CHARACTERIZATION AND SIMULATION OF A 3.3 KW PEM FUEL CELL

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Fuel cells revolutionize conventional heat and power supply. Worldwide, experts forecast a promising future for the Polymer Electrolyte Membrane Fuel Cell (PEMFC) in mobile, portable and stationary applications. Many investigations concerning fuel cell measurements have been published recently. Those examinations generally focus on voltage-current-curves with a constant fuel utilization as a constraint in the experiments [1]. Therefore, this method does not meet demands of an overall energetic description and a new measurement strategy has to be developed. The analysis technique was applied to a 3.3 kW PEMFC. Afterwards, the results were evaluated in order to provide the basis for a simulation.

METHOD OF MEASUREMENT AND EXPERIMENTAL PROCEDURE

From an energetic point of view the obtainable electric power from a preset hydrogen flow is of high interest. If a constant hydrogen stream is ducted to a fuel cell and the electric current of a connected load is increased, the power output generally passes through a maximum (Fig. 1). A fuel cell is operated most effectively in this peak. Therefore, experiments are performed to determine these optima depending on several influences. A manifold variety of independent parameters affects the fuel cell performance. Covering all dependencies with a precise increment exceeds the experimental feasibility. Consequently, some essential parameters have to be identified. In this case partial load operation and different hydrogen production processes are considered. One fundamental differing parameter of the gas processing is the hydrogen concentration in the anode feed gas, which is varied from 40% up to 90% in the dry gas. This variable is permutated in the experiments with the hydrogen flow (describing partial load). Hence, a two dimensional plane is spanned.
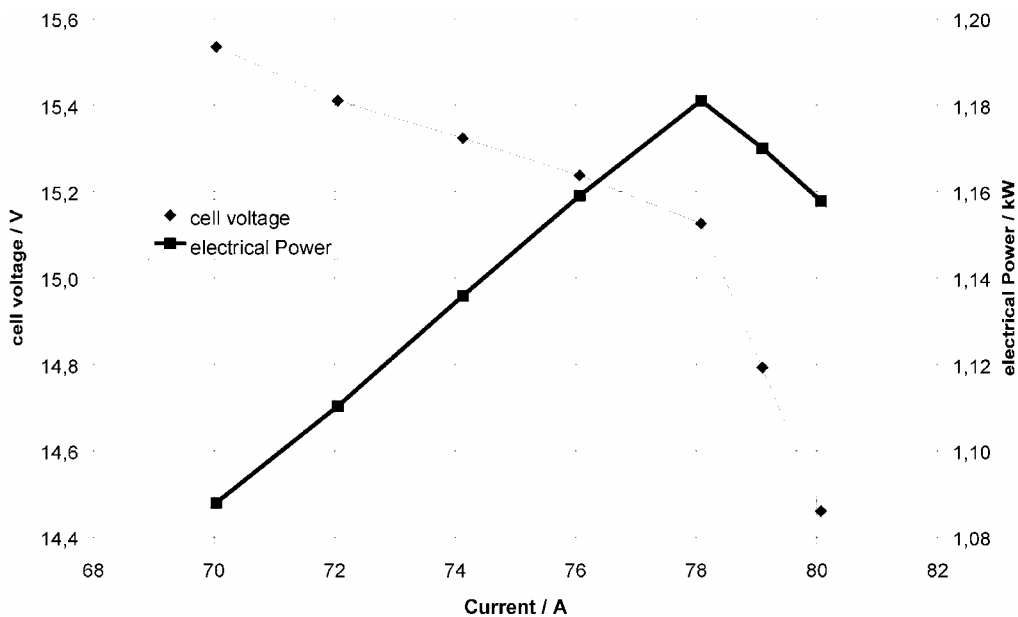

Fig 1.: Voltage-current- power-current-curves of a Siemens fuel cell stack with 10 Nl/min pure hydrogen

Beside these important two factors other influences are of secondary interest. In the following measurements the fuel cell temperature (40 °C – 70 °C), the carbon dioxide concentration in the anode inert gas (0% - 100%) and the stoichiometric cathode air ratio (1,5 – 4) are varied. In order to reduce the experimental procedure the influences of the minor parameters are carried out in one centric point of the plane (70% hydrogen concentration, 50% partial load) to reveal the partial dependencies. For these less relevant parameters reference values have to be defined, which have

to be constant above the reference plane. These values are: fuel cell temperature 60 °C, air ratio 3, no carbon dioxide in the anode feed.

After discussing the independent variables (input) the manner of evaluating the resulting data (output) has to be considered. From an energetic point of view the two pressure drops (anode and cathode) and operating efficiencies are relevant. First, the electric and thermal efficiencies are defined as electric and thermal power output respectively divided by the enthalpy of the fed hydrogen stream (lower heating value).

$$\eta_{el} = \frac{P_{el}}{\dot{n}_{H_2,in} \cdot \Delta h}; \quad \eta_{th} = \frac{\dot{Q}}{\dot{n}_{H_2,in} \cdot \Delta h}$$

Additionally, the fuel utilization is calculated from the experimental data defined as:

$$\eta_{fu} = \frac{\dot{n}_{H_2,utilized}}{\dot{n}_{H_2,in}}$$

Thus, five output parameters depending on five input variables are defined. This measurement technique was applied to a Siemens PEM fuel cell. The stack consists of 20 cells and has 3.3 kW electric power output if operated with pure hydrogen and 3 kW on blended hydrogen-rich gases respectively. For operating the fuel cell under various conditions an appropriate test facility was set up.

EVALUATION
To exemplify a typical evaluation a diagram is displayed (Fig. 2). Measurements are symbolized by the points and the surface reflects the best fitted function. The generated plane is based on an equation found by importing the data into the software TableCurve™ 3D. This program has been designed to automatically fit large numbers of candidate surface-fit equations in a fully automated fashion. The selected equations are empirical and have no physical background but show reasonable interpolating values and boundary behavior.
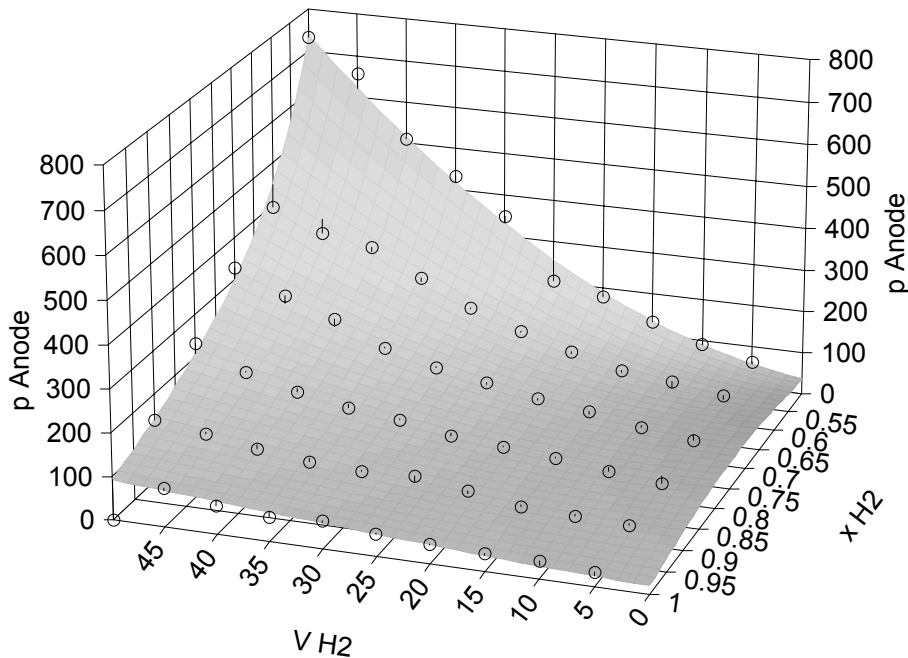

Fig 2: Example of 3-dimensional evaluation and curve fitting

After evaluating the data above the reference plane, partial dependencies are considered one-dimensionally and trend lines are fitted. The trend lines are normalized at the point, where the partially varied parameter has the reference value mentioned above. Thereby multiplicands are generated with the meaning of correction factors.

Below the five output parameters are presented as a function of the five input variables.

$$\Delta p_{Anode} = EXP\left(1{,}5358 - 194{,}66 \cdot 10^{-6} \cdot x_{H_2}^2 + 65{,}893 / x_{H_2} + 0{,}5946 \cdot \sqrt{\dot{V}_{H_2}}\right)$$
$$\cdot \left(3{,}435 \cdot 10^{-3} \cdot T + 0{,}794\right) \cdot \left(-60{,}32 \cdot 10^{-3} \cdot \lambda + 1{,}181\right) \cdot \left(2{,}858 \cdot 10^{-3} \cdot x_{CO_2} + 1\right)$$

$$\Delta p_{Cathode} = \left(5{,}464 + 9{,}971 \cdot \dot{V}_{H_2} + 0{,}001 \cdot \dot{V}_{H_2}^3\right)$$
$$\cdot \left(-471{,}5 \cdot 10^{-6} \cdot T^2 + 0{,}05215 \cdot T - 0{,}4319\right) \cdot \left(12{,}93 \cdot 10^{-3} \cdot \lambda^2 + 0{,}314 \cdot \lambda - 57{,}86 \cdot 10^{-3}\right)$$

$$\eta_{fu} = \left(0{,}4313 + 1{,}986 / x_{H_2} + 0{,}02 \cdot \dot{V}_{H_2} - 361 \cdot 10^{-6} \cdot \dot{V}_{H_2}^2\right)$$
$$\cdot \left(-54{,}3 \cdot 10^{-6} \cdot T^3 + 8{,}413 \cdot 10^{-3} \cdot T^2 - 0{,}4267 \cdot T + 8{,}043\right)$$
$$\cdot \left(-41{,}5 \cdot 10^{-3} \cdot \lambda^2 + 0{,}283 \cdot \lambda + 0{,}526\right) \cdot \left(-28{,}11 \cdot 10^{-6} \cdot x_{CO_2}^2 + 5{,}454 \cdot 10^{-3} \cdot x_{CO_2} + 1\right)$$

$$\eta_{el} = \left(\frac{1}{1{,}937 + 4{,}981 \cdot 10^{-5} \cdot x_{H_2}^{2,5} - 5{,}08 \cdot 10^{-6} \cdot x_{H_2}^3 + 6{,}62 \cdot 10^{-6} \cdot \dot{V}_{H_2}^3}\right)$$
$$\cdot \left(-43{,}96 \cdot 10^{-6} \cdot T^3 + 6{,}668 \cdot 10^{-3} \cdot T^2 - 0{,}3297 \cdot T + 6{,}272\right) \cdot \left(56{,}66 \cdot 10^{-3} \cdot \lambda + 0{,}83\right)$$

$$\eta_{th} = \left(0{,}9264 - 7{,}11 \cdot 10^{-3} \cdot \dot{V}_{H_2} - 1{,}457 / \dot{V}_{H_2}^{0,5}\right) \cdot \left(-562{,}7 \cdot 10^{-6} \cdot T^2 + 0{,}03657 \cdot T + 0{,}831\right)$$
$$\cdot \left(46{,}032 \cdot 10^{-3} \cdot \lambda + 0{,}8619\right) \cdot \left(-34{,}22 \cdot 10^{-6} \cdot x_{CO_2}^2 + 5{,}879 \cdot 10^{-3} x_{CO_2} + 1\right)$$

It has been controlled if these equations are consistent with basic boundary conditions e.g. maximum efficiency, positive definite functions, etc. These equations can be adapted to other electric power outputs for modeling of other fuel cells by adjusting the hydrogen volume flow linearly.

SIMULATION
Those information were programmed in ASPEN Plus® and the corresponding flowsheet will be explained according to figure 3. The anode feed gas is separated into the converted permeated hydrogen in correlation to the equation of η_{fu}. This unit operation might require a heat stream HEAT3. The complete PERMEAT reacts with air in the reactor KATHODE and the product gas is fed to a heat exchanger. The losses are calculated by the sum of all heat streams minus the electrical and thermal power (according to η_{el} and η_{th}). Finally, the necessary input pressures are computed by the pressure drops ($\Delta p_{Cathode}$ and Δp_{Anode}).

This simulation is a useful tool to calculate the overall stack performance based on five input variables. Thereby interaction of components like gas processes or pumps with the fuel cell can be investigated efficiently on a simulation basis. The accuracy of the results is fairly high, because the origin of the simulation are measurements at a real fuel cell.
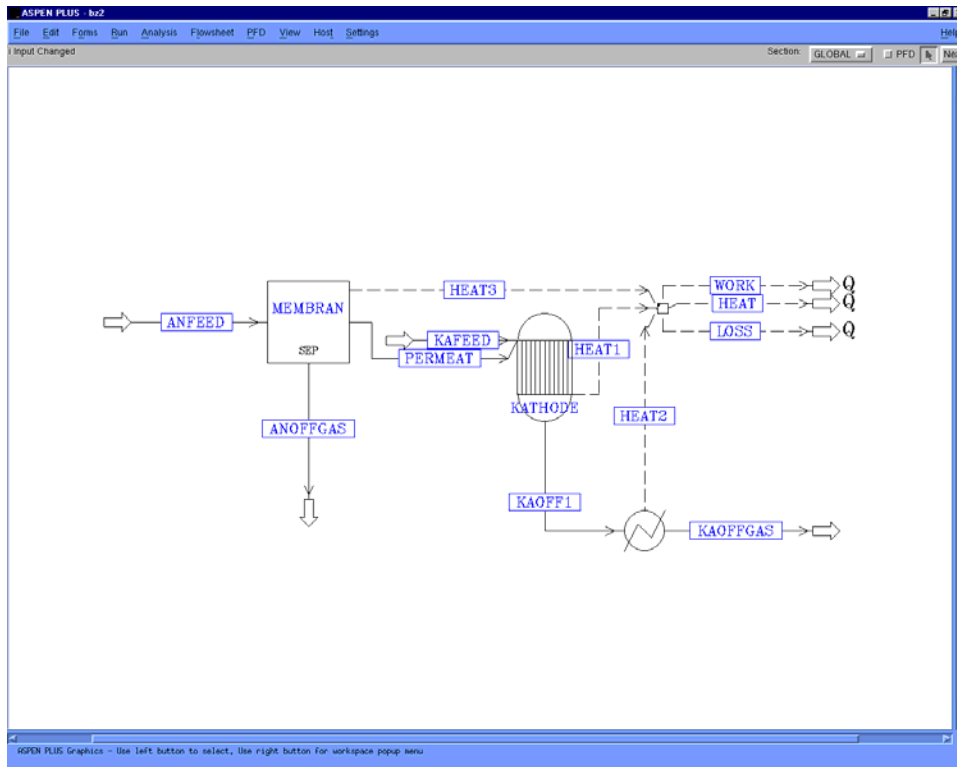
Fig. 3: Flowsheet of fuel cell simulation with ASPEN Plus®

CONCLUSION

A new method of characterizing a fuel cell stack was presented, which enables an energetic simulation. Especially the fuel utilization, the thermal and electric efficiency are measured in the operating optima. This technique was applied to a Siemens fuel cell and the results were evaluated that real effects of the stack can be simulated.

References:
[1] Chahine, R.: Characterization of a Ballard Mk5-E PEM fuel-cell stack, Volume: 2001, Issue: 136, August, 2001, pp. 14