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Optimization of a 200 kW SOFC cogeneration power plant
Part I: Variation of process parameters

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Abstract

In order to benefit from the high electrochemical efficiency of solid oxide fuel cells (SOFC), a detailed balance of plant (BOP) 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 carried out. All calculations start from a basic plant concept with a simple flowsheet and a basic parameter set of SOFC operation and economic data. Changes in costs of electricity (COE) and plant efficiency are determined for the variation of cell operation parameters. This includes the influence of air temperature increase in the stack, degree of internal reforming, cell voltage and fuel utilization. The results indicate two classes of cell parameters. Cell voltage and fuel utilization show a cost optimum characteristic, whereas the other parameters have a uniform influence on efficiency and costs of electricity. © 1998 Elsevier Science S.A. All rights reserved.

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1. Introduction

Solid oxide fuel cell (SOFC) technology has at present not yet reached a stage of development where it could be competitive with conventional power plants. Extensive long-term development work is still required in order to achieve in a fuel cell stack under real operating conditions with natural gas [1] or coal gas [2] the high electrochemical efficiencies theoretically possible. In addition, a process concept has to be developed, which is based on components having low investment costs and low energy consumption. The tasks of stack and periphery development are strongly interconnected. Plant optimization therefore requires a tool, which takes the characteristic behaviour of stack and periphery and their interactions into account.

Large centralized SOFC systems with pressurized operation can, in principle, reach very high efficiencies of the order 70%. But competitive conventional large systems show essential progress in plant efficiency (about 60%) and have very low investment costs, which cannot be reached by the SOFC in the near future.

Small SOFC systems in the 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 various temperature levels. There is a realistic chance to enter the market in this power class, because competitive conventional small cogeneration systems may justify higher investment costs.

Fig. 1 shows a simple concept of a 200 kW SOFC based on natural gas. On purpose, no optimization was implemented. As a typical feedstock, the Groningen natural gas was chosen. This gas consists mainly of methane (81.3 mol%). Higher hydrocarbons have low concentrations (ethane 2.9 mol%, propane 0.4 mol%, others 0.2 mol%). The rest is nitrogen (14.3 mol%) and carbon dioxide (0.9 mol%). The lower heating value (LHV) is 708 kJ/mol.

It is further assumed that stack operation with a degree of 50% internal methane reforming would be possible. According to the present status of SOFC stack development the values of other main parameters for cell operation are summarized in Table 1. A pressure drop of 20 mbar at each gas side is assumed. We also take into account, that the pressure drop in the gas channels of a solid oxide fuel

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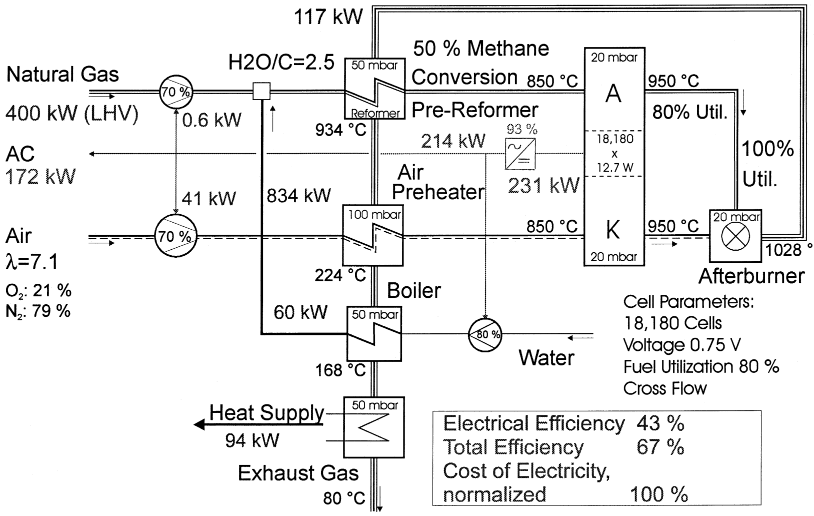

Fig. 1. Basic concept of a SOFC combined heat and power plant.

cell (planar type) will be of the order 1 to 10 mbar and the pressure drop in the manifolding system will be optimized [3]. In addition it is assumed, that a high lifetime can be reached. Data for operation over 2 years with relatively low degradation of about 0.5%/1000 h are already available for cell operation with hydrogen [4].

Up to now, mainly energetic aspects of SOFC plants are discussed [5]. The aim of the present study, presented in three parts, is to elucidate the influence of parameter changes (Part I) and the influence of plant design (Part II) on the economy of a CHP SOFC plant. Finally an overall system optimization will be carried out (Part III). In addition to finding out how and to which extent optimization is possible, crucial aspects of operation or critical components can be determined.

2. Balance of plant (BOP) analysis

For an energetic analysis of a small-sized combined heat and power SOFC plant (Fig. 1), the commercial flow sheet simulator PRO/II (SimSci) was 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, so that these components could be simulated. A SOFC stack modelling program [6] is integrated as a FORTRAN subroutine. The performance characteristic of the simulated fuel cell is described in Fig. 2. The current voltage curve shows that an adjustment of the cell voltage at 0.75 V leads to a mean current density of 170 mA/cm^2 and a power density of 1.3 kW/m^2.

Table 1
SOFC reference data

Degree of methane prereforming	50%
Fuel temperature at stack inlet	850°C
Air temperature at stack inlet	850°C
Air temperature increase in stack	100 K
Fuel utilization, related to natural gas at plant inlet	80%
Cell voltage	0.75 V
Pressure drops in stack:	
anode side	20 mbar
cathode side	20 mbar
Fuel cell design: flat concept, self supported electrolyte, cross flow	

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 system. Before entering the prereformer, it is mixed with steam ($H_2O/C = 2.5$ mol/mol) produced in a heat integrated boiler. The prereformer is heated recuperatively by the hot gas leaving the afterburner. The large air stream requires an energy demand of 41 kW for compression. Then the air is preheated recuperatively up to 850°C. In the SOFC stack a gross electric DC power of 231 kW is produced. After subtracting the energy loss of the inverter and the energy demand for compression remains a net AC power output of 172 kW. Thus the electrical plant efficiency is 43%. Taking into account the produced heat of 94 kW which

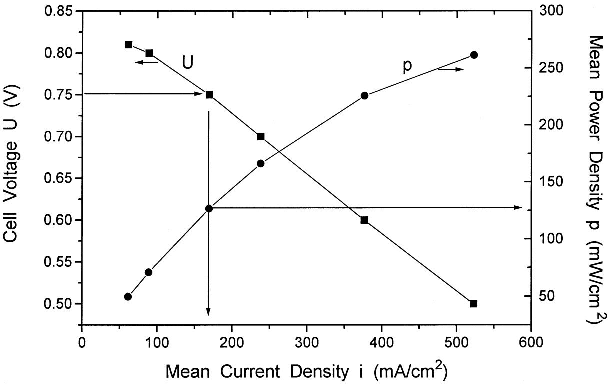

Fig. 2. Current voltage curve (cell parameter values as listed in Table 1).

can be used a total plant efficiency of 67% is obtained. These are the values of the unoptimized basic case of the assumed 200 kW SOFC plant.

3. Method of cost analysis

Previously, only the investment costs of selected components, especially the air preheater, were estimated [7]. In this study various aspects of power plant simulation such as influence of operational parameters on size and performance of peripheral components and SOFC stack are focused on one final parameter, the costs of electrical energy production. Cost analysis can then possibly lead to a more economic power plant operation. Investment costs and other costs of the energy production are based on the assumptions listed in Table 2. All prices are given in US$.

3.1. Investment cost

3.1.1. Investment cost of a SOFC stack

The investment costs of the SOFC stack are estimated in the following way.

(i) The cost calculation is based on the material prices and the thickness of the fuel cell components (planar SOFC concept with self-supported electrolyte)

- anode: Ni–ZrO_2, 0.05 mm
- electrolyte: Y–ZrO_2 (+Yb), 0.1 mm
- cathode: $LaMnO_3$ (+Sr), 0.05 mm
- bipolar plate: $LaCrO_3$ (+Mn), 2.5 mm

For a single cell of 10×10 cm^2 having a volume of 27 cm^3, a material price of US$5 is calculated. The dominant cost part is caused by the bipolar plate, which contributes to these costs with 87%.

(ii) For cell fabrication an additional cost factor of 2.0 is taken into account. The costs of US$10 for the single cell (see Table 2) are in good agreement with prices published for similar SOFC cells [8].

(iii) For stack fabrication an additional cost factor of 1.5 is taken into account. Stack fabrication includes manifolding and insulation. Finally the complete specific SOFC investment costs are US$1500/m^2 related to the geometric active fuel cell area.

3.1.2. Investment cost of peripheral components

The investment costs of the peripheral components are based on actual industrial prices. For the peripheral equipment a lifetime of 10 years, which is equal to the depreciation time, is assumed. Depending on the specific material stress situation under plant operation this assumption should be confirmed by a separate study.

3.1.3. Investment cost for complete plant building and operation

The remaining investment costs for the complete plant are costs for piping, control and building. These investment costs are estimated in such a way that the investment costs of all peripheral components are multiplied by a factor 2.5. Thus the peripheral component costs given in the following are higher than the original costs of the apparatus. It should be pointed out that in the SOFC investment costs this factor is not included. These additional investment costs are distributed only over the peripheral components as described above.

3.2. Sensitivity analysis of cost of electricity (COE) for the economic parameter

In a first part of the sensitivity analysis, the economic reference data are varied. An increase of each parameter value gives a specific change in costs of electricity. This specific sensitivity value is characterized by a sensitivity number, given in %. For example, an increase of the natural gas price by 10% leads to an COE increase of 4.4%. In this case the sensitivity number of the natural gas price is +44%. Table 3 gives the results for the base case.

Table 2
Economic reference data[a]

Investment cost:	
Single fuel cell unit (10×10 cm^2)	US$10
Stack	additional cost factor = 1.5
Peripheral components	industrial prices
Piping, control, building, etc.	additional cost factor = 2.5
Financing of investment cost:	
Interest rate	8% per year
Depreciation time	10 years
Operation data:	
Plant load time	7000 h/a
Cell life time	40,000 h
Operation cost and profit: stack replacement costs are taken into account	
Natural gas price	3.1 cents/kW h
Useful heat credit	2.7 cents/kW h

[a] Currency exchange rate 1.5 DM/US$.

Table 3
Sensitivity of the economic parameter with respect to electricity production cost (starting from the economic reference data) for the basic plant concept with SOFC reference data

	Sensitivity number
Investment cost:	
Stack (first set for 40,000 h)	+21%
Additional cost factor for piping, control, building, etc.	+34%
Financing of investment cost:	
Interest rate	+21%
Depreciation time	−30%
Operation data:	
Plant load time	−50%
Cell life time	−16%
Operation cost and profit:	
Natural gas price	+44%
Useful heat credit	−9%

It should be pointed out, that for other plant concepts different results will be obtained.

Moreover the sensitivity analysis involves both
- the influence of different parameter values of stack operation and
- the influence of different power plant concepts

on the electrical energy production costs. In all cases the variations start from the simple base case without gas recycling (Fig. 1). The dominant results of the study are the changes in the COE. The absolute value of the COE is difficult to calculate at present because of various uncertainties. More important, however, is the relative change (in %) induced by a certain measure which has a much higher accuracy. Therefore, the cost analysis presented here should be characterized as 'difference cost analysis method.'

4. Efficiencies and cost of electricity for the base case

The simple basic plant concept (Fig. 1) achieves an electrical efficiency of 43%. The electrical energy production costs for this case are taken as 100%. In general, three types of cost contribute to the COE. In detail, the costs are composed of capital costs of SOFC stack and peripheral components, of operational costs (including replacement costs of SOFC stack after 40,000 h operation time) and of the useful heat credit (Table 4).

It can be seen, that the large air stream plays a dominant role in the heat balance of the process. This has consequences with respect to investment costs and the 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.

Table 4
Partition of cost of electricity

	Cost of parts (%)
(a) Capital cost	
SOFC	21
Inverter	3
Natural gas blower	1
Prereformer	3
Boiler	2
Air blower	5
Air preheater	12
Heat exchanger useful heat	5
Total capital cost = 52%	
(b) Operation and maintenance (O and M)	
Natural gas	44
Water	1
Maintenance and SOFC substitute	12
Total O and M cost = 57%	
(c) Useful heat credit	−9
	100%

Furthermore the capital costs of the SOFC stack and its substitute contribute to about one third to the COE. These costs can be lowered by both cheaper SOFC materials and fabrication techniques and by higher cell performance resulting in less active area.

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.

5. Optimization by parameter variation

An important part of the sensitivity study deals with the influence of the cell parameters on power plant operation and the resulting changes in COE. Table 5 gives an overview on the results obtained. According to the dominant role of the cooling air the air ratio λ, which characterizes the air stream with respect to natural gas stoichiometric combustion, and the amount of heat exchanged in the recuperative air preheater (in relation to 100 kW chemical heat input by natural gas) are listed in the first columns.

5.1. Parameter with uniform influence on efficiency and cost of electricity

The main target of further process development is to reduce the large amount of air supply ($\lambda = 7.1$ in the base case). Alternative stack cooling concepts are necessary to improve plant operation. Here, two possibilities from the process engineering point of view are discussed: internal natural gas reforming and recycling of the hot cathode exhaust gas by the use of a fan or a jet pump (injector). Due to the present limits of fuel cell development, natural gas has to be partially reformed outside the fuel cell (base case: 50%). Otherwise the fast reforming reaction would cause a rapid cooling at the cell inlet [9,10]. The electrochemical waste heat has to be removed by a large air stream.

So, when SOFC operation with higher internal reforming rates would be possible (up to 100%), lower values of the air ratio would be necessary. Considerable advantages with respect to electrical efficiency and costs can be achieved (see Fig. 3 and Table 5). An air ratio of 3.0 for internal reforming results in an increase of electrical efficiency to 49%. The COE are reduced by 23% in comparison to the base case (50% internal reforming) and by 40% in comparison to complete external reforming.

Nevertheless, even for complete internal reforming an appreciable amount of air remains. The corresponding heat to be exchanged in the air preheater is of the order of the chemical heat input by natural gas (see Table 5). Therefore

Table 5
Plant optimization by parameter variation for the basic plant concept (without gas recycling)

	Air ratio	Heat exchanged in air preheater (kW, normalized)[a]	Electric plant efficiency (%)	Total efficiency (%)	Cost of electricity normalized
Basic parameter set (BPS)	7.1	208	43	67	100
Cell voltage					
0.6 V	9.9	290	28	62	134
0.75 V (BPS)	7.1	208	43	67	100
0.8 V	6.3	185	48	68	112
Fuel utilization					
40%	3.4	99	21	76	126
70%	5.9	174	39	70	94
80% (BPS)	7.1	208	43	67	100
Reforming					
External	10.7	312	38	60	129
50% Int. (BPS)	7.1	207	43	67	100
Internal	3.0	86	49	72	77
Air temperature increase in stack					
50 K	14.9	436	32	42	179
100 K (BPS)	7.1	208	43	67	100
150 K	4.5	133	47	71	81

[a] Values related to 100 kW chemical heat input by natural gas (LHV).

it is important to take additional measures, which in principle should lead to

- further lowering of the air ratio and/or
- reduction of air processing costs.

In Fig. 4 the influence of the air temperature increase in stack on the electrical plant efficiency and the costs of electricity is shown. The data given in Table 5 indicate, that the temperature difference essentially influences the demand of cooling air. The air ratio increases dramatically, when the temperature difference is lowered to 50 K. In this case 22 efficiency points are lost by plant power consumption for air compression (gross plant efficiency DC: 58%, loss inverter: 4%-points, plant efficiency: 32%). As a result the costs of electricity increase dramatically. In opposite direction, if stack operation with 150 K temperature difference is possible, the COE are 19% lower in comparison to the base case.

5.2. Parameter with cost-optimum characteristic

The influence of cell voltage on the electrical plant efficiency and on the costs of electricity is shown in Fig. 5. The efficiency increases with increasing cell voltage. Plant efficiency of 50% is reached at 0.81 V. The COE show a minimum at 0.75 V. At higher cell voltages the current density is low and therefore the number of cells becomes high. In this case the costs of the SOFC stack are much higher than in the case of low cell voltage. At lower cell voltages the electrical plant efficiency becomes low. As a consequence a large natural gas stream is consumed, which is a cost-dominant factor.

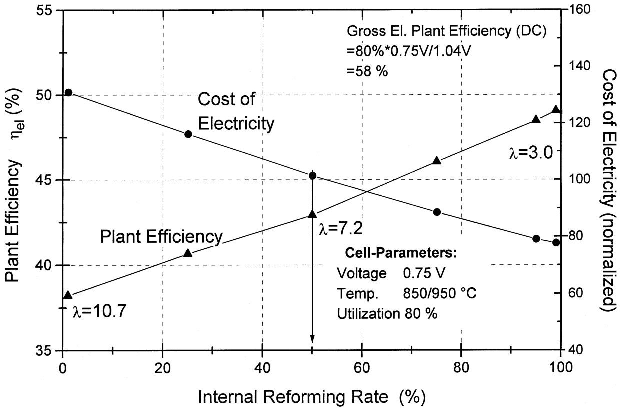

Fig. 3. Variation of internal methane reforming rate.

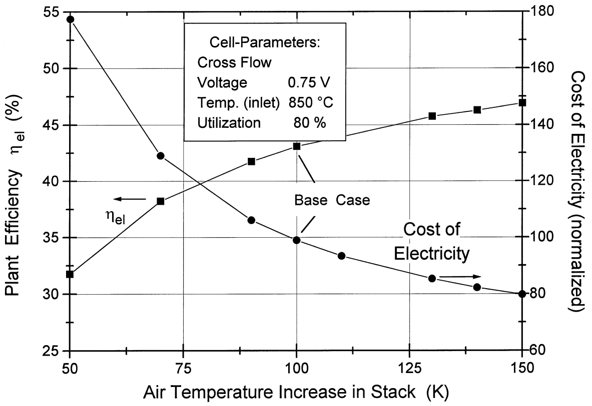

Fig. 4. Variation of air temperature increase in the stack.

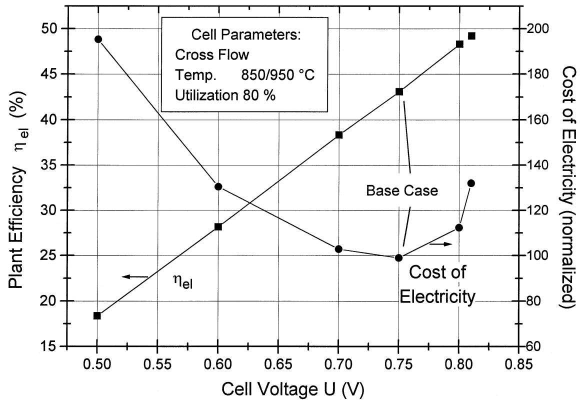

Fig. 5. Variation of cell voltage.

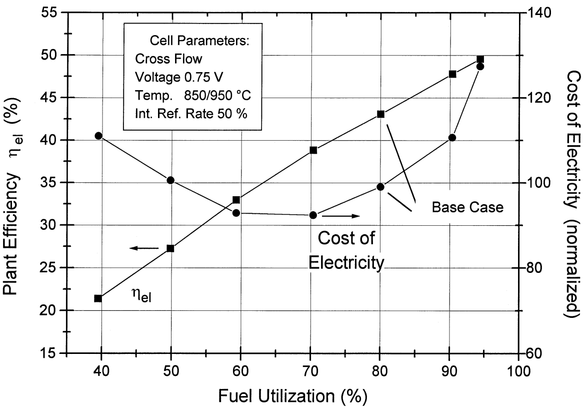

Fig. 6. Variation of fuel utilization in the stack (related to natural gas feed).

In Fig. 6 and Table 5, the results of a parameter variation of the fuel utilization in the SOFC are shown. Fuel utilization is related to the natural gas feed stream (fuel utilization related to the gas stream at stack inlet would be lower in case of anode gas recycling). The electrical plant efficiency can be raised up to 50%, when the fuel utilization is adjusted to about 95%. But high fuel utilizations require low gas velocities in the gas channels of the SOFC. At the end of the cells there are only low partial pressures of hydrogen in the gas. Consequently, the mean current density is low. To convert the last part of the fuel gas into electricity means that many cells have to be installed in the stack. The investment costs increase and the capital costs for the SOFC overcompensate the back pay for the high electrical efficiency. For the basic plant concept with the typical set of parameter values a fuel utilization of 65% is optimal.

6. Conclusions

For a combined heat and power plant with a solid oxide fuel cell (SOFC) in the range of 200 kW a valuation method for different plant concepts is developed. By energetic simulation of the whole plant, which consists of the fuel cell stack and the gas processing periphery, and by analysis of investment and operational costs a sensitivity study of cell parameters with respect to costs of electricity (COE) is carried out.

In general two main cost-influencing factors are detected: (1) the demand on preheated air for stack cooling requires peripheral units for compression and heat exchange and leads to an additional energy consumption; (2) the demand on cell area for optimal electrochemical performance has a strong influence on stack investment costs.

In more detail the variation of cell parameters in case of a simple flowsheet without gas recycling (base case) has strong influences: (1) reduction of COE by nearly 50%, when external reforming is replaced by complete internal reforming; (2) reduction of COE by about 20%, when the air temperature increase inside the stack rises from 100 to 150 K; and (3) reduction of COE by about 5%, when the fuel utilization is adjusted from 80% to an optimal value of 65%.

From these results, it can be concluded that research and development work should concentrate on the following items: (1) internal reforming of methane (anode material development and appropriate stack design); (2) stack development with large air temperature increase, e.g., by integrated air preheater (material development and stack design); (3) reduction of internal resistances in the solid oxide fuel cell (electrochemistry, material development, stack design).

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