SMALL SCALE PEM FUEL CELLS IN COMBINED HEAT/POWER CO-GENERATION

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Key words: *fuel cells, polymer electrolyte, electrical and thermal power*

ABSTRACT:
PEM technology can be used for stacionary applications in combined heat and electric power generation. Due to low operating temperature, and comparatively high electricity possibilities, they are particulary suited for fuel cell application in family home.

1. INTRODUCTION

Currently rapid changes in international local energy market structures are observed. These trends are known under terms like liberalization, deregulation and privatization The restructuring of the energy system will lead on the one hand to a unification of large electricity and gas suppliers, but on the other hand to efficient small energy service companies installing decentral, flexible and low cost energy conversion technologies.

One business area of the smaller companies will be the residential electricity and heat supply in buildings. The combined heat and power has a considerable higher fuel efficiency than conventional technologies. This trend will be supported in Europe by new directives for residential buildings for further tighten reduction goals for heating demand.

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E.g. in Germany a new law expected for 1999 will require that so called low energy houses with 50 – 70 kWh/m²year be built.

Today, mostly internal combustion engines are used for this purpose. The use of fuel cells will introduce further benefits due to their higher electrical efficiency and their negligible emissions of pollutants such as NO_x, particulates, CO etc., which in fuel cell systems are caused by the conversion of fossil fuels into H_2. If the fuel cell system is powered by hydrogen produced from regenerative energies, the total system can be considered as emission free.

Although the H_2-O_2 fuel cell was discovered already in 1839 by W. Grove no real introduction into the market has taken place up to now, except for space applications.

In recent years considerable progress has been achieved in the development of electric vehicles powered by polymer electrolyte fuel cells (PEMFC) (e.g. Daimler-Benz, Ballard, Toyota). For stationary applications 200 kW PAFC units manufactured by ONSI are commercially available. Even portable fuel cells based on the PAFC system[1] and the PEMFC system[2,3] have been demonstrated.

In this paper stationary applications of fuel cells will be discussed for combined heat and power generation. Particular emphasis will be given to residential fuel cells.

2. STATIONARY FUEL CELL APPLICATION

2.1 BASICS OF THE STATIONARY FUEL CELL APPLICATION

Electric power generation in stationary fuel cells is in competition to thermal processes where the maximum energy efficiency is given by the CARNOT cycle. The theoretical electrical efficiency (η^*_{el}) for the electrochemical and the thermal processes are as follows:

CARNOT cycle

$$\eta^*_{el} = \frac{T_2 - T_1}{T_2} \tag{1}$$

fuel cell

$$\eta^*_{el} = \frac{\Delta G}{\Delta G + T\Delta S} \tag{2}$$

The theoretical electrical efficiency values will be reduced in reality by additional process losses. In fuel cells they are mainly caused by internal resistive and polarization losses producing so called JOULE heat. Therefore, thermal energy in fuel cells (Q_{FC}) is generated as reversible heat Q_R ($T\Delta S$) and as JOULE heat (Q_J).

$$Q_{FC} = Q_R + Q_J \tag{3}$$

At lower electrical load less JOULE heat is generated. Therefore with decreasing load not only the electrical efficiency η_{el} will increase but due to reduced resistive losses α increases as well. In practice, however, at very low load, η_{el} is decreasing again, caused by electricity consumption of auxiliary aggregates (e.g. pumps). This is shown in the following figure.

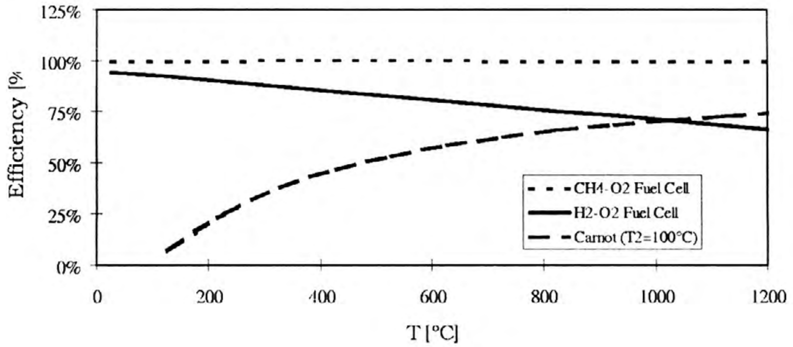

Fig. 1: Temperature dependence of the energy efficiency of fuel cells and the Carnot cycle

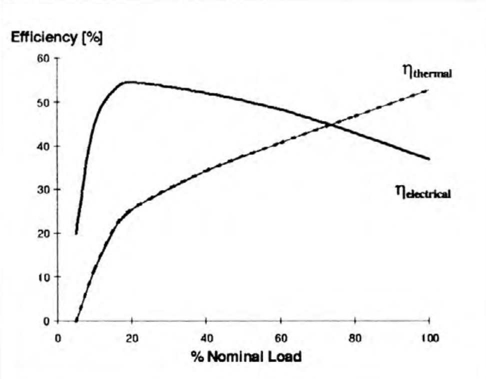

Fig. 2: Electrical (η_{el}) and thermal (η_{th}) efficiency of a PEMFC vs. load

The quotient of the electrical energy (P_{el}) and usable thermal energy (Q_{th}) is an important operating parameter of the fuel cell system. This electrical energy–thermal energy–relation α is defined as follows:

$$\alpha = \frac{P_{el}}{Q_{th}} \tag{4}$$

and is strongly depended on the electrical load:

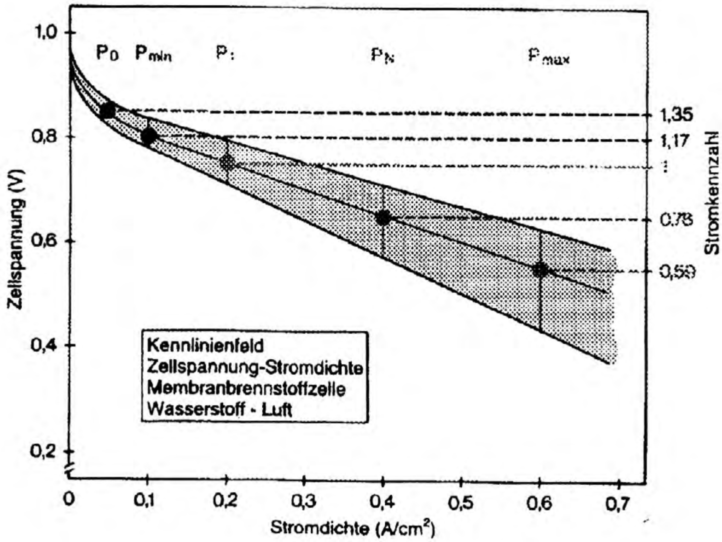

Fig. 3: Electrical energy–thermal energy–relation α vs. electrical load for a PEMFC[4]

2.2. DEMAND FOR STATIONARY FUEL CELLS

Stationary fuel cells can be used in larger scale (> 200 kW) for district use or in smaller scale (< 10 kW) for residential use. Important parameter for the residential use are the possible (small) size of the FC, the start up time, and the operating conditions. These conditions should permit a discontinuous operation and fast load change.
The next table shows, which FC type can fulfill this demand.

From this table follows that the PEMFC system should be the best system for the residential use, caused by its fast start-up time, the discontinuous operation, and the broad power range. Unfortunately most fuel cell systems are best operated at constant load. E.g. at larger electrical power changes also larger temperature changes are observed the same time, leading to internal mechanical stress in the FC and therefore to a life time reduction especially at high temperature FCs. A further development of materials with nearly equal thermal extension coefficients can reduce these problems. However in order to overcome this problem SULZER has developed a SOFC-system with a special heat exchange system (HEXIS) and is regulating the different heat/power demand mostly by an external burner.

Tab. 1: Operating conditions of different fuel cells

FC type	T_{stack} [°C]	start-up time	size [kW]	operation
PEMFC	80	1–3 sec	1–50	discontinuous operation, 10–100 % of rated power
PAFC	180	3–5 h	250–600	permanent operation, 50–100 % of rated power
MCFC	650	1–3 d	300–500	permanent operation
SOFC	900	1–3 d	2–100	permanent operation

2.3. COMBINED HEAT AND POWER GENERATION USING A MODEL PEMFC

The electrical efficiency of PEMFCs is influenced by the fuel stoichiometry and various other operating conditions. To study the influence of these operating condition a hydrogen fueled model system containing a 700 W stack made from 20 cells having an active area of 100 cm^2 (***Fig. 4***) has been constructed.

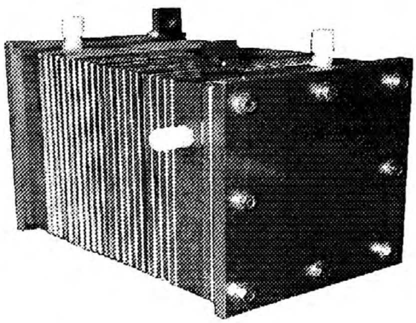

Fig. 4: 20 cell PEMFC model stack (ZSW)

This system contained a control unit for fuel and oxidant flow. Furthermore a cooling and a gas humidification system was included. The electrical parameters as well as the coolant inlet and outlet temperatures were continuously monitored. Furthermore, the test rig contained a DC/AC-converter. Fuel and oxidant stoichiometries were kept constant under varying load. The electrical current was used to control the power output of the stack. The stack was well insulated in order to avoid thermal losses.

Fig. 5 shows a typical current-voltage curve for this stack. From current-voltage curves under different operating conditions, optimized parameters for combined heat and power generation have been derived.

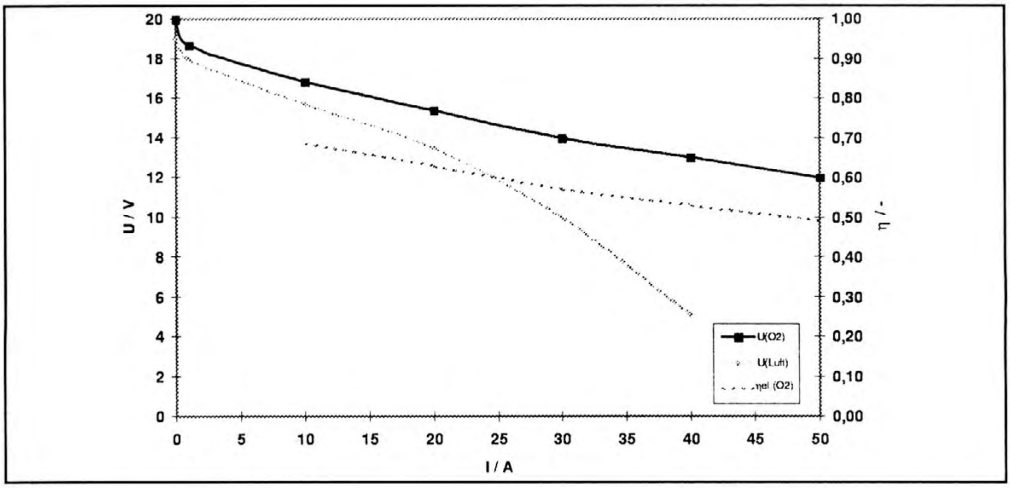

Fig. 5: *Current-voltage curves for the 20 cell PEMFC model stack active area 100 cm^2, H_2-consumption 85%, air consumption 30% T_{stack}: 42°C....79°C, η_{el} with respect to the lower heating value*

It is evident that the electrical efficiency is decreasing with increasing load. At 40% nominal load an electrical efficiency of 60% is achieved, which reduces to 40% at 75% nominal load. From the current-voltage curves the electric power and the heat generation can be calculated. In Fig. 6 these values are shown depending on the stack current and the operating temperature. Numerical values are compiled in Tab. 2.

Tab. 2: Heat and electricity production of the 20 cell model stack

% P_{max}	i / mAcm^{-2}	P_{el} / W	$\dot{Q}_{el}$ / W	% $\dot{Q}_{max}$	$T_{vorlauf}$ (?)/ °C
20	100	140	130	12,5	42
40	200	281	250	23,8	49
60	300	425	360	34,3	55
75	430	525	527	50,2	63
85	500	595	625	59,5	67
100	700	700	1050	100	72

It can be seen from Fig. 6 and Tab. 2 that useable heat is produced above of 40% of the nominal electrical load of the fuel cell. At 75% nominal electrical load already

50% of the maximum heat production is achieved. At full electrical load (100 %) the heat production is higher by about the factor 1.5.

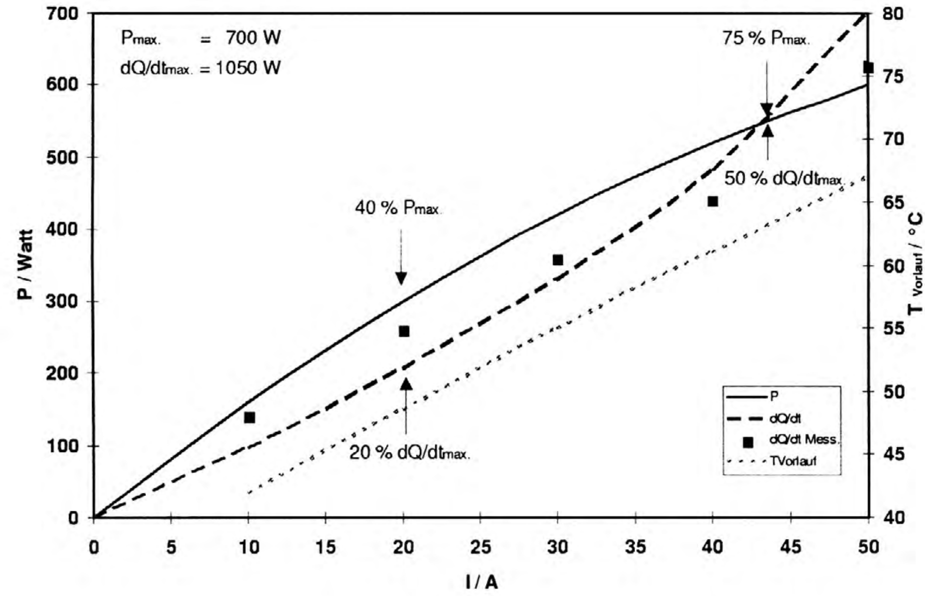

Fig. 6. Characteristic curves P_{el}-I and dQ/dt-I curves for the 20 cell stack

The heat production below an operating temperature of 60 °C is above the values calculated theoretically from the lower heating value of hydrogen. This is caused by the condensation of water vapor inside the stack. Above 60 °C water condensation occurs mostly outside the stack. In total 89...92% of the thermal energy generated in the fuel cell could be recovered by the model system.

3. COMBINED HEAT AND POWER GENERATION SYSTEMS FOR RESIDENTAL HOMES USING WITH 5 KW PEMFC

3.1. SYSTEM AND SYSTEM COMPONENTS

The fuel cell is one part of the power generation system. But the system is made of other system components as the hydrogen supply and the DC/AC converter, too. A flow diagram of the co-generation system with a PEMFC is sketched in Fig. 7.

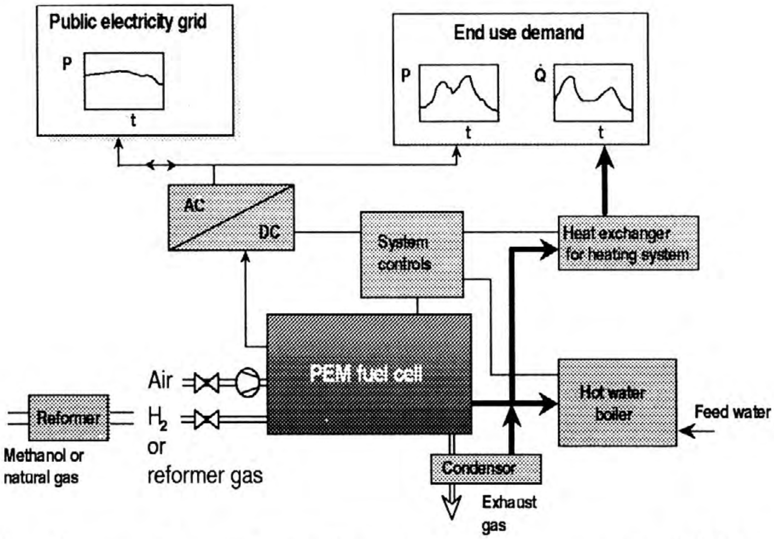

Fig. 7: Flow diagram of a small natural gas residential co-generation PEMFC (Siemens)

3.1.1. FUEL REFORMER

In carbon-fuel operated FCs fuel converters are responsible for producing hydrogen from a variety of fuels like natural gas, methanol, ammonia, LPG etc.. The reformer/purification unit must be customized to the individual operating requirements (load dynamics). For dynamic PEMFC especially with small fuel converters the problem is their complexity with subsystems like desulphurizer, reformer, CO shift-reactor and CO removal system ($\leq$ 10 ppm), which can be Pd-membranes or selective oxidizers. For low kW_{el}-class PEMFC systems miniaturized natural gas reformer technologies are described in more detail in[5]. For large applications the specific reformer costs for natural gas operated PEMFC systems will be about 2/3 of the stack costs themselves[6] in small units they will probably approximate the stack costs.

3.1.2. GAS AND HEAT FLOW SUBSYSTEMS

PEMFC can be characterized by their operating pressure level. The lowest secondary energy demand is necessary for unpressurized systems. The highest energy densities and material intensity can be reached with pressurized systems. The pressure is typically below 3 bar, resulting in relatively simple hydrogen/air blowers. The exhaust gases have to be removed from the system confinement, however no over-the-roof ventilation stack will generally be required in residential systems. The heat generated will be taken out by a circulating flow of water, which can also be stored in conventional warm water storage equipment, thus lowering system complexity.

3.1.3. DC / AC CONVERTER AND SYSTEM CONTROLS

In grid connected residential FC systems the electricity has to be transformed to the grid quality and safety specifications. The development of FC integrated inverters will eventually require least costs, which can only be reached by a highly integrated single-chip-design of power and control logics within the system controller. Specific inverter investment costs, which can be as low as 400 DM/kW$_{el}$ today, may well reach 50 DM/kW$_{el}$ when mass produced in the future[7].

3.1.4. SAFETY COMPONENTS

For small residential FC co-generation systems, generally installed in the basement of single family residences, special attention must be paid to safety. Preliminary results of a German inspection authority require a forced ventilation of about 5 h^{-1} either by natural or forced convection. An alternative is the installation of cheap customized sensors at locations of highest possible hydrogen concentrations, requiring customized low maintenance sensors as under development in Europe[8] and the U.S[9].

3.2. HEAT AND POWER GENERATION WITH A 5 KW PEMFC

A typical load profile for a family home during wintertime is shown in Fig. 6. Simultaneously to the load profile the heat and power generation by a 5 kW PEMFC system, which is electrically conducted is shown. It is evident that the fuel cell follows the electricity demand. However, the heat demand is considerably larger than the electricity demand under these operating conditions. Therefore an extra heater will be required to supply the additional thermal energy which is required. The differences between electrical and thermal power requirements are much smaller during summertime.

Based on the thermal load profile shown in figure 6 and experimental data measured with the model system, it can be calculated that combined heat and power generation using a PEMFC- module can cover 100% of the electricity demand of a typical family home. However, by this electricity demand drive operation only 40% of heat demand are covered by the fuel cell. Therefore, for economic reasons the fuel cell will typically be operated in the heat conducted mode during wintertime. Surplus electricity will be fed into the grid.

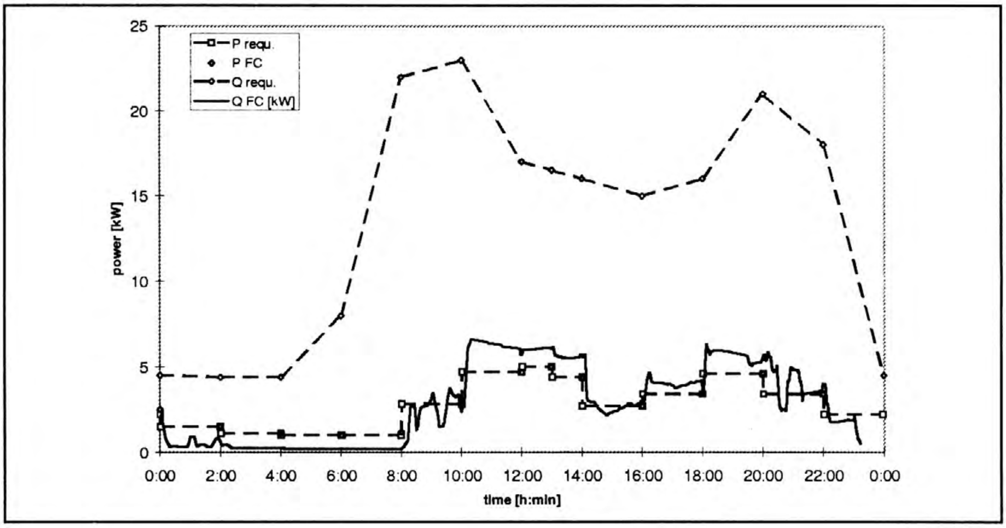

Fig. 8. Daily electric power and heat requirements (P_{req}, Q_{req}) and generations (P_{BZ}, Q_{BZ}) by a 5 kW PEMFC, electrically conducted of a family home during wintertime

4. FURTHER DEVELOPMENT

The most challenging task for PEMFC introduction in combined heat and power generation in family homes will be a dramatic reduction of the system cost. At about 2,500 DM/kW the co-generation system with a PEMFC and a natural gas reformer has a good market chance.

This can be achieved by the following improvements:

- the fuel cell stack — the use of less expensive materials for membranes and bipolar plates and the simplification of the flow field geometry, will allow considerable cost reductions.
- fuel processing — improved gas processing e.g. by improved reformer-shift converter modules combined with CO-cleaning inside the stack leads to a considerable simplification of fuel cell control and operation.
- integrated control — construction of integrated PEMFC-heating modules will reduce the number of components used thus leading to significant cost reductions..

5. ACKNOWLEDGEMENTS

Support from the Stiftung Energieforschung Baden-Württemberg for the project with the 5 kW PEMFC is gratefully acknowledged. This paper based on papers from J. Garche and U. Bünger [10].

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MALE PEM GORIVE ĆELIJE U PROCESU KOGENERACIJE

SAŽETAK:

Gorivni spregovi na bazi PEM tehnologije se mogu koristiti za stacionarnu primenu kod kombinovane proizvodnje toplotne i električne energije. Zahvaljujući njihovoj niskoj radnoj temperaturi i relativno visokim strujnim karakteristikama gorivni spregovi na bazi PEM tehnologije su naročito pogodni za primenu u porodičnim kućama.