OPTIMIZATION OF SMALL SOFC PLANTS WITH FLEXIBLE POWER/HEAT RATIOS AND THEIR FUTURE APPLICATION

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ABSTRACT

An energetic and economic analysis of a decentralized natural gas-fuelled SOFC-power plant in the range of 200 kW capacity is carried out. Plant efficiencies, power/heat ratios and changes in costs of electricity are determined for variation of cell operation parameters as well as for variation of the flowsheet. The results indicate that it is possible to develop different plant concepts covering a wide range of power/heat ratios between about 1 and 3. In all cases low costs of electricity can be reached by optimization. Especially plant concepts with internal reforming and cathode gas recycling offer broad application potentials. In the second part of this paper some aspects of todays energy market will be analysed in order to come up with recommendations for the developers to enable fuel cells to play an important part in future energy supply systems.

INTRODUCTION

Small SOFC systems in the 100 kW to 1 MW range offer the possibility of cogeneration. Waste heat produced in the non-ideal electrochemical process can in principle be offered as useful heat at different temperature levels. There is a realistic chance to enter the market in this power class, because competitive conventional small cogeneration systems have relatively high investment costs.

The Research Center Jülich in cooperation with industry contributes in different research areas to the development of a Combined Heat and Power (CHP) SOFC plant in the 200 kW range (1,2). As shown in Fig. 1 in such a plant natural gas and air are electrochemically converted into electricity and heat. In this example the stack operates with natural gas that is 50% pre-reformed.

The results presented here are based on calculated plant data of a comprehensive simulation study (3). This paper deals with the influence of parameter changes and plant design on the power to cogeneration heat ratio. An overall system optimization is carried out, which leads to a selection of plant concepts having a broad range of power/heat ratios with
minimized costs of electricity (COE). In this paper only SOFC plant concepts with heat supply at a low temperature level are described.

Discussions about an environmentally compatible energy management in industry place special emphasis on combined heat and power techniques. The crucial factors of their use were and are the company's internal heat and power needs and their simultaneous occurrence, the prices of power, heat and fuels, the available energy technologies and their investment and operating costs.

BALANCE OF PLANT AND COST ANALYSIS

For energetic analysis of the small size CHP SOFC plant (Fig. 1) the commercial flow sheet simulator PRO/II (SimSci) is used. This program simulates the mass flow and calculates the energy demand of common peripheral units. For special components like jet pumps and hot gas fans characteristic correlations are separately specified. A SOFC stack modelling program (4) is integrated as a FORTRAN subroutine.

In Fig. 1 the flowsheet of a basic plant concept is shown. The natural gas stream (400 kW LHV) is compressed to overcome the pressure losses in the apparatus. After subtracting the energy loss of the inverter and the energy demand for compression a net AC power output of 172 kW remains. Thus the electrical plant efficiency is 43%. Taking into account the additionally produced useful heat of 94 kW a total plant efficiency of 67% is obtained for this unoptimized base case (Table I, case 1).

The investment costs of the SOFC stack are based on the material prices and the thickness of the fuel cell components (planar SOFC concept with self-supported electrolyte). The investment costs of the peripheral components are based on actual industrial prices for peripheral components. The electrical energy production costs for this case are normalized to 100%.

The large air stream plays a dominant role in the heat management of the process. This has considerable consequences with respect to investment costs and own energy consumption of the plant. The capital costs of the air blower and the air preheater contribute with 17% to the COE. In addition, the energy consumption of the blower lowers the plant efficiency so that the natural gas costs are increasing. Therefore a main goal of optimization is to minimize the fresh air stream. Furthermore, the capital costs of the SOFC stack and its substitute contribute to about one third to COE. These costs can be lowered by both cheaper SOFC materials and fabrication techniques and by higher cell performance resulting in smaller active areas. Nearly half of COE is caused by natural gas costs. Higher plant efficiency directly influences this cost portion. Therefore, an important goal of cost optimization in general is to increase plant efficiency by both higher cell voltage and by low energy consumption.
RESULTS FOR DIFFERENT OPTIMIZATION ROUTES

Many calculations are carried out for varying cell parameters and for different flowsheets. From these results it can be seen, that plant optimization can be done in different ways by parameter and flowsheet variation.

Optimization of Electric Plant Efficiency

If the aim of plant optimization is a high electric plant efficiency, this can be reached by the following cell parameter changes leading to lower air ratios as can be seen from Table I. A stepwise increase of electric plant efficiency by 2 or 3 % points each can be reached by

- increase of internal reforming from 50 to 75 %
- increase of air temperature increase in the stack from 100 to 130 K
- increase of cell voltage from 0.75 to 0.77 V
- increase of fuel utilization from 80 to 85 %

Further increase of electric plant efficiency can be reached by change of the flowsheet from the simple basic concept to cathode gas recycling by a hot gas fan. Only in cases 3 and 4 the COE are significantly low.

Increase of Useful Heat and Minimization of Waste Heat

If the aim of plant optimization is high cogeneration heat supply, this can be reached for example by an increase of the electrochemically produced excess heat in the stack. For case 7 in Table II a decrease of cell voltage from 0.75 to 0.6 V results in an increase of heat efficiency by 12 % points. But the electric plant efficiency decreases drastically by 15 % points, so that the COE are unacceptably high for steady state operation.

A better optimization route is demonstrated with cases 2, 6, 8 and 9. Here the waste heat leaving the plant is continuously lowered (increase of total efficiency):

- In cases 2, 6 and 8 the amount of exhaust gas is lowered (low air ratios)
- Further increase in heat efficiency (up to 42 %) and in total efficiency (82 %) is reached, when the amount of steam in the exhaust gas is lowered.

This can be done by introducing an anode gas recycle loop (case 9). This leads to low amounts of steam leaving the plant and thus the heat loss by steam condensation outside the plant is low.

In general the efficiencies depend strongly on the cell parameters assumed and can reach very high values. Drenckhahn and Lezuo (5) calculated very high electric plant efficiencies (50 %) and total efficiencies (94 %) for a plant concept with anode steam/water recycling, complete internal reforming and an air temperature increase in the stack of 200 K.
Optimization by Selection of Plant Concepts with Different Power/Heat Ratios and Low Costs of Electricity

From the application point of view and with respect to market introduction finally two characteristic plant data are most important:
• the power/heat ratio and
• the cost of electricity

Therefore a selection of calculated cases was carried out with respect to low COE. Table III shows 6 cases, which cover a range of power/heat from 0.9 to 2.7. The COE slightly increase from about 70 to 90 % in comparison to the base case.

Three main classes of plant concepts can be distinguished:
• For low power/heat ratios of about 1 plant concepts with cathode gas recycling (or/and with anode gas recycling, see Table II, case 9) are optimal.
• For power/heat ratios of about 2 complete internal reforming is the best solution.
• For higher power/heat ratios one should choose cell parameters, which increase the energy conversion to electricity in the cells like high voltage (case 4) and high fuel utilization (case 5). In these cases the COE are somewhat higher.

STRUCTURES OF INDUSTRIAL ENERGY USE AND SUPPLY

Within the last three decades the use of final energy carriers in German industry has not only been reduced, but has also changed considerably in its structure. Owing to their simpler handling and higher efficiency, the more cost-effective and also more ecological energy carriers of natural gas and electricity have expanded and reached a share of 36 % and 30 %, respectively, in the industrial energy market, whereas the classic energy carriers of coal and oil have decreased (6). This development is to be seen as a response to the changing conditions on the international market entailing the need for a continuous technology replacement process, which indeed has taken place in conjunction with a significant increase in the rate of industrial automation.

The reduction of the specific energy consumption in German industrial production is to be seen as an important characteristic and also as a mark of success in this development, involving a decrease of the gross value added (GVA) from roughly 1500 kWh/1,000 DM GVA to approx. 850 kWh/1,000 DM GVA between 1970 and 1994. Due to the conversion to electricity-based processes, progressing automation or more automatic control, on the other hand, the electric intensity increased from 225 kWh/1,000 DM GVA to 234 kWh/1,000 DM GVA within the same period (7).

Neither the sum of changes nor the efforts at reducing industrial heat demand by more efficient energy use have led to a fundamental change in the industrial energy demand structure. At the present time, about 65 % of the industrially used energy carriers is needed

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for the production of process heat (8). It is thus obvious that the layout of combined heat and power plants is primarily oriented towards heat demand.

Since the available CHP techniques also differ with regard to their utilisable temperature level - engines up to 180 °C (9) or gas turbines up to 500 °C (10) - the analysis of the temperature level needed and the importance of the corresponding processes and industries has great information value for future strategies. Results of such analyses are outlined in Fig. 2 (11,12).

Great demand can be recognized in the low temperature range between 100 °C and 300 °C, expressed by the level of energy carrier input. In this temperature range, heat supply for petrochemical distillation and refinery processes, for processes in organic chemistry, in the food and drink industry, the paper industry, the textile industry and the capital goods industry as well as space heat supplies are of primary importance.

The high temperature range above 800 °C is characterized by two main areas of demand. The first is in the range of 900 °C and is particularly determined by processes in the chemical industry, the nonmetallic mineral industry and the nonferrous industry, whereas high-temperature heat in the range of 1500 °C is required by the iron and steel producing industry as well as the glass and ceramics industry.

A more detailed analysis of the energy management in the different branches of industry shows that the importance of combined heat and power techniques varies widely, which can be seen from the respective contribution to electricity consumption. A factor governing industrial use is the operationally required temperature or the temperature level extractable from CHP techniques. It is generally below 500 °C so that CHP is primarily used in plants with low temperature requirements. Consequently, the CHP contribution to operational electricity supply is above the 14 % average in these industries, e.g. 39 % in refineries, 31 % in the chemical industry or 41 % in the paper industry. In contrast, the CHP contribution is only 7, 2 and 1 percent in industries needing high process temperatures, such as the nonmetallic mineral industry, iron and steel, and electricity-intensive processing industries such as nonferrous metal processing (13).

FUTURE ENERGY MANAGEMENT

The perspectives for the future use of CHP plants are considered to be positive due to the high efficiency and simple handling of such plants, on the one hand, and because of the still existing demand for the use of environmentally more benign energy production plants, so that additional fields of economically interesting application appear feasible. This also means that the use of CHP techniques can no longer be restricted to heat and electricity production alone, but new supply concepts should also include refrigeration. Such comprehensive integrated system concepts go beyond past industrial practice, but would be in line with the change from classic energy supply to modern energy management. These integrated supply concepts, Fig. 3, are increasingly discussed especially in view of the high pressure of cost and
competition in industry, and it is considered meaningful for several reasons to assign the
operation and organization of energy supply to third parties.

The general problem of operating heat-oriented conventional systems in compliance with
demand is not eliminated by potentially integrated systems. However, a comprehensive use of
all possibilities will increase the utilization factor and thus improve plant economics. Further
progress towards a more effective and thus both lower-cost and environmentally less
detrimental energy management could be provided by the availability of fuel cell technology,
which seems to be capable of fulfilling a large number of requirements for efficient and
environmentally acceptable energy use. A first argument in favour of this technology is
constantly high electrical efficiency even for small units, so that this technique would be
commensurate with the development observable in many branches of industry, according to
which heat demand decreases in favour of electricity demand, which is also reflected in an
increasing ratio of power to heat demand. The development of this characteristic is shown by
approximation in Table IV for some groups of industries (13). The trend also to be derived
from other sources can be clearly seen, i.e. the power characteristic rises on average, but is
not a static quantity since it changes within certain bandwidths as a function of operating
conditions, load factor etc. Such fluctuations represent a considerable problem for
conventional CHP techniques, since their flexibility with respect to a changing power/heat
production ratio during operation is restricted.

Fuel cell technology is characterized by a much higher flexibility; electricity and heat
production will be variable within wide limits, so that changing operational requirements can
be met. The low emission values relative to the [kWhu] unit result from the very good
electrical efficiency of the fuel cells and from the reaction processes which, in many cases,
suppress pollutant formation. When operating a phosphoric acid cell, for example, emission
values are obtained for nitrogen oxide, carbon monoxide as well as hydrocarbons, which only
amount to fractions of the quantities emitted during gas engine or gas turbine operation.

With respect to economics, however, it must be stated that it cannot be foreseen at present
whether and when the reductions in emissions by a technology can be expressed in terms of
money so as to become economically relevant. For this reason, fuel cell technology will first
have to compare with other techniques in terms of conventional economics. The currently
published investment cost expectations constitute a severe obstacle to introduction in the near
future. Whereas the investment costs range from 1,500 to 2,000 DM/kWel for conventional
CHP techniques, at plant outputs below 1 MWel, approx. DM 4,000 is specified for
corresponding high-temperature fuel cell plants (14). Such a large deviation from competing
techniques makes an introduction doubtful, especially since internal electricity production in
industry becomes less attractive and approaches profitability limits due to regulatory
measures, such as the abolition of coal subsidies, the decrease in industrial electricity prices
and in the return for electric power generation.
RECOMMENDATIONS FOR ACTION

The influence of the different yearly energy cost components for an industrial demand case (heat and power) shows essential differences with regard to the used technique, (a) boiler and power purchase, (b) gas engine and partial power purchase or (c) SOFC, Fig. 4. Because of the high investment costs for fuel cells, the capital costs have a dominant influence on the economic viability and lead to the most expensive supply variant. Development work for fuel cell technology will therefore have to concentrate on reducing the investment costs to a level at which direct competition with competing techniques becomes possible. That point will be reached at specific investment costs of around 1700 DM/kW (installed power), shown as the fourth beam (d) in Fig. 4 (15). This step appears necessary in order to adapt fuel cell technology to future conditions. Due to progressive changes in the field of several forms and quantities of useful energy, fiercer competition must be assumed for CHP technology in general and for the different techniques in particular. The initiated deregulation of the electricity markets crucially contributes to this development because it exerts great pressure on electricity prices. Since, at the same time, the market prices for gas and oil seem to remain stable, no fundamental economic advantages will arise for CHP technology with respect to heat supply either. On the whole, this means that greater attention must be paid in future to compliance with classic basic principles. These basic rules imply that sufficiently high and uniform heat requirements (space and process heat) must be ensured, which should be spatially concentrated, so that cost-intensive heat networks do not become too long and thus cancel out the primary-energy benefits of CHP technology due to excessive line losses. This makes it necessary to also develop new supply concepts in addition to new techniques to account for energy services, which have played a minor role in the past, but are becoming more and more important.

CONCLUSIONS

SOFC technology offers the possibility of flexible power to cogeneration heat ratios. By variation of the cell parameters and the flowsheet special concepts can be designed for different applications. By addition of further components like a natural gas boiler SOFC systems with power/heat ratios much lower than 1 can be designed. On the assumption, that the advantages of the fuel cell apply also to the complete fuel cell based plant and that the high cost reduction goal will be reached, the fuel cells will enrich future energy management systems by opening new dimensions.

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Fig. 1: Basic concept of a SOFC combined heat and power plant (case 1)

Table I: Optimization of electric plant efficiency by parameter and concept variations (exhaust gas temperature = 80 °C)

| Case | 1  | 2  | 3  | 4  | 5  | 6  |
|------|----|----|----|----|----|----|
| Degree of internal reform. (%) | 50 | 75 | 75 | 75 | 75 | 75 |
| Air temp. increase (stack) K | 100| 100| 130| 130| 130| 130|
| Cell voltage V | 0.75| 0.75| 0.75| 0.77| 0.77| 0.77|
| Fuel utilization % | 80 | 80 | 80 | 80 | 85 | 85 |
| Anode gas recycle | -  | -  | -  | -  | -  | -  |
| Cathode gas recycle | -  | -  | -  | -  | -  | fan |
| Air ratio | 7.1 | 5.1 | 3.7 | 3.6 | 4.3 | 1.5 |
| Electric plant efficiency % | 43 | 46 | 48 | 50 | 52 | 55 |
| Heat efficiency % | 24 | 24 | 24 | 22 | 19 | 22 |
| Total efficiency % | 67 | 70 | 72 | 72 | 71 | 77 |
| Power/heat ratio kW_e/kW | 1.8 | 1.9 | 2.0 | 2.3 | 2.7 | 2.5 |
| Cost of electricity % | 100 | 87 | 78 | 81 | 89 | 101 |

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Table II: Increase of heat efficiency by changing the cell voltage (case 7) and increase of total efficiency by minimization of waste heat

| Case | 1 | 7 | 2 | 6 | 8 | 9 |
|------|---|---|---|---|---|---|
| Degree of internal reform. | % | 50 | 50 | 75 | 75 | 75 | 50 |
| Air temp. increase (stack) | K | 100 | 100 | 100 | 130 | 130 | 100 |
| Cell voltage | V | 0.75 | 0.6 | 0.75 | 0.77 | 0.73 | 0.75 |
| Fuel utilization | % | 80 | 80 | 80 | 85 | 75 | 80 |
| Anode gas recycle | - | - | - | - | injector | - |
| Cathode gas recycle | - | - | - | fan | injector | - |
| Air ratio | - | 7.1 | 9.9 | 5.1 | 1.5 | 1.5 | 5.1 |
| Electric plant efficiency | % | 43 | 28 | 46 | 55 | 45 | 40 |

a) Exhaust gas temperature = 80 °C:

| Heat efficiency | % | 24 | 34 | 24 | 22 | 31 | 42 |
| Total efficiency | % | 67 | 62 | 70 | 77 | 76 | 82 |
| Power/heat ratio kWd/kW | 1.8 | 0.8 | 1.9 | 2.5 | 1.5 | 1.0 |
| Cost of electricity | % | 100 | 131 | 87 | 101 | 73 | 93 |

b) Exhaust gas temperature = 40 °C:

| Increase in heat effic. | %points | 10 | n.c. | 12 | 22 | 22 | 9 |
| Heat efficiency | % | 34 | n.c. | 36 | 44 | 53 | 51 |
| Total efficiency | % | 77 | n.c. | 82 | 99 | 98 | 91 |
| Power/heat ratio kWd/kW | 1.3 | n.c. | 1.3 | 1.3 | 0.9 | 0.8 |
| Cost of electricity | not calculated |

Table III: Optimization by selection of plant concepts with flexible power/heat ratios and low COE

| Case | 8b | 8a | 3 | 10 | 4 | 5 |
|------|----|----|---|----|---|---|
| Degree of internal reform. | % | 75 | 75 | 75 | 100 | 75 | 75 |
| Air temp. increase (stack) | K | 130 | 130 | 130 | 100 | 130 | 130 |
| Cell voltage | V | 0.73 | 0.73 | 0.75 | 0.75 | 0.77 | 0.77 |
| Fuel utilization | % | 75 | 75 | 80 | 80 | 80 | 85 |
| Anode gas recycle | - | - | - | - | - | - |
| Cathode gas recycle | injector | injector | - | - | - | - |
| Exhaust gas temperature | °C | 40 | 80 | 80 | 80 | 80 | 80 |
| Air ratio | - | 1.5 | 1.5 | 3.7 | 3.0 | 3.6 | 4.3 |
| Electric plant efficiency | % | 45 | 45 | 48 | 49 | 50 | 52 |
| Heat efficiency | % | 53 | 31 | 24 | 23 | 22 | 19 |
| Total efficiency | % | 98 | 76 | 72 | 72 | 72 | 71 |
| Power/heat ratio kWd/kW | 0.9 | 1.5 | 2.0 | 2.1 | 2.3 | 2.7 |
| Cost of electricity | % | n.c. | 73 | 78 | 77 | 81 | 89 |
Fig. 2: Temperature of process-heat and centres of demand

Fig. 3: Heat and power supply concept
Table IV: Development of the characteristic value of the power/heat ratio

| Industry                                      | 1987 | 1992 |
|-----------------------------------------------|------|------|
| process manufacturing industry                |      |      |
| non metallic minerals industry                 | 0,15 | 0,16 |
| iron and steel producing industry             | 0,12 | 0,13 |
| non ferrous industry                          | 1,43 | 1,34 |
| chemical industry                             | 0,50 | 0,51 |
| pulp and paper industry                       | 0,50 | 0,56 |
| Investment good industry                      |      |      |
| engineering industry                          | 0,46 | 0,57 |
| construction of vehicles                      | 0,65 | 0,76 |
| e-technics, light engineering, optics         | 0,80 | 1,06 |
| Consumer good industry                        |      |      |
| glass, fine ceramic industry                   | 0,19 | 0,23 |
| textile industry                              | 0,38 | 0,47 |
| food industry                                 | 0,23 | 0,28 |

Fig. 4: Yearly cost of different energy supply variants

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