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Testing and model-aided analysis of a 2 kW_{el} PEMFC CHP-system

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Abstract

A prototype PEMFC CHP-system (combined heat and power) for decentralised energy supply in domestic applications has been installed in the Fuel Cell Testing Laboratory at the Institut für Werkstoffe der Elektrotechnik (IWE), Universität Karlsruhe (TH). The system, which was developed at the Zentrum für Sonnenenergie- und Wasserstoff-Forschung ZSW, Ulm (FC-stack) and the Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg (reformer) is operated and tested in close cooperation with the Stadtwerke Karlsruhe. The tests are carried out as part of the strategic project *EDISon*, which is supported by the German Federal Ministry of Economics and Technology (BMWA).

The performance of the system is evaluated for different operating conditions. The tests include steady state measurements under different electrical and thermal loads as well as an analysis of the dynamic behaviour of the system during load changes. First results of these steady state and dynamic operation characteristics will be presented in this paper.

Keywords: PEMFC; CHP-system; BoP; System testing

1. Introduction

1.1. Literature survey

In the early 1990s, many authors already pointed out the increasing importance of fuel cell based domestic combined heat and power generation systems [1,2]. At that point in time it was expected that these systems could be the first fuel cell systems for commercialisation, with utility and gas companies supporting this development. However, it took the good part of a decade until the first prototype systems were finally reported by utility companies, heating appliance manufacturers and R&D centres in Europe, Japan, and the US [3–6]. Gradually, further steps towards industrialisation and product development were reported [7–9] including long-term performance [4], system efficiencies [9,10] and cost analyses [11]. In parallel, researchers developed simulation based models of CHP systems as reported for instance in [12–14]. However, despite intensive efforts, a product launch can be expected only in a few years. Reasons for this are still insufficient operational experiences with the systems and, in many cases, a short life span of the fuel cells employed. In addition, the operation management has to be optimised and the efficiency of the systems must be increased.

1.2. BMWA lead-project EDISon

The claim for CO_2 reduction and the phasing out of nuclear energy in Germany will cause a reorganisation of the energy scenery towards distributed power generation. Within the framework of the EDI Son project (Integration of Distributed Energy Systems via Innovative Communication and Management Structures), one of the first leadprojects of the German

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Nomenclature

LHV	lower heating value ($J\,mol^{-1}$)
$\dot{n}$	mole flow ($mol\,s^{-1}$)
η	efficiency
$\Delta_R H^0_{298\,K}$	heat of reaction ($kJ\,mol^{-1}$) at 298 K and 1.013 bar

Federal Ministry of Economics and Labour (BMW A), intelligent electricity grids were deployed by use of distributed, innovative generation, storage, information and communication systems. The infrastructure developed within the project allows the large-scale implementation of distributed generators and makes them usable to gather economical and qualitative advantages for the grid operation as well as for the power production.

Today's supply structures for electricity have strict top–down architecture, which admit energy flow in one direction, from the high to the low voltage grids only. The needed flexibility of the low-voltage grids, concerning the ability to implement a great number of distributed generation systems, is not given.

In the approach of the EDISon project, the existing central and hierarchic supply structure will be supplemented by measuring devices and bidirectional communication systems for all voltage levels.

These units may control an increasing distributed power generation and even manage a bidirectional energy flow within the same or between different voltage levels.

In the supply area of the Stadtwerke Karlsruhe, all upcoordinator of the EDISon project, several pilot installations of distributed systems were carried out. One of them an innovative 2 kW_{el} PEM fuel cell system including reformer.

1.3. Fuel cell CHP-system

The fuel cell system developed by the Centre for Solar Energy and Hydrogen Research Ulm (ZSW) and the Fraunhofer Institute for Solar Energy Systems Freiburg (ISE) is situated at a test bench at the Institut für Werkstoffe der Elektrotechnik IWE, Universität Karlsruhe (TH).

The PEMFC CHP system operates with natural gas, which is converted to hydrogen by a steam reforming unit including a CO shift step. A CO purification is carried out by selective oxidation. The product gas, which is fed to the stack, exhibits a CO concentration < 50 ppm. The PEMFC stack consists of 80 cells with an electrode area of 126 cm^2 each. Further components in the system are a desulphurisation unit, a water purifying unit, compressors for air and fuel and a power inverter for grid connection. A data acquisition and control unit is used to operate the system and to carry out different tests. The complete system supplies 2 kW electricity and approximately 4 kW heating power at 60 °C for domestic hot water and space heating. In its function as a demonstration system, it is intended to provide not only operating experience but also reliable data about the efficiency of fuel cell CHP plants with natural gas reformers in a decentralised energy supply. A detailed description can be found in the following sections.

The unit is in operation since Mai 2004 and had to pass a range of tests with the main focus on modulation times and overall behaviour. By testing the fuel cell heat and power plant the project partners achieved new insights about applications for the residential energy supply. Should the achievements remain that positive, the system may absolutely compete with those of other manufacturers.

2. System description

2.1. Reformer unit

The CHP unit is fully automatically controlled via a Siemens SPS. The visualisation of the plant was done with the program ProTool™. Process relevant data (temperatures etc.) can be monitored and controlled, thus a variable operation control (for example variation of the reforming temperature, steam to carbon ratio) is possible. Under its rated operation conditions, Fraunhofer ISE's reformer system produces 2 $Nm^3\,h^{-1}$ hydrogen containing carbon dioxide (CO_2), water vapour and small quantities of methane and carbon monoxide (CO). Besides the actual steam reforming reactor, the reformer system includes a burner, several integrated heat exchangers and a CO shift reactor (medium temperature shift, MTS) for CO reduction. In Fig. 1 each unit operation in the PFD (right-hand-side) is linked to the corresponding part of the actual system (left-hand -side).

The natural gas and process water streams are heated up in integrated heat exchangers by the exhaust gas from the burner and the hydrogen rich product gas (reformate). No electrical heater is needed.

The steam reforming process is generally defined by the following Eqs. (1) and (2).

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2; \quad \Delta_R H^0_{298\,K} = 206.1\,kJ\,mol^{-1} \quad (1)$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2; \quad \Delta_R H^0_{298\,K} = -41.2\,kJ\,mol^{-1} \quad (2)$$

The reaction Eqs. (1) and (2) are sufficient to describe the reformer system completely.

Under certain process conditions (small temperature in the outlet of the reforming zone, steam to carbon ratio too small) carbon can be formed. A cause can be the thermal cracking of methane in accordance with reaction (3).

$$CH_4 \Leftrightarrow C + 2H_2; \quad \Delta_R H^0_{298\,K} = 75\,kJ\,mol^{-1} \quad (3)$$

The occurrence of the crack reaction (3) is suppressed by an over-stoichiometric addition of process water. The steam to

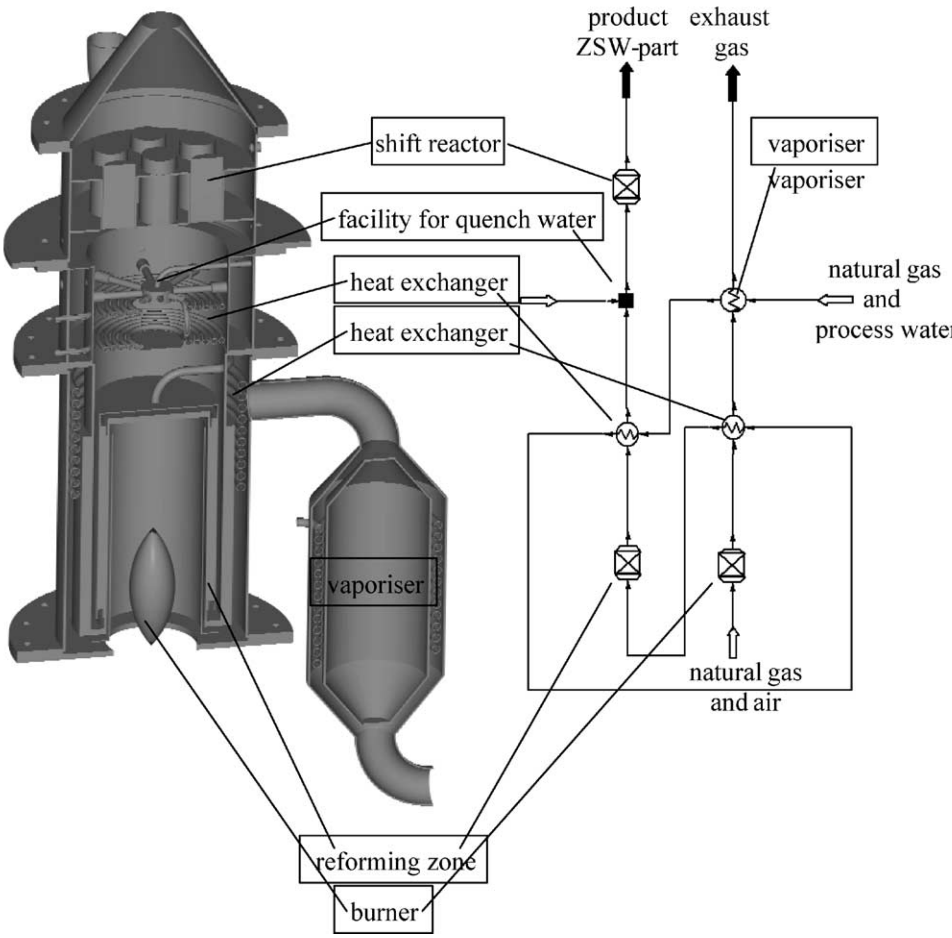

Fig. 1. Flow sheet of the reformer system and cross section of actual system.

carbon ratio (S/C-ratio) is defined as a quotient of process water and natural gas. The S/C-ratio is monitored/controlled as a process relevant parameter. If it sinks below a critical value the reformer system goes into an "emergency stop", in order to prevent the formation of carbon.

The catalyst of the reformer which is a metal honeycomb structure coated with a wash-coat and platinum. The heat for the endothermic reaction (1) will be transferred by radiation and convection from a burner. The anode off-gas from the fuel cell, which contains unconverted hydrogen, can be used thermally in the burner, raising the total efficiency of the reformer which is defined as the quotient of the produced hydrogen to total amount of natural gas supplied to the CHP plant (4).

$$\eta_{\text{ref}} = \frac{\dot{n}_{\text{H}_2,\text{reformer out}} \times \text{LHV(H}_2)}{\dot{n}_{\text{CH}_4,\text{total in}} \times \text{LHV(CH}_4)} \tag{4}$$

Fig. 2 represents the experimentally determined dry composition of the reforming product gas as a function of the temperature as well as simulated values (thermodynamic equilibrium) with the program ChemCad$^{\text{TM}}$. The measurements were carried out with an S/C-ratio of 3 and at 60% capacity. The CO, CO_2 and CH_4 content are measured with an IR spectrometer, the H_2 content with a thermal conductivity detector.

The measurements are in close accordance with the thermodynamic calculations.

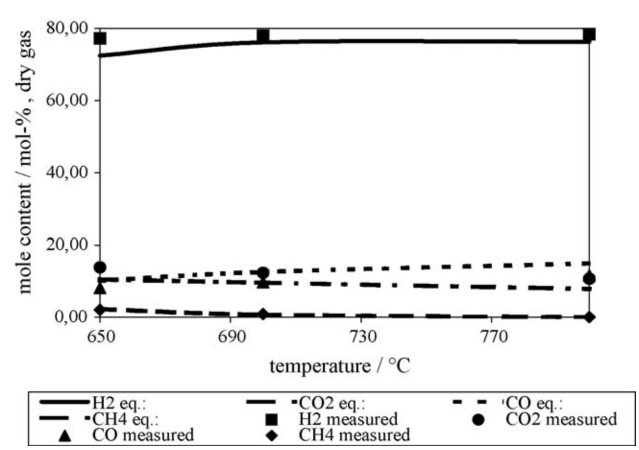

Fig. 2. Gas composition of the dry reforming product gas in dependence of the temperature, measured and simulated (S/C-ratio = 3, operation at 60% of full capacity).

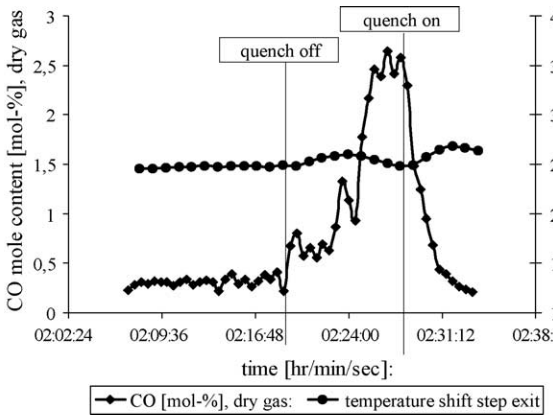

Fig. 3. Influence of the quench water on the CO mole content.

The reformate will be quenched with water, therefore the thermodynamic equilibrium (see Eqs. (1) and (2)) is shifted to the product side. Fig. 3 shows the influence of the quench water on the CO content after the shift reactor.

Experiments at the Fraunhofer ISE showed that the carbon monoxide concentration with quench water can be reduced by the factor 10.

An energy balance for the entire reformer system is presented in Fig. 4. The numbers show the energy streams of the reformer system (Fig. 1) for an S/C-ratio of 2.7, an overall S/C-ratio (incl. quench water) of 5.6 and a reformer capacity of 80%.

The supplied enthalpy stream ($\dot{H}_{CH_4,chem}$) contains the chemical energy of the natural gas. The outlet flow from the reforming system contains the thermal energy of the reformate, the thermal energy of the exhaust gas and the chemical

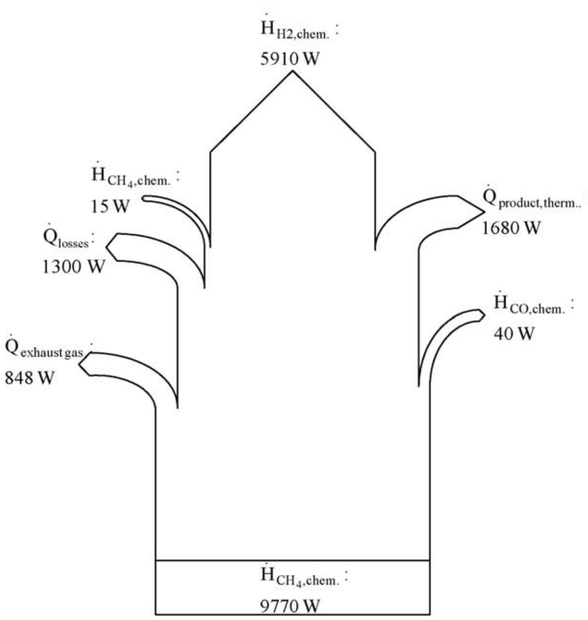

Fig. 4. Energy balance of the reformer system (Sankey diagram).

Table 1
Measured reformer efficiency with and without anode off-gas usage

Efficiency of the anode	Measured efficiency of the reformer system in %
Without off-gas	60
70%	73

energy of the reformer gas. Additionally, heat losses (estimated values) are considered.

Experiments at the Fraunhofer ISE showed that the reformer efficiency can be increased (Eq. (4)) if the anode off-gas is re-circulated to and burned in the burner (see Table 1). The efficiency of the anode is defined as:

$$\eta_{\text{anode}} = 1 - \frac{\dot{H}_{H_2,FC,out}}{\dot{H}_{H_2,FC,in}} \tag{5}$$

The Sankey diagram (Fig. 4) illustrates that the efficiency can be improved if the insulation of the reformer system is optimised reducing heat losses.

A goal of the reformer system is to reach a carbon monoxide content of about 0.3 vol.% (dry gas). The following CO removal step (PrOx) by "ZSW" did not tolerate a higher CO inlet content. It could be confirmed that this value is reached in all reformer operating conditions, a second shift reactor (e.g. LTS, low temperature shift reactor) is not necessary. A new type of air cooling allows to control the temperature very accurately and a nearly isothermal operation of the MTS is possible. Fig. 5 shows the temperature and the CO content in dependence on the time at load changes.

2.2. Fuel cell stack unit

The fuel cell subsystem consists of an 80 cells PEMFC stack (membranes: GORE 5561, 126 cm^2 active area each) with an air circulation cathode system (circulation with integrated re-circulation blower and additional air feed blower, humidity heat exchanger and air filter). The stack cooling system includes a liquid deionised water cooling circuit with pump, reservoir, deionisation unit and heat exchangers. A

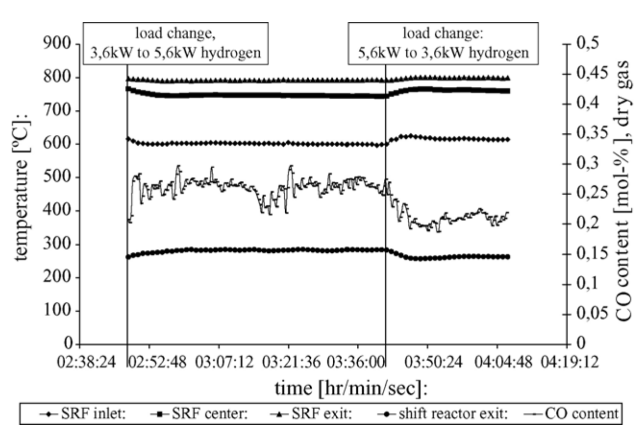

Fig. 5. Temperature and mole content in dependence on the time and alternation of load.

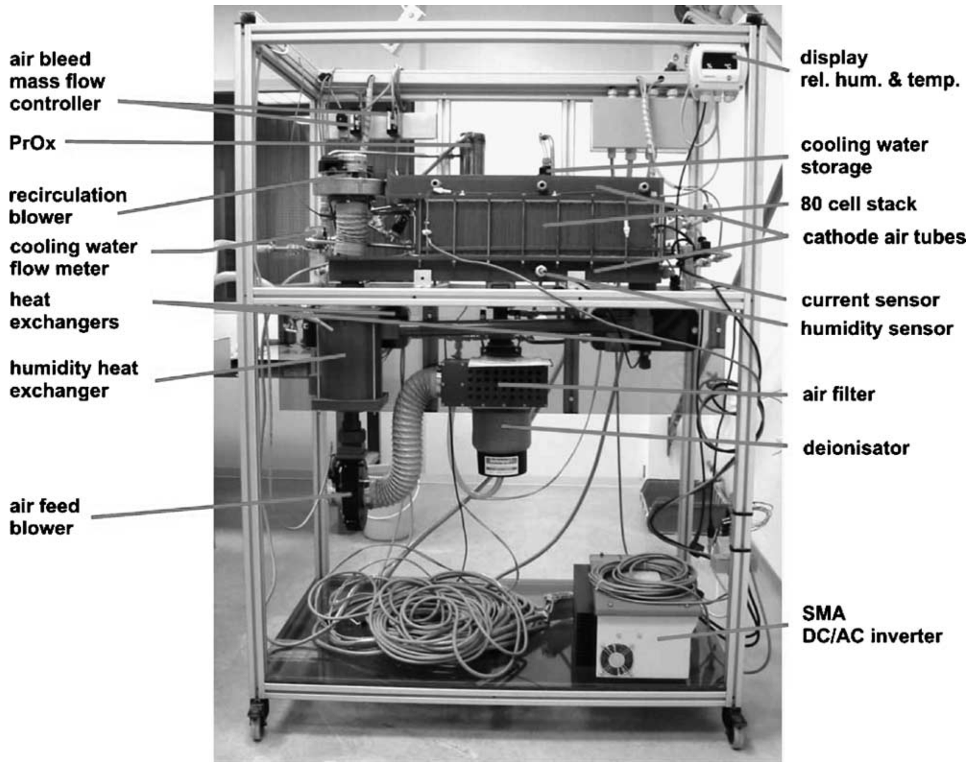

Fig. 6. The fuel cell subsystem.

dc/ac inverter for direct grid connection and sensors for pressure, temperature, humidity and single cell voltages (Fig. 6) complete the system.

The fuel cell stack is operating in a re-circulating air operation mode under nearly atmospheric air pressure to increase the system efficiency. A radial blower recycles the cathode air. Product water accumulates as steam in the air system and can be used for membrane humidification. Additional humidity re-circulation is realised using a combined humidity heat exchanger. Due to the low operating pressure at the cathode side, a radial blower with low energy consumption is used for the air supply. A particle filter is integrated upstream to this blower. An external humidification of the fuel cell stack is not required. The flow of input air is adjusted by a control loop regulating the relative humidity of the system, which is measured by the humidity sensor.

The heat removal is carried out via the primary cooling circuit using deionised water. The cooling water flows through the pump, over the PrOx, the stack and two heat exchangers. The heat is removed by the first heat exchanger to the secondary cooling circuit (house cooling connection). The second heat exchanger warms up the fuel cell before start up to an operation temperature of 45 °C. The electric conductivity of the cooling water can be measured and reduced by a deionising cartridge connected in parallel to an adjustment valve. The dc/ac inverter supplies the electricity generated by the stack to the grid. The periphery consumes max. 10% of generated electrical power at full load. The efficiency of the fuel cell subsystem averages 29–30% referred to hydrogen feed.

The reformate (max. 0.3% CO; dew point 45 °C) produced by the Fraunhofer ISE reformer unit passes a PrOx reactor (developed by ZSW and located in the fuel cell subsystem), where a certain air flow (“air bleed”) is added to the reformate stream at the inlet and outlet of the PrOx. The anode residual gas (stack utilisation approx. 70%) is fed back to the reformer. The PrOx-(fine) purification reduces the CO-concentration below 50 ppm.

In Fig. 7 the characteristics of the PEM fuel cell stack are displayed. The first stack current voltage characteristic was

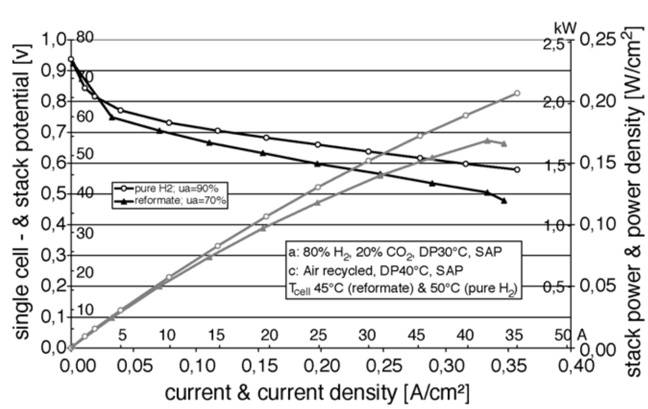

Fig. 7. Current voltage and current power characteristic of the stack.

recorded with pure hydrogen. The stack reached an electrical power of 1.9 kW with an average single cell voltage of 0.6 V and a current of 40 A. The dc/ac inverter has a short-time input power of 2.2 kW, so the characteristic ends by 45 Å.

The second characteristic was recorded using simulated reformate gas (humidified hydrogen with 20% carbon dioxide and traces of CO). The PrOx was supplied with up to 3700 ppm CO and 4% air bleed. 2% air bleed was also added to the fuel gas at the PrOx outlet. The concentration of carbon monoxide at the stack inlet varied between 10 and 20 ppm during the recording of the characteristic.

The single cell voltage fell below 0.6 V at 25 Å (approx. 1.2 kW) at a constant anode utilisation of 70%. The peak power was reached at an average cell voltage of 0.5 V and 42 Å (approx. 1.7 kW). Because of high utilisation the stack voltage was falling faster above 42 Å (due to mass transfer problems).

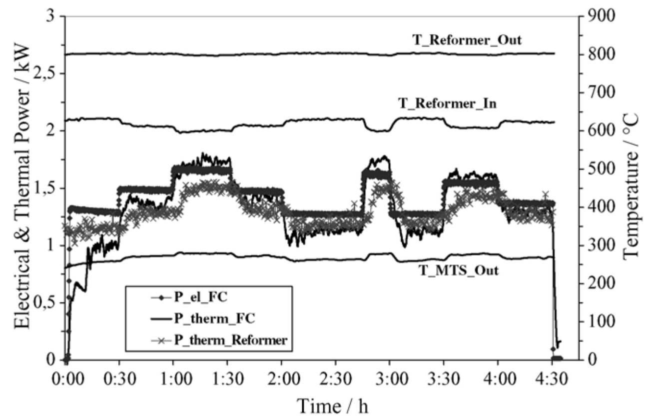

Fig. 8. Time-dependent behaviour of power and reformer temperatures during different load changes.

3. System testing equipment

The IWE at the Universität Karlsruhe (TH) is co-partner of a fuel cell test laboratory (FC-TestLab) since October 2003, in which fuel cell systems and components are tested. The FC-TestLab is operated in cooperation with the European Institute for Energy Research (EIfER), an European Economic Interest Group that was created in 2001 by the French utility Electricité de France (EdF) and the Universität Karlsruhe (TH).

In the FC-TestLab fuel cell systems for stationary applications (fuel cell heating systems, CHP systems) are examined in terms of capability, efficiency and stability in the context of national and international research projects. Main focus is the investigation of the dynamic behaviour (start up, load changes, shut down) and the connection to the electrical grid. Beside complete systems also components like fuel cell stacks can be tested. The laboratory is equipped with three test cabins, which allow independent operation of several systems.

Each test cabin offers gas connectors (natural gas, H_2, N_2, CO, CO_2, O_2, compressed air), a DI water supply and connectors for the electrical grid feed-in. Alternatively the systems can be charged with different electrical loads. Furthermore, thermal loads are available for the simulation of heating systems and for the determination of the thermal efficiency of a fuel cell system during different operating conditions.

4. Testing results and discussion

After successfully installing the EDISon system extensive measurements were made in order to be able to characterise the system behaviour. The single components of the EDISon system had only been operated and tested separate from each other, before the installation in the test laboratory at the IWE. In the first tests the main focus was therefore put on the characterisation of the thermal and electrical operating behaviour for different operating points of the EDISon system.

During further tests, the steady state and dynamic behaviour of the system was examined.

The accomplished measurements were limited thereby to a system output power of the EDISon-system in the range corresponding to 3.7–5.1 kW hydrogen power.

4.1. Electrical and thermal characterisation

For defining the thermal and electrical output power of the EDISon-system, different operating points were adjusted during a test over 4.5 h and the resulting characteristic recorded. In Fig. 8 the most important reformer temperatures (reformer input temperature T_Reformer_In, reformer output temperature T_Reformer_Out, output temperature of the middle temperature shift T_MTS_Out) as well as the electrical and thermal power of the PEM fuel cell stack (P_el_FC, P_therm_FC) and the thermal power of the reformer cooling circuit (P_therm_Ref) are displayed.

Starting at a system output power of 3.7 kW H_2 at the beginning of the measurement, every 30 min a load change was implemented (3.7 kW − 4.4 kW − 5.1 kW − 4.4 kW − 3.7 kW − 5.1 kW − 3.7 kW − 4.75 kW − 4.05 kW). This can be clearly seen in the characteristics of the electrical output power of the fuel cell stack, which follows directly the applied load changes.

From the characteristics of the thermal output power of the fuel cell stack, it can be recognised that it lags behind the electrical output power with a delay of several minutes. The decisive factor is therefore the inertia of the mass warming of the stack and the relatively low heat transfer coefficients. The good adaptation to the load changes can be seen clearly.

The thermal output power of the reformer cooling circuit shows similar characteristics. A good adaptation to the according load conditions and the inertia of the thermal mass of the reformer can be seen.

The results of the characterisation are displayed in Table 2.

Table 2
Measured thermal and electrical output power as a function of the adjusted percentage system power

System power (%)	Hydrogen power (kW)	FC electrical power (kW)	FC thermal power (kW)	Reformer thermal power (kW)	Total thermal power (kW)
50	3.70	1.275	1.100	1.150	2.250
55	4.05	1.375	1.300	1.250	2.550
60	4.40	1.475	1.400	1.300	2.700
65	4.75	1.550	1.550	1.400	2.950
70	5.15	1.650	1.700	1.500	3.200

4.2. Steady state behaviour of the system

The steady state operating behaviour of the system was determined by performing a test for 5 h. The operating point was chosen at a system power of 3.7 kW H_2. The result is shown in Fig. 9.

Beside the most important reformer temperatures (see Section 4.1) again the electrical and thermal power of the PEM fuel cell stack is displayed.

After approximately 2 h a minimal decrease of the electrical output power of the fuel cell stack can be observed, but re-stabilising again during subsequent process measurements at 1.2 kW and confirming the results of the measurements in 4.1.

Also the thermal output power averages the value according to the measurement in 4.1. The closed loop control characteristic of the fuel cell stack cooling circuit can be seen clearly.

4.3. Dynamic behaviour of the system

The dynamic characteristic of the fuel cell CHP system marks a further important and interesting point in the analysis of systems. To be able to persist as a power generation system under real conditions, certain demands on the load adaptation potential of the CHP system are made.

Therefore, during different test procedures the system behaviour on dynamic load changes was examined more precisely.

In order to confirm the dynamic characteristic of the system relative to the size of the load changes, including also the smaller step changes and to complete and to prove the results in 4.1, two tests according to Fig. 10 were recorded.

In the first measurement starting at a hydrogen power of 3.7 kW the EDISon system was charged with load ramps each of 0.35 kW H_2. The time duration of the ramps was about 0.5 h. The second measurement was performed in the same way in reverse starting at 5.1 kW H_2.

As already seen in 4.1 the electrical output power follows directly the load changes. The thermal output power of the fuel cell stack lags behind again the electrical output power. Both reaching and confirming the average values of 4.1.

It was proven extensively in 4.1 that the system is able to perform high load step changes and to adapt to load changes within minutes. A stabilisation period of about half

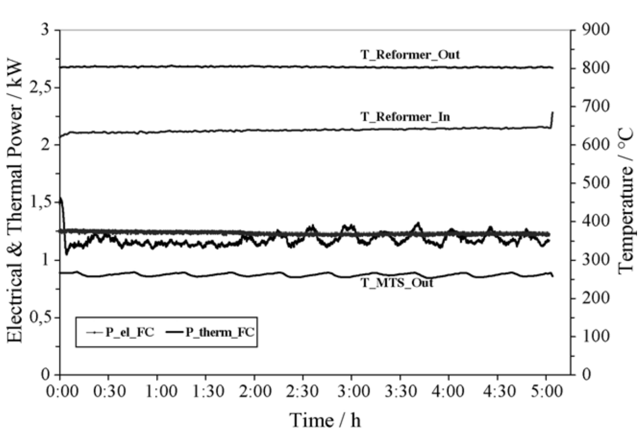

Fig. 9. Time-dependent behaviour of power and reformer temperatures during the static operating point at 3.7 kW hydrogen power.

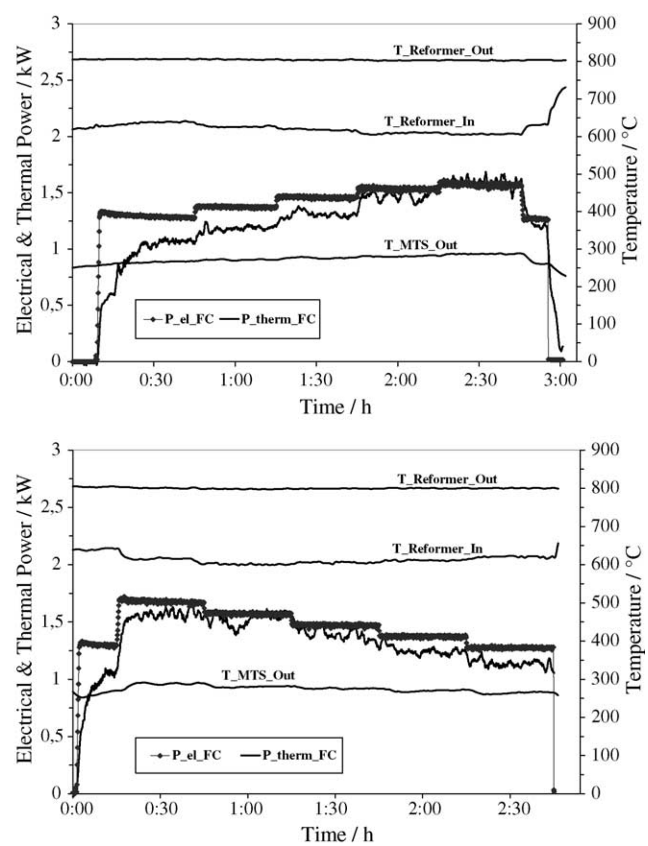

Fig. 10. Time-dependent behaviour of power and reformer temperatures during ramped load: (a) increasing, (b) declining.

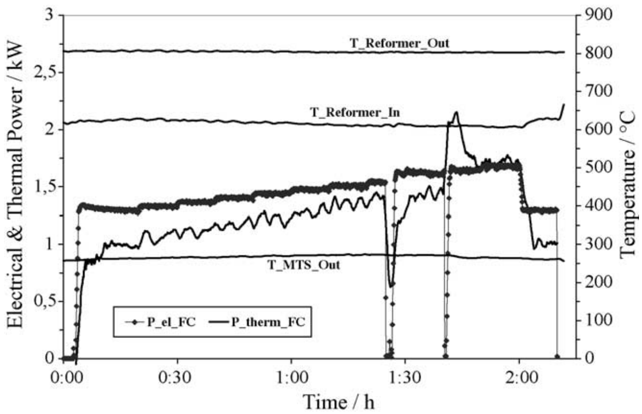

Fig. 11. Time-dependent behaviour of power and reformer temperatures during ramped load in 10 min steps.

an hour was however, needed in the CHP system after a load change. Considering however typical load profiles of power demand, load changes within short time periods are often necessary.

The results of measurement to examine the system behaviour at relatively fast load changes are shown in Fig. 11.

Starting at a hydrogen power of 3.7 kW load ramps each of 0.15 kW H_2 and 10 min duration were applied. The electrical output power of the fuel cell stack reaches again the values according to 4.1, whereas the thermal output power stays always below the values of the characterisation (4.1). This is attributable to the fact that 10 min is not enough to reach the corresponding stationary operating point of the stack, which would provide the maximum thermal output power.

The two drops in the electrical power in Fig. 11 are attributable to a short-time operation failure (idle state) of the power inverter.

5. Model-aided analysis tool

In parallel, a model-aided system analysis tool, based on system tests, will be developed for the modelling of different types of fuel cell systems. In the experimental modelling approach a general system model is parameterised on the basis of measured data of a system. The aim of this model is to get information about the efficiency of the system and individual system components, to reveal problems during operation and to analyse the optimisation potential.

The model is to provide information about input and output values, internal variables of state as well as the system efficiency in the static and in the dynamic operation mode. The modelling is based on a variable, parameterisable system model (i.e. applicable to as many different systems as possible) with sub-components according to Fig. 12.

Beside the development of new models for the sub-components of the CHP system, known simulation based models for the sub-components (like reformer unit and PEMFC) as reported for instance in [15–20] are adapted to fit into the general system model.

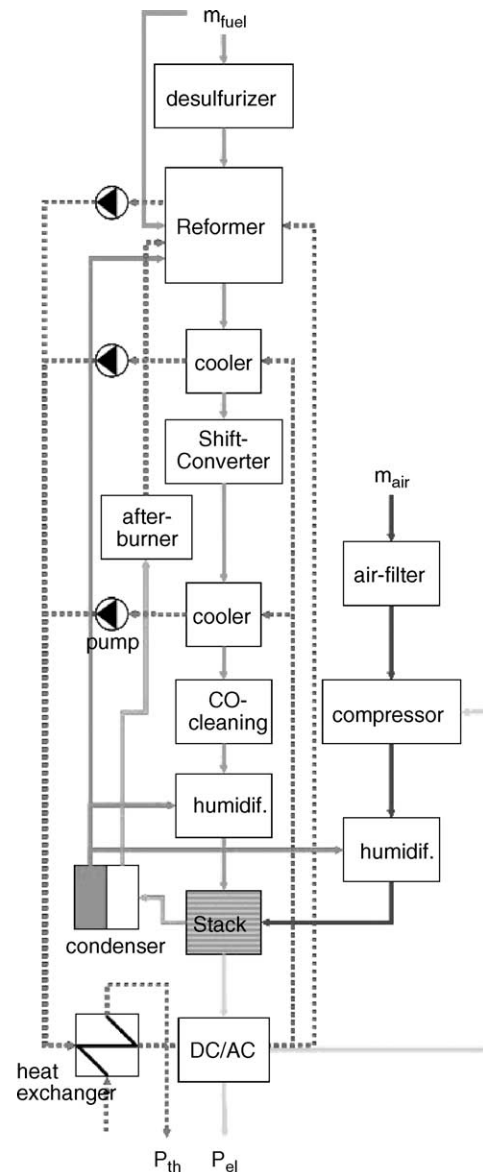

Fig. 12. Example of a PEMFC CHP system model.

The parameters necessary for the description of the system and its components are determined by measured data using suitable identification methods.

The system behaviour is described by sets of characteristic curves, state space and differential equations using Matlab/Simulink^{TM}.

A first evaluation of the procedure is performed with the EDISon system. Since this system is accessible in as much detail as possible, all system values and parameters can be measured. By simulation of static operating points as well as dynamic processes and subsequent comparison with measurements on the real system, the model will be verified.

6. Conclusions

With the measurements described here it was shown that the EDISon system is able to perform maximal load step changes in the range of 3.7–5.1 kW hydrogen power. Also load changes within a period of 10 min can be performed with only a small performance loss in the thermal power. The resulting system dynamics are sufficient for most applications. The EDISon system also shows very good results in the total power output rising expectations of relatively good efficiencies.

Further work will be done in the field of characterisation of the system regarding the following aspects:

- Measurements at an expansion of the system hydrogen power range of 3 kW H_2 to 5.9 kW H_2
- Detailed acquisition of the gas flows for calculating the system efficiencies.
- Charging the system with real load profiles of electrical and thermal power demands.

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