OPTIMIZATION OF GAS PROCESSING FOR SOLIDE OXIDE FUEL CELL POWER PLANTS

E. Riensche, U. Stimming and G. Unverzagt
Institute of Energy Process Engineering (IEV)
Research Centre Jülich (KFA)
D-52425 Jülich, Germany

ABSTRACT
In order to benefit from the high electrochemical efficiency of solid oxide fuel cells, a skillfull balance of plant has to be developed. An energetic and economic analysis of a decentralized natural gas-fuelled SOFC-power plant in the range of 200 kW capacity is presented. Starting from a simple flowsheet process concepts with external and internal reforming and gas recycling by blowers or jet boosters are described. Cathode gas recycling by jet booster turns out to be more advantageous with respect to electricity production cost than gas recycling by hot gas fans. Cost analysis is applied to such plant concepts.

1. INTRODUCTION
The energy conversion efficiency of fossil fuels has to be increased because of environmental concerns and preservation of dwindling resources. Fuel cell plants promise many advantages with respect to efficiency and environment. The application of solid oxide fuel cells (SOFC) in power plants for the generation of heat and power is desired for both application in small and large scale units because of the high operating temperature. But for a successfull market introduction also the operational efficiency has to be taken into account.

Various results of power plant optimization such as temperature differences in heat exchangers, numbers of fuel cells and also the electrical efficiency are combined into one final parameter, the cost of electrical energy production. Cost analysis could then lead to more economic rather than efficient power plant operation. The exact cost of energy production is a result of the assumptions in table 1 and may be discussed. But the aim is to show the influence of different power plant concepts on the electrical energy
production cost starting from a simple base case (price basis 1994: 100 cents = 1 US$ = 1.6 DM (german mark) = 160 Pf).

2. BASE CASE

All studies start from a simple power plant concept as illustrated in fig. 1. The main parameters for cell operation and cost calculation are summarized in table 1. For power plant analysis the flow sheet simulator PRO/II (SimSci) is used. Data obtained from a fuel cell stack modelling program where used to simulate the fuel cell. This simple flowsheet achieves an overall electrical efficiency of 43.1 % and electrical energy production cost of 0.159 US$/kWh (equal to 25.5 Pf/kWh).

The electrochemical parameters influence power plant operation. In figure 2 the result of a parameter variation of the fuel utilisation in the SOFC is shown. The electrical efficiency can be raised up to 50 %, when using the fuel utilisation to 100 % in the cell. But high fuel utilisations result in a decrease in current density. At the end of the cells there are only low partial pressures of hydrogen and carbon monoxide in the gas. The current density is therefore low. To convert the last part into electricity means that many cells have to be installed in the stacks. The investment cost increase and the capital cost for the SOFC compensate the back pay for the high electrical efficiency. With this typical parameter set a fuel utilisation of approx. 70 % is optimal.

The main target of further process development is to reduce the large amount of air supply (λ=7.1 in the base case). Alternative stack cooling concepts are necessary to improve plant operation. This paper shows three possibilities from the process engineering point of view: internal natural gas reforming and recycling of the hot cathode exhaust gas by the use of a fan or a jet pump (injector).

3. INFLUENCE OF EXTERNAL AND INTERNAL REFORMING

Due to the present limits of fuel cell development, natural gas has to be partially reformed outside the fuel cell (base case: 50%). The electrochemical waste heat has to be removed by a large air stream (λ=7.1 in the base case). When operating the SOFC with higher internal reforming rates advantages with respect to electrical efficiency and cost can be achieved, see fig. 3. An air ratio of approx. 3.0 with internal reforming results in an increase of electrical efficiency to 48 %. The electrical energy production cost can be reduced to a value below 0.125 US$/kWh.
4. CATHODE GAS RECYCLING BY HOT GAS FANS

The idea of a cathode gas recycle loop is to preheat the incoming air by mixing it with the hot cathode exhaust gas. In order to overcome the pressure loss in the cathode gas loop a hot gas fan can be installed. Due to technical limits the operating temperature of a hot gas fan is limited. Roughly with a high operating temperature a lower pressure rise can be achieved. The total pressure loss in the cathode loop caused by the SOFC and the gas manifolding is set to 20 mbar. Of course several fans can be installed in series to achieve higher pressures.

In figure 4 an optimized flowsheet with a hot gas fan is shown. The figure 5 shows the results of a parameter study in which the air ratio was varied. With a cathode gas recycle loop the air ratio can be reduced to 1.0 and the temperature increase of 100 K in the SOFC is maintained. The electrical efficiency is increased up to 50 % at \( \lambda = 1.0 \). The electrical production cost is minimal at \( \lambda = 1.5 \) with a value of 0.139 US$/kWh. In the recycle loop the oxygen partial pressure decreases with lower air ratios at power plant inlet. Low oxygen partial pressure results in lower current densities. In order to achieve 80 % fuel utilisation many single cells have to be installed. The investment cost increase extremely at high recycling ratios. Therefore from the economical point of view a \( \lambda \) of 1.5 is desired.

5. CATHODE GAS RECYCLING BY INJECTORS

An other possibility of air preheating is to recycle the hot exhaust gas from the cathode by use of a jet pump or also called injector. The cold air stream is compressed to relatively high pressure and drag along hot recycle air stream by momentum exchange. Injector calculations /3/, /4/ are applied to a SOFC power plant.

Figure 6 shows the new flowsheet with an injector. In figure 7 the result of the variation of the air ratio similar to that of fan case is shown. The electrical efficiency is at \( \lambda = 2.0 \) maximal with 46.7 %. At lower air ratios the injector loading increases, so that higher driving pressures are necessary in order to build up the pressure rise of 20 mbar in the loop. The electrical energy consumption for gas compressing lowers the overall electrical efficiency. The minimum electrical production cost is achieved with \( \lambda = 1.5 \). A cost reduction of approx. 0.031 US$/kWh is achieved compared to the base case. To lower the values of air ratio there are two main effects. Similar to the fan case the SOFC investment cost increase because of the lower oxygen partial pressure in the loop. But additionally the decrease of electrical efficiency reduces the return for electrical power generation.
The application of an injector is furthermore advantageous in order to overcome higher pressure losses in the recycle loop. To overcome higher pressure losses in the SOFC several expensive hot gas fan have to be installed. This yields in higher electrical power generation cost. For an injector only the driving gas pressure has to be increased. There are no additional investment cost.

6. CONCLUSIONS

With respect to environmental aspects the development and optimization of SOFC power plant operation aim to about 50 % for a decentralized small scale unit with 200 kW capacity. But in order to reach a successful market introduction also the electrical energy production cost have to be considered. Only when a SOFC power plant achieves the same operational efficiency compared to small energy production units - like small gas and steam turbines - the fuel technology is considered as a real alternative to conventional techniques. This work showed several possibilities to improve plant efficiency. At the present point of view overall electrical power plant efficiencies of more than 50% with reduction of energy production cost is possible also for small units.

ACKNOWLEDGEMENT

The work was funded in part by the Commission of the European Communities (JOULE II Program).

REFERENCES

1. Riensche, E., Fedders, H., A parameter study on SOFC Plant Operation for Combined Heat and Power Generation, 3rd International Symposium on Solid Oxide Fuel Cells, Honolulu, Hawaii (1993)
2. Rechenauer, CH., Achenbach E.: Dreidimensionale mathematische Modellierung des stationären und instationären Verhaltens oxidkeramischer Hochtemperatur-Brennstoffzellen, Forschungszentrum Jülich (Jül-2752), April 1993
3. Schlag, Hans-Peter, Experimentelle und theoretische Untersuchungen zur Berechnung der Kennlinie von gasbetriebenen Einphaseninjektoren und Gutaufgabeinjektoren, VDI-Fortschrittberichte, Nr. 313, Düsseldorf 1993.
4. Achenbach, E., Riensche, E., Unverzagt, G., Gas Processing of SOFC-Plants, European SOFC Conference, October 1994 Lucerne, page 153162.
Table 1: Basic Parameter Set for a typical SOFC Power Plant (Base Case)

| Parameter                                      | Value         |
|------------------------------------------------|---------------|
| Single Cell Voltage                           | 0.75 Volt     |
| SOFC Operating Temperature, In/Out            | 850/950 °C    |
| Internal Reforming Rate                       | 50 %          |
| Fuel Utilisation                              | 80 %          |
| Single Cell Life Time                         | 40.000 Hours  |
| Single Cell Production Cost (10x10 cm)        | 15.13 DM      |
| Factor for Manifolding, Control Techniques,... | 2.5           |
| Interest                                      | 8 %           |
| Depreciation Time                             | 10 Years      |
| Plant Load                                    | 7000 Hours/Year|
| Heat Return up to 80 °C                       | 0.025 US$/kWh |
| Result: Electrical Power Plant Efficiency     | 43.1 %        |
| Result: Electric Power Production Cost        | 0.1594 US$/kWh, 25.5 Pf/kWh |

Fig. 1: Flow Sheet of a typical SOFC Power Plant (Base Case)
Fig. 2: Influence of Fuel Utilisation on Power Plant Efficiency and Cost

Fig. 3: Variation of the Natural Gas Reforming Rate
Fig. 4: Power Plant concept, Cathode Gas Recycle Loop by a Hot Gas Fan

Fig. 5: Variation of Air Ratio, Cathode Gas Recycle Loop by a Hot Gas Fan
Fig. 6: Power Plant concept; Cathode Gas Recycle Loop by an Injector

Fig. 7: Variation of Air Ratio, Cathode Gas Recycle Loop by an Injector