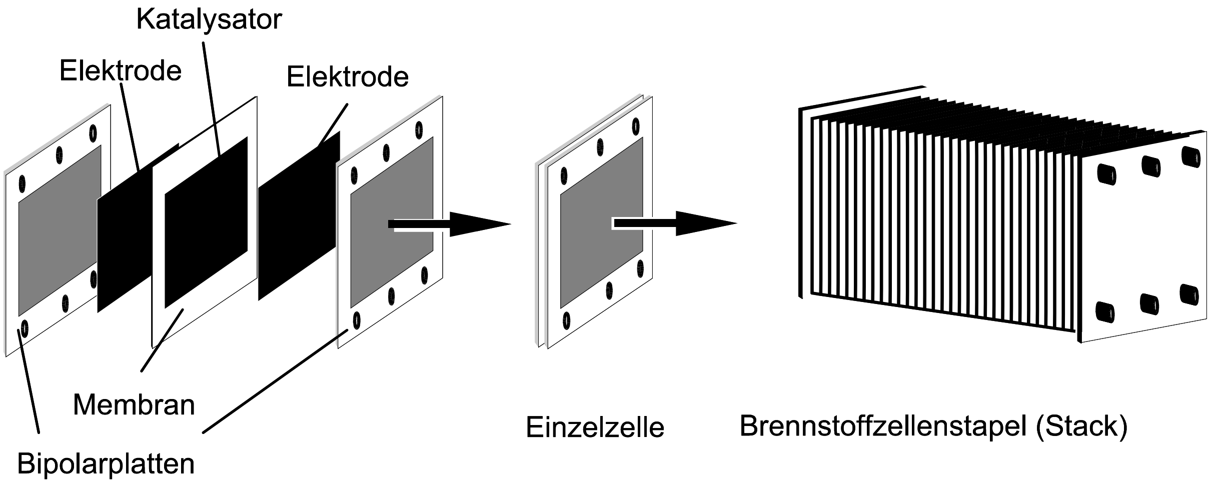

Fig. 2.3: Schematic representation of a fuel cell stack

The gases are distributed to the gas channels of the individual cells and recombined after flowing through the cell stack. Usually, the fuel gas and the combustion air are carried in a cross-flow because this is the simplest stack setup. The cell units are connected in parallel on the gas side and in series on the voltage side.

2.5 The fuel cell system

In general, a fuel cell energy conversion system consists of four components: gas process system, energy conversion, electrical system, system technology (see Fig. 2.4). The inverter, which converts the direct current generated in the cell into grid alternating current, is a universal electronic component and is simply downstream of the stacks.

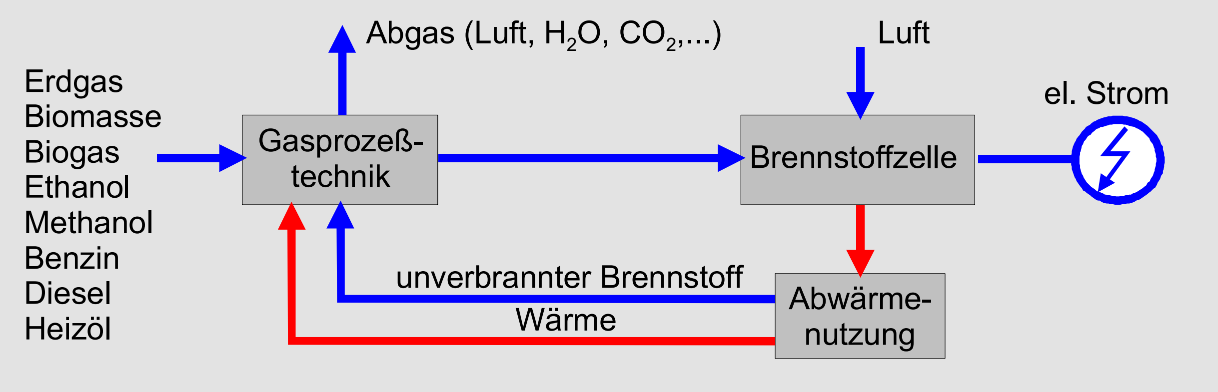

Fig. 2.4: Simplified scheme of a fuel cell system

However, the other sub-areas can have very different dimensions for the different fuel cell types. While ultrapure gases that can only be obtained by complex processes are used for the alkaline cell, high-temperature fuel cells such as MCFC and SOFC have the option of reforming the natural gas or coal gas used internally. Peripheral devices for reforming the fuel gas used to hydrogen are no longer necessary and the plant is given a comparatively simple structure. However, appropriate catalysts must be introduced into the electrode space (usually nickel compounds for reforming and copper for the further conversion of carbon monoxide).

In addition to the fuel cell stack, energy conversion includes the entire reuse of the escaping gases (e.g. by catalytic post-combustion). Here, too, there are big differences due to the cell properties. In the case of high-temperature cells, combined heat and power or process steam generation is a good option, while the waste heat from alkaline cells or the (low temperature) PEMFC, which is at a temperature of approx. 80° C, can be used to heat domestic water.

3 Operation of PEM fuel cells

The PEMFC works with hydrogen or with carbon dioxide-containing reformer gas as fuel and can be operated with air on the cathode side. The advantages of PEMFC are in particular the uncomplicated handling of the solid electrolyte (PE membrane), the low weight and the high power density due to the good proton conductivity of the electrolyte. A major disadvantage, however, is the susceptibility to carbon monooxide (CO), which requires a high purity of the fuel gas. The carbon monooxide is absorbed by the anodic precious metal catalyst (platinum) and deactivates it after a short time. For reforming, i.e. the conversion of hydrocarbons with the addition of water to hydrogen and carbon dioxide, an external, upstream process step is required. This also includes the subsequent purification of the reformer gas from carbon monooxide (CO).

Another difficulty in the operation of the PEM fuel cell is the so-called water management. The membrane is only proton-conductive when moist, so water must remain in the cell at all times. On the other hand, flooding of the cathode with reaction water must be prevented. The operation of the cell comes to a standstill in both cases (drying out and flooding). The development of high-temperature PEMFC (operating temperature between 120 and 200°C) has increased the CO tolerance compared to low-temperature PEMFC (operating temperature between 60 and 80°C) and at the same time greatly simplified the complex water management process for humidifying the membrane.

3.1 Water

The resistivity of the membrane is strongly dependent on the water content and temperature. The water content of the membrane in fuel cell operation depends on the operating condition of the cell. Factors such as the current density, the water transport effects and the moisture of the gases influence the local water content of the membrane. The different water transport processes within the membrane are shown in Fig. 3.1. The protons that migrate through the membrane carry water molecules to the cathode in their hydrate shell. This electro-osmotic water transport (*xHydr*) reduces the water content of the electrolyte on the anode side (hydrogen) and increases on the cathode side (oxygen or air). The water gradient in the electrolyte is additionally increased by the reaction water produced on the cathode side and causes constant re-diffusion of the water (*xDiff*). The re-diffusion of the water can be supported by an increased gas pressure on the cathode side. This effect is called hydraulic permeation (*xPerm*). The water effectively transported through the membrane (*xeff*) must be supplied to the anode to maintain the water content and conductivity of the membrane. This can be done, for example, by moistening the hydrogen.

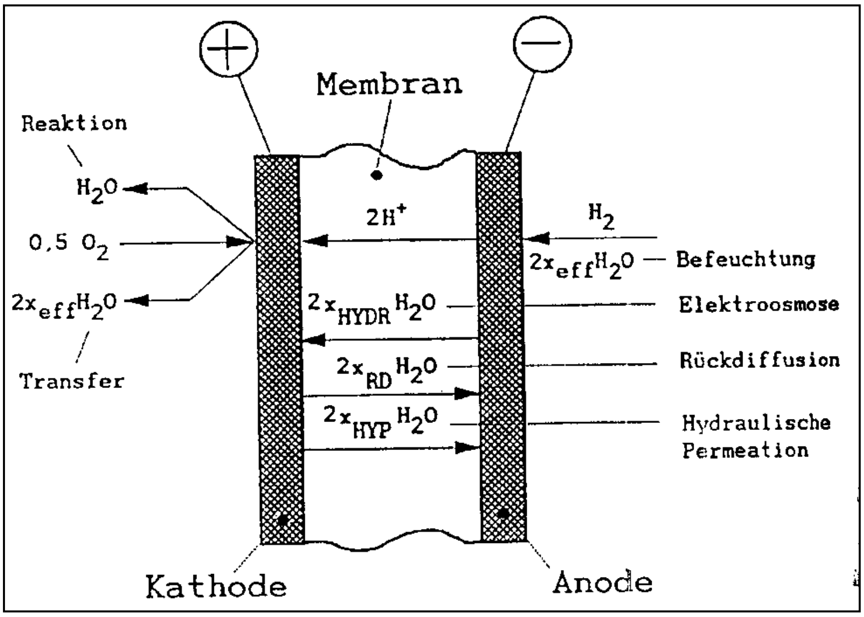

Fig. 3.1: Water transport processes in the electrolyte of a PEMFC

3.2 Hydrogen turnover

Depending on the cell type or cell geometry, many fuel cells are not able to fully convert the hydrogen supplied and therefore have to be operated with a surplus. For this reason, the gas outlets of the cell in these fuel cells are open *(open end*) so that hydrogen that has not been converted can leave the cells. For reasons of efficiency, it makes sense to use the hydrogen that cannot be converted by the fuel cell to other applications within the system after it leaves the fuel cell. For example, the surplus hydrogen can be used to operate a burner for hydrogen production or other heating purposes (see section 2.6). When gas outlets are closed and sales are virtually complete, this is referred to as *dead-end operation*. However, even with these cells, it is usually necessary to open the gas outlets, at least for a short time, in order to prevent collecting water from flooding the gas distribution structure and thus the reaction from coming to a standstill. This process is usually carried out with a solenoid valve, which is opened at intervals so that the water can be expelled (*purging*).

3.3 Air ratio λ

The oxygen intended as a reaction partner is taken from the ambient air, as in many fuel cell applications. The calculation of the air volume flow results directly from the hydrogen flow and the composition of the air under the assumption of ideal gases $x_{O_2}^{Luft}$:

$$\dot{V}_{Luft}^{ein} = \lambda \cdot \dot{V}_{Luft}^{\text{stö}} = \lambda \cdot \frac{\dot{V}_{O_2}^{\text{stö}}}{x_{O_2}^{Luft}} = \lambda \cdot \frac{\dot{V}_{H_2}^{ein}}{2 \cdot x_{O_2}^{Luft}} \quad 3.1$$

In the above equation, λ represents the ratio of the supplied air to the air necessary for the stoichiometric conversion of the supplied hydrogen stream. It is also possible to relate the air ratio to the hydrogen flow actually converted. However, it is not known from the outset to what extent the hydrogen supplied will actually be converted. The air ratio is an important factor influencing the operating behavior of a fuel cell and the design of the periphery of a fuel cell system.

4 Thermodynamic basics

At the two electrodes of fuel cells, regardless of type, the same *gross reaction* always takes place as so-called *cold combustion* (cf. Formula 1.1). The partial reactions at the anode and cathode vary from type to type and are based on the chemical nature of the electrolyte (see Fig. 1.1). The chemical energy stored in the fuel is converted directly into electrical energy via an electrochemical reaction. The maximum work to be gained corresponds to the free enthalpy of reaction Δ_{RG} of the cell reaction:

$$\Delta_R G = \Delta_R H - T\Delta_R S \, . \tag{4.1}$$

In reversible operation, the highest achievable voltage is given by the free enthalpy and is calculated with the following relation:

$$U_{rev} = -\frac{\Delta_R G}{zF} \, . \tag{4.2}$$

This means:

$Urev$	electric potential difference (voltage between the electrodes) [V],
ΔG	free enthalpy of the reaction [kJ $^{mol-1}$],
z	Number of electrons transferred in the electrode reaction,
F	Faraday constant [F = 96487 C $^{mol-1}$].

In contrast to reversible cell voltage, thermoneutral cell voltage does not refer to the free enthalpy Δ_{RG0}, but to the reaction enthalpy Δ_{RH0} under standard conditions:

$$U_{th} = -\frac{\Delta_{\mathrm{R}} H}{zF} \, . \tag{4.3}$$

Under standard conditions (T = 298.15 K, activity of all species = 1), the reversible cell voltage is $Urev,o$ = 1.23V ($Urev,u$ = 1.18V) and the thermoneutral cell voltage is Uth,o = 1.48V (Uth,u = 1.25). The indices (o, u) indicate whether the values refer to the upper or lower reaction enthalpies (Δ_{RG}, Δ_{RH}).
However, the numerical value for the electrical potential difference is not always constant, but varies depending on pressure and temperature according to the dependence of the free enthalpy ΔG on these quantities. Expressed in formulas, the temperature dependence is:

$$\left(\frac{\partial U_{rev}}{\partial T}\right)_p = -\frac{1}{zF}\left(\frac{\partial \Delta_R G}{\partial T}\right)_p = \frac{\Delta_R S}{zF} < 0 \tag{4.4}$$

and the pressure dependency:

$$\left(\frac{\partial U_{rev}}{\partial p}\right)_T = -\frac{1}{zF}\left(\frac{\partial \Delta_R G}{\partial p}\right)_T = -\frac{\Delta_R V}{zF} > 0\,. \qquad \mathbf{4.5}$$

Accordingly, the temperature dependence is given by the entropy change in the reaction Δ_{RS} and the pressure dependence by the volume change in the reaction $\Delta_{RV.}$ The gaseous components can be treated as ideal gases at low pressures. The total dependence of the electric potential difference *Urev* on pressure, temperature and composition can be described in this case using the NERNST equation using the activities of the reacting species:

$$U_{rev}(T,a) = U_{rev}^{0} - \frac{RT}{zF}\ln\left[\frac{a_{H_2O}}{a_{H_2}a_{O_2}^{0,5}}\right] + \frac{1}{zF}\int_{298}^{T}\Delta_R S dT\,. \qquad \mathbf{4.6}$$

This means:

R	general gas constant [8.314 J $^{\text{grad-1 mol-1}}$],
T	absolute Temperature [K],
Ai	activities of the species involved in the reaction.

The equation shows that the thermodynamic equilibrium stress decreases with increasing temperature and increases with increasing pressure (see Fig. 4.1). When the cell is operated with air instead of pure oxygen, lower equilibrium voltages are also to be expected due to the lower oxygen partial pressure.

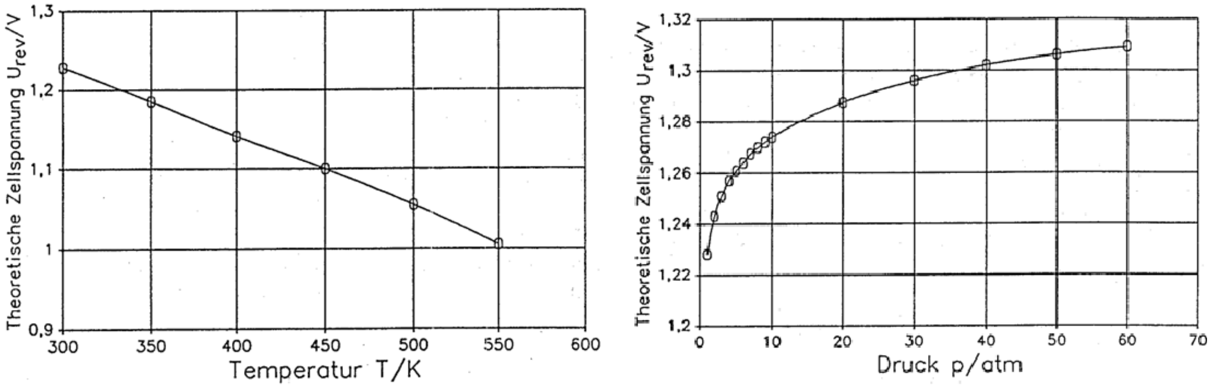

Fig. 4.1: Dependence of the reversible cell voltage on temperature and pressure

The maximum (ideal) efficiency that is possible with reversible operation of the cell unit is obtained by relating the reversible cell voltage or the change in the free enthalpy to the change in the reaction enthalpy:

$$\eta_{U,\max} = \frac{\Delta_R G}{\Delta_R H^0} = \frac{-U_{rev} zF}{\Delta_R H^0}\,. \qquad \mathbf{4.7}$$

Under standard conditions, the maximum efficiency is $\eta_{U,max}$ = 0.83. The difference between the free reaction enthalpy and the reaction enthalpy is the reaction entropy. It is emitted as heat and is linked to the so-called reversible overvoltage $\Delta Urev$:

$$\Delta U_{rev} = \frac{-T\Delta_R S}{zF}. \qquad \textbf{4.8}$$

The previous considerations are almost exclusively related to reversible systems. In real fuel cells, however, there is no longer any reversibility of the cell reactions even at low current densities, and the value of the cell voltage increasingly decreases with further load on the cell due to higher current densities. In numerous electrode reactions, such as oxygen reduction and oxygen development, the resting potential is already lower than the reversible electrode potential. The characteristic current-voltage characteristics of fuel cells and the typical loss mechanisms are discussed in more detail in the following section.

5 Kinetics

If electricity is taken from a fuel cell, the terminal voltage deviates from the quiescent voltage, just like in battery systems. The reason for this lies in the occurrence of so-called overvoltages (polarizations) at the electrodes, i.e. voltage losses relative to the resting potential of the respective electrode. In this context, it is important to note that the current-voltage characteristic of a fuel cell is composed of the current-potential curves of the individual electrodes (anode and cathode) and the voltage drop at the electrolyte resistance. This reveals a fundamental problem: The voltage difference between electrode and electrolyte, the so-called absolute potential, is unknown and measurements are not accessible in principle. However, when one speaks of individual voltages, which are often referred to as equilibrium electrode potentials, one always means cell voltages that are measured against an auxiliary / reference electrode. The reference value for all electrode voltages is the normal hydrogen electrode, whose individual voltage is set to zero by international convention. In addition to the *reversible voltage difference* (see Chapter 3), three further loss mechanisms (overvoltages) of fuel cells are described below:

1. Penetration overvoltage,
2. Concentration overvoltage,
3. Ohm's overvoltage.

5.1 Penetration Surge

The passage overvoltage *ηD* of an electrode is based on the finite speed of the charge passage of the electrons through the phase boundary electrode / electrolyte (i.e. electron conductor / ion conductor). The speed of passage depends on the species involved in the passage reaction, the electrolyte as well as the electrocatalysts (e.g. precious metals). There is an exponential relationship between current density and penetration overvoltage, which is described by the BUTLER-VOLMER equation. It is for each individual electrode:

$$i = i_+ - |i_-| = i_0\left(\exp\left[\frac{\alpha zF}{RT}\,\eta_D\right] - \exp\left[\frac{-(1-\alpha)zF}{RT}\,\eta_D\right]\right). \qquad \textbf{5.1}$$

This means:

i	Current density [A $^{cm-2}$]
$i0$	Exchange current density [A $^{cm-2}$]
$i+$	anodic partial current density of the electrode [A $^{cm-2}$]
i_-	cathodic partial current density of the electrode [A $^{cm-2}$]
α	a symmetry factor that indicates in which region of the HELM-HOLTZ´ bilayer the transition state of the reaction to be activated arises
z	Number of electrons transferred in the electrode reaction
F	Faraday constant [F = 96487 C $^{mol-1}$]
η_D	Penetration Surge [V].

At the phase boundary electrode / electrolyte there is a dynamic equilibrium, i.e. even in the equilibrium state ($\eta D = 0$) the phase limit is constantly exceeded by charge carriers in both directions, although no current flows outwards through the electrode. The *current of the same magnitude for* $\eta D = 0$ *in both directions is called the exchange current density* i0 and is thus a measure of the speed at which the equilibrium is adjusted. The exchange current density, together with the factor $\alpha zF/RT$, *determines* the level of the penetration overvoltage.

In electrochemical systems, the magnitude of the exchange current density varies in a wide range from fractions of μA/cm² (e.g. oxygen reduction) to a few A/cm² (e.g. reduction of silver ions to silver). Compared to oxygen reduction, the exchange current densities of hydrogen oxidation are 3 to 4 orders of magnitude higher (mA range). In contrast to the concentration supervoltage, the penetration overvoltage is a characteristic quantity for the respective electrode reaction (electrocatalyst, electrolyte, temperature), which cannot be reduced even by optimized electrode design.

5.2 The Concentration Surge

The electrochemical reactions take place on the electrode surfaces. The conversion reduces the concentration of the reactants near the electrode surface. To ensure that the reaction does not come to a standstill, the reactants must be supplied by diffusion. At the same time, the concentration of the reaction products that have to be removed increases. These mass transport processes, which take place in the immediate vicinity of the electrode exclusively by diffusion, are generally described by the 1st FICK´ law. In individual systems and assuming a linear decrease in concentration, this is simplified for a component to the expression:

$$\dot{n} = D\frac{(c_0 - c_s)}{\delta}. \tag{5.2}$$

This means:

$c0$	undisturbed concentration [mol $^{dm-3}$],
Cs	Surface concentration [mol $^{dm-3}$],
D	diffusion coefficient [cm² $^{s-1}$],
δ	Thickness of the Nernst diffusion layer [cm],
$\dot{n}_i$	Flow rate of species i [mol $^{s-1}$].

Due to the transport of substances in the electrolyte and the electron transport in the electrical conductors, equal amounts of charge are transported in each case when the current flows. The material turnover in the fuel cell is calculated as follows:

$$\dot{n} = \frac{i \cdot A}{zF}. \qquad 5.3$$

Inserted into the preceding equation, the result is:

$$i = zFD\frac{(c_0 - c_s)}{\delta}. \qquad 5.4$$

The maximum current density with which a fuel cell can be loaded is reached when the reaction on the surface of the electrode is so fast compared to the mass transport that the concentration on the electrode surface *cs* drops to zero. The following expression is obtained for the so-called limit current density *iL* :

$$i_L = zFD\frac{c_0}{\delta}. \qquad 5.5$$

The concentration overvoltage, i.e. the voltage drop caused by the mass transport, is calculated from the difference in the concentration-dependent electrochemical potential within the electrolyte:

$$E = E^0 - \frac{RT}{zF}\ln c_0, \qquad 5.6$$

and on the electrode surface:

$$E_s = E^0 - \frac{RT}{zF}\ln c_s. \qquad 5.7$$

For the concentration overvoltage, we now get:

$$\eta_{Konz} = E - E_s = \frac{RT}{zF}\ln\frac{c_s}{c_0}. \qquad 5.8$$

or after the introduction of the simplified form of the 1st FICK´ law

$$\eta_{Konz} = \frac{RT}{zF}\ln\left(1 - \frac{i\delta}{zFDc_0}\right). \qquad 5.9$$

5.3 The Ohm´ surge

The ohm losses in the cell occur due to the transport resistances during ion transport through the electrolyte and electron transport through the electrode material as well as the current distribution structure and the current arresters. To describe the Ohm´ overvoltage, the definition equation applies:

$$\eta_{Ohm} = iR_{Ohm}. \qquad 5.10$$

In this equation, *i is* the current density and *ROhm* is the total resistance of the cell, which is composed of electronic, ionic, and contact resistors.

6 Performance characteristics

With this knowledge of thermodynamics and kinetics in fuel cells, the performance-related key figures of fuel cells can now be discussed.

6.1 The current-voltage curve

For the characterization of fuel cells, so-called current-voltage curves are usually considered. As shown in Fig. 6.1, the voltage is plotted against the current density. The curve always has the typical course shown. It starts at a voltage $U0$ in the unloaded state. The voltage $U0$ is below the reversible cell voltage $Urev$, since irreversible processes already take place at rest. Due to the penetration overvoltage, the voltage drops relatively sharply at low loads and then passes through a weakly decreasing linear range. In this range, cell operation is dominated by the Ohm´ overvoltage. The concentration overvoltage then limits the maximum current density of the fuel cell. The voltage drops sharply to supply the electrodes with reactants and drops to zero when the cut-off current density is reached.

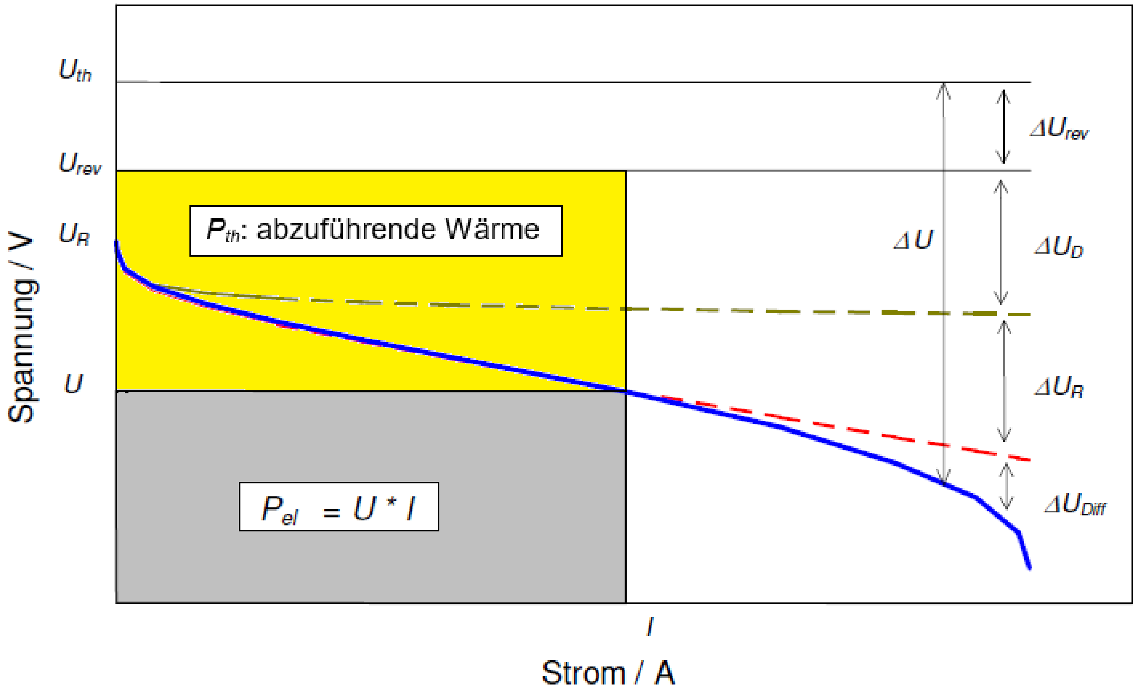

Fig. 6.1: Typical current-voltage curve of a fuel cell

This means:

$\Delta Urev$	reversible voltage difference,
ΔUD	Penetration overvoltage,
DUR	Ohm's overvoltage,
$\Delta UDiff$	Concentration overvoltage.

6.2 Efficiency calculation

The effective cell voltage *Ueff* is determined after subtracting all losses (reversible voltage difference plus overvoltages) from the reversible cell voltage *Urev* :

$$U_{eff} = U_{rev} - \eta_D - \eta_{Konz} - \eta_{Ohm} \,. \qquad \textbf{6.1}$$

The ratio of the effective cell voltage and that of the reversible cell voltage is called the **voltage efficiency U** η:

$$\eta_U = \frac{U_{eff}}{U_{rev}} = -\frac{U_{eff}}{\Delta_R G^0} zF \,. \qquad \textbf{6.2}$$

The so-called **Turnover level *Time*** (or Fuel Utilization) provides information about the utilization of fuel in the fuel cell. The turnover ratio is defined as the ratio of hydrogen converted to hydrogen supplied:

$$\eta_{um} = \frac{\dot{n}_{H_2}^{um}}{\dot{n}_{H_2}^{ein}} \,. \qquad \textbf{6.3}$$

If you multiply the voltage efficiency and the conversion rate, you get the **overall efficiency** η of the fuel cell:

$$\eta_{ges} = \eta_U * \eta_{um} \,. \qquad \textbf{6.4}$$

From a technical point of view, however, the **power efficiency** η_P of the fuel cell is of greater relevance. This refers directly to the electrical power that can be taken from the cell. The calculation of the power efficiency P η can be carried out with the help of the following equation, among others:

$$\eta_P = -\frac{P_{el}}{\dot{n}_{Brenngas} \Delta_R H^0} = -\frac{U_{Stack} \cdot I}{\dot{n}_{Brenngas} \Delta_R H^0} \,. \qquad \textbf{6.5}$$

Another way to determine the power efficiency η_P is the ratio of the effective cell voltage to the *thermoneutral cell voltage*. By multiplying by the Fuel η Utilization, the power efficiency **Pη *of the fuel cell*** is also obtained:

$$\eta_P = \frac{U_{eff}}{U_{th}} \eta_{um} = -\frac{U_{eff}}{\Delta_R H^0} zF \eta_{um} \,. \qquad \textbf{6.6}$$

The power efficiency describes the proportion of hydrogen power used that the fuel cell makes usable in the form of electrical power and thus enables a comparison of the fuel cell with other energy systems.

The amount of heat produced during the processes in the fuel cell is also interesting. The parameter used for this purpose is the **thermal efficiency** η_{th}:

$$\eta_{th} = \frac{\Sigma \dot{Q}}{\dot{n}_{H_2}^{ein} \cdot \Delta h_u} \quad . \qquad \textbf{6.7}$$

The thermal efficiency compares the heat generated to the hydrogen power used. This refers to the total waste heat that is dissipated from the fuel cell in various ways for operation at a constant temperature. Due to various loss effects, such as insufficient insulation or unusable, latent heat in the off-gas streams, it is usually not possible to make the entire thermal output available for further use. In this respect, thermal efficiency is also a measure of the quality of the insulation and the utilization of the waste heat from the fuel cell.