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Optimization of a 200 kW SOFC cogeneration power plant. Part II: variation of the flowsheet

Ernst Riensche[a,*], Josefin Meusinger[a], Ulrich Stimming[b], Guido Unverzagt[c]

[a]Forschungszentrum Jülich GmbH, Institut für Energieverfahrenstechnik (IEV), PO Box 1913, D-52425 Jülich, Germany
[b]Technische Universität München, Institut für Festkörperphysik und Technische Physik, James-Franck-Str. 1, D-85747 Garching, Germany
[c]Deutsche Shell AG, PO Box 501264, D-50972 Köln-Godorf, Germany

Abstract

An energetic and economic analysis of a decentralized natural gas-fuelled solid oxide fuel cell (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 and plant efficiencies are determined for variations of the plant concept. Flowsheets with gas recycling by blowers or jet boosters are described. Cathode gas recycling by jet boosters turns out to be more advantageous with respect to the costs of electricity than gas recycling by hot gas fans. The influence of pressure drop in the cathode gas circuit is analyzed. In case of anode gas recycling an internal steam circuit exists. This has the advantage that the external steam generator is eliminated and that the steam concentration in the exhaust gas is reduced. Therefore, a higher amount of excess heat can be used. Removal of useful heat at higher temperature levels diminishes the driving temperature differences and enlarges the heat exchange area of the recuperative heat exchangers located downstream. © 1998 Elsevier Science S.A.

Keywords: Solid oxide fuel cell; Cogeneration; Cost analysis; Plant optimization

1. Introduction

Solid oxide fuel cells (SOFCs) convert the chemical energy of the fuel gas directly to electrical energy. Therefore, they can theoretically achieve high electrical efficiencies. The high operating temperature of SOFC opens good possibilities for cogeneration applications.

SOFC technology has, at present, not yet reached a stage of development where it could be competitive with conventional power plants. Therefore, 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 interaction into account.

SOFC systems up to the 10 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.

To reach a high total plant efficiency it is important that the amount of the exhaust gas is as low as possible. Then, the unusable heat content, which remains in the gas after cooling down to about 100°C in the last cooling step of the process, is minimized. It is also important, that the steam content in the exhaust gas is as low as possible. The amount of unused heat of condensation, which takes place in a temperature range below 100°C, is also minimized. This heat management of the system can be optimized by anode gas recycling including the excess steam and by a high degree of internal reforming so that the amount of fresh air is as low as possible.

The possibility of heat production at high temperature levels leads to an interesting question. On the one hand, the quality of the heat is increased and a higher price per

* Corresponding author.

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kWh of the heat can be obtained with a positive influence on the costs of electricity (COE). On the other hand, changes in process design are necessary, because heat exchange at varying places of the flowsheet has to be foreseen. If high temperature excess heat to a lower part is used recuperatively within the direct SOFC process environment, such configurations in principle can lead to a deoptimization of the plant [1]. The question is: are the COE reduced?

Up to now, mainly energetic aspects of SOFC plants are discussed. The aim of the sensitivity study, presented in three parts, is to elucidate the influencing factors on the economy of a combined heat and power (CHP) SOFC plant.

For the energetic analysis of a small size combined heat and power SOFC plant the commercial flow sheet simulator PRO/II (SimSci) is used. This program simulates the mass flow and calculates the energy demand of the common peripheral units. For special components like jet pumps and hot gas fans characteristic correlations are separately specified, so that these components can be simulated. A SOFC stack modelling program [2] is integrated as a FORTRAN subroutine. For each energetic simulation a corresponding economic calculation is carried out. The method used for cost analysis is described in part I [3] of the presented sensitivity study.

In part I the sensitivity of cell parameter values on the COE is described. In this paper (part II) the influence of plant design on the economy of the SOFC plant is analyzed. Possibilities of gas recycling and production of useful heat at high temperature levels are discussed. Changes in flowsheet design are focused on gas processing concepts with reduced investment costs of the peripheral components. These concepts have carefully to be designed to avoid plant operation with high additional energy consumption.

In part III an overall system optimization will be carried out. With the results of this study, which is based on the present state of SOFC development, it will be possible to decide, at which points most crucial deficiencies in current components or processes can be detected and future research work can be directed at.

2. Balance of plant analysis for the reference case

In Fig. 1 the flowsheet of a basic plant concept is shown. The SOFC reference data are listed in Table 1. The natural gas stream (400 kW LHV) is compressed to overcome the pressure losses in the components. 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 additionally produced useful heat of 94 kW a total plant efficiency of 67% is obtained. These are the values of this simple unoptimized base case of the assumed 200 kW SOFC plant.

The method of cost analysis is described in detail in part I [3]. The investment costs of the SOFC stack are estimated.

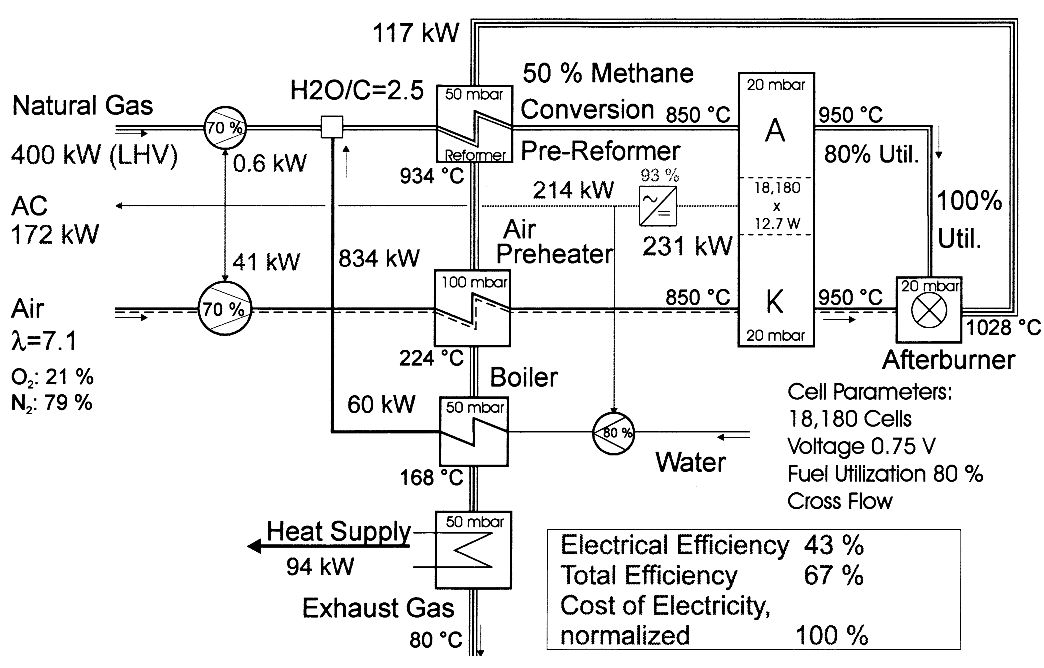

Fig. 1. Basic concept of a SOFC combined heat and power plant.

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

For a single cell of 10×10 cm^2 having a volume of 27 cm^3 a material price of $5 is calculated. The dominant cost part is caused by the bipolar plate, which contributes to these costs with 87%. For cell fabrication an additional cost factor of 2.0 and 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 $1500/$m^2$ related to the geometric active fuel cell area.

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.

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 of 2.5. Thus, the peripheral component costs given in the following are higher than the original costs of the apparates.

The simple basic plant concept (Fig. 1) achieves an electrical efficiency of 43%. The costs of electricity for this case are normalized to 100%. In general, three types of cost parts contribute to the COE. In detail the cost parts for capital costs of SOFC stack and peripheral components, for operational costs (including replacement costs of SOFC stack after 40 000 h operation time) and of the useful heat credit are listed in Table 2.

It can be seen, that the large air stream plays a dominant role in the heat balance of the process. This has strong 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.

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 smaller active areas.

3. Optimization by flowsheet variation

3.1. Principle possibilities of flowsheet design

For a small scale CHP SOFC plant mainly the following possibilities of flowsheet design are discussed [4,5]:

3.1.1. Gas processing on the fuel side

1. reforming of natural gas with steam;
2. reforming of natural gas with steam and carbon dioxide (in case of anode gas recycling);
3. partial oxidation of natural gas.

3.1.2. Oxidant and cooling medium

1. air;
2. oxygen enriched air.

3.1.3. Gas processing in the stack periphery

1. recuperative heat exchange for fuel and air preheating and steam production;
2. recycling of water to the anode inlet by anode gas recycling;
3. recycling of water to the anode inlet by recuperative cooling of the anode outlet gas and condensation of part of the steam and separation of the water;
4. cathode gas recycling.

Table 2

Partition of the costs of electricity (COE)

	Cost 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&M)	
Natural gas	44
Water	1
Maintenance and SOFC substitute	12
Total O&M cost = 57%	
(c) Useful heat credit	−9
Total	100

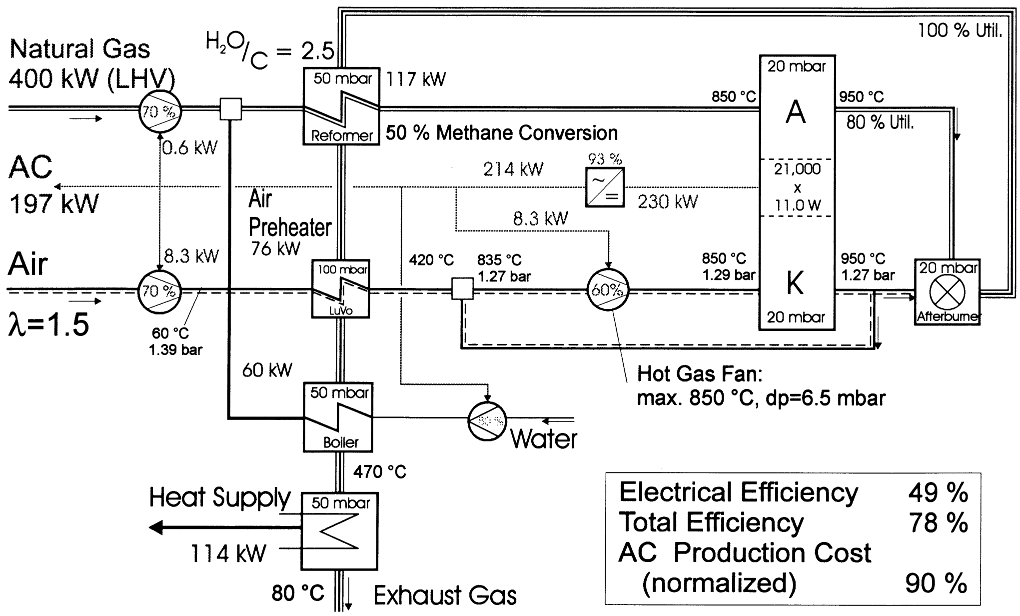

Fig. 2. SOFC plant concept with air preheating mainly by cathode gas recycling (three hot gas fans in series).

3.1.4. *Enthalpy use of the stack outlet gases*

1. position of the afterburner at stack outlet;
2. position of the afterburner in a medium position of the heat exchanger network;
3. heat supply of the fuel gas by the exhaust gas;
4. separation of fuel and air loop;
5. different concepts of the recuperative heat exchange network, especially if useful heat is required at a high temperature level.

In the present study for all flowsheets the following design criteria are applied:

1. reforming of natural gas with steam;
2. use of air;
3. position of the afterburner at stack outlet and
4. heat supply of the fuel gas by the exhaust gas.

In the basic plant concept heat integration is realized by recuperative heat exchange for fuel and air preheating and steam production. Alternatively, gas recycling of the stack outlet gases leads to promising process variants. The main advantage is that for example the cooling of air can be realized by mixing a small fresh air stream with recycled hot depleted air. To overcome the pressure drop in such circuits usually conventional blowers are used. The disadvantage of these blowers is that the working temperature is only about 400°C. This requires an additional expensive heat exchange system within the gas circuit. Therefore, in this study alternative components for gas recycling are considered.

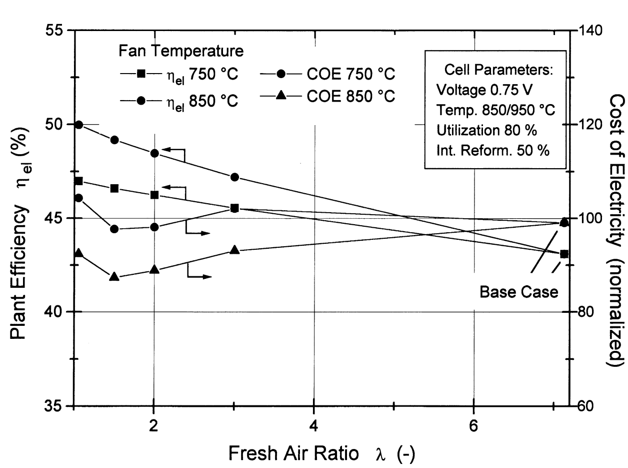

Fig. 3. Variation of fresh air stoichiometric ratio for cathode gas recycling with three hot gas fans in series (different highest permissible fan temperatures).

3.2. *Cathode gas recycling*

3.2.1. *Cathode gas recycling by hot gas fans*

The idea of a cathode gas recycle loop is to preheat the incoming air by mixing with the hot cathode exhaust gas. In order to overcome the pressure losses in the cathode gas loop a hot gas fan instead of a conventional blower can be installed. Due to technical reasons at higher operating temperatures a lower pressure rise can be achieved. The total pressure loss in the cathode gas loop caused by the SOFC and the gas manifolding is set to 20 mbar. Several fans can be installed in series to achieve a sufficient pressure rise.

In Fig. 2 an optimized flowsheet with a hot gas fan is shown. Fig. 3 shows the results of plant simulations, in which the fresh air ratio was varied. For high air ratios only a small part of the cathode outlet gas is recycled. In this case air preheating by heat exchange is dominant. The

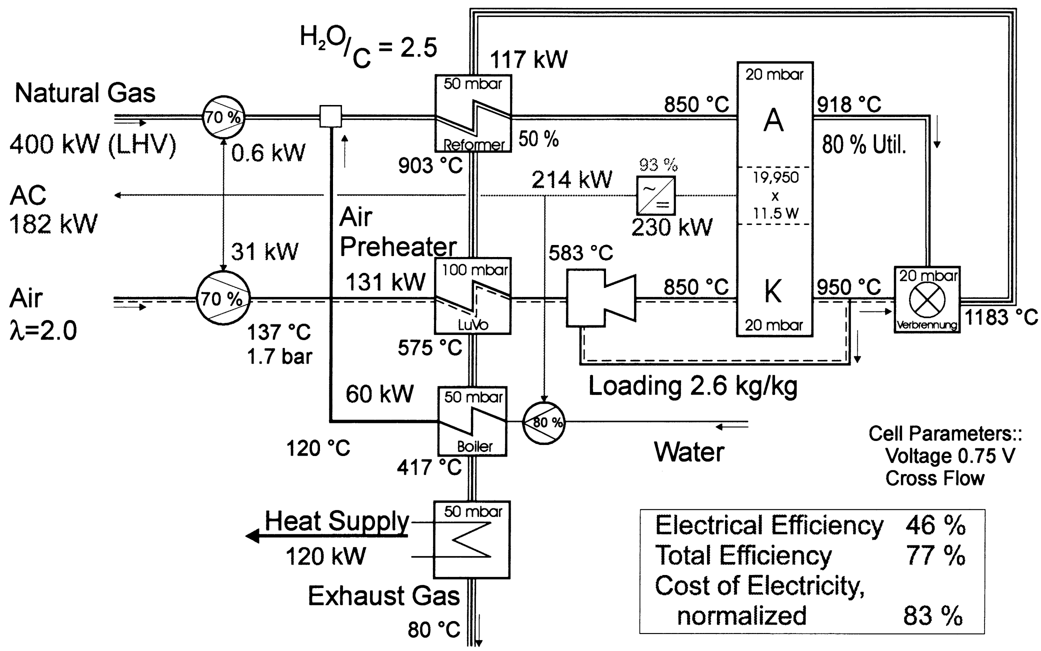

Fig. 4. SOFC plant concept with air preheating mainly by cathode gas recycling (jet pump).

plant efficiency is high, but the electricity production costs are still high caused by the expensive air preheater. The fresh air ratio can be reduced to 1.0, while the temperature increase of 100 K in the SOFC is maintained. The electrical plant efficiency is increased up to 50% at $\lambda = 1.0$. The COE are minimal at $\lambda = 1.5$. In the recycle loop the oxygen partial pressure decreases with lower air ratios. Low oxygen partial pressure results in lower current densities. In order to achieve 80% fuel utilization the stack must contain many cells. The investment costs increase extremely at high recycle ratios (low fresh air ratios). Therefore, from the economical point of view a fresh air ratio of 1.5 is best.

3.2.2. Cathode gas recycling by a compressor driven jet pump (injector)

For air preheating by recycling the hot cathode exhaust gas alternatively a jet pump (injector) can be used. Such a component has low investment costs [5]. The cold air stream is compressed to relatively high pressure and then drags along hot recycled depleted air by momentum exchange. A design program for gas injectors [6] was adjusted for typical SOFC anode and cathode gas loops. These injector calculations are applied to the SOFC power plant concept with cathode gas recycling. Fig. 4 shows the flowsheet design.

In Fig. 5 the influence of the fresh air ratio on efficiency and COE is shown. For an air ratio of 2.0 the electrical plant efficiency is maximal with a value of 47%. At lower air ratios two disadvantages become dominant. The injector loading increases, so that higher driving pressures are necessary in order to built up the pressure rise of 20 mbar in the loop. The electrical energy consumption for gas compressing lowers the overall electrical efficiency. Similar to the fan case the SOFC investment costs increase because of the lower oxygen partial pressure in the loop. The minimum COE (83% in comparison to the base case) are achieved with an air ratio of 1.7.

3.2.3. Influence of pressure drop in the cathode gas loop

In Fig. 5 the simulation results for a pressure drop of 50 mbar in the cathode recycle loop are also shown. In this case generally higher driving pressures for injector operation are necessary. Consequently the additional energy consumption of the plant is higher, which lowers the plant efficiency. Compared to the base case the reduction of the COE is only about half the cost reduction for the 20 mbar case. Therefore, a careful design of stack and manifolding should provide conditions for gas flow with low pressure drops.

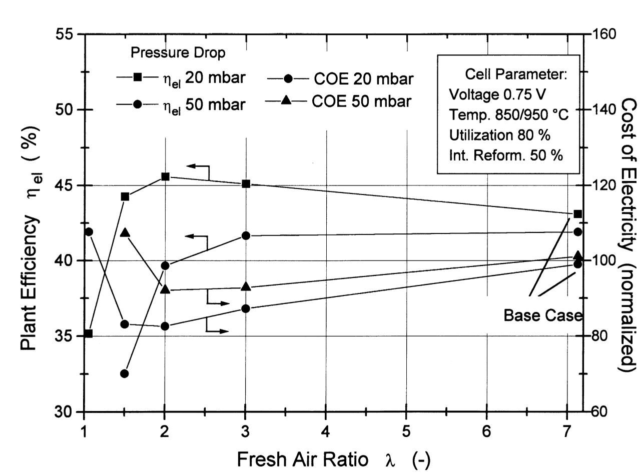

Fig. 5. Variation of fresh air stoichiometric ratio for cathode gas recycling with a jet pump (different pressure drops in the gas loop).

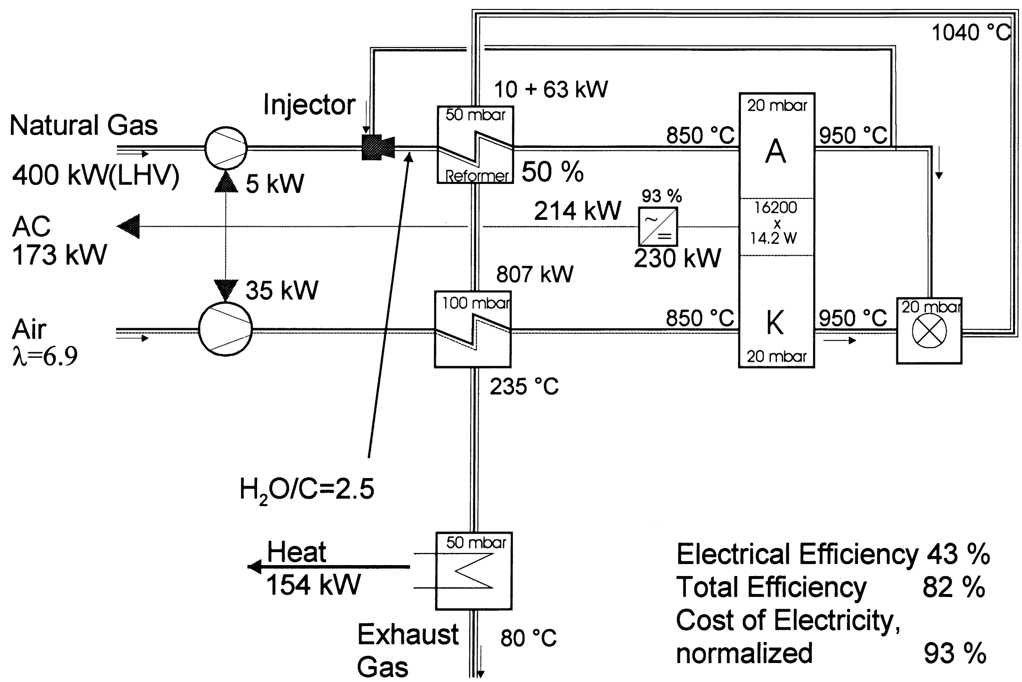

Fig. 6. Anode gas recycling with an injector (case 2a).

3.3. Anode gas recycling

Instead of external steam production in the base case (case 1a) H_2O produced in the electrochemical reaction of the fuel cell can be used, when a part of the hot anode outlet gas is recycled to the prereformer inlet. Gas recycling can be realized with blowers, hot gas fans or injectors (case 2a and b), which is illustrated in Fig. 6. Another possibility (case 3) is to recycle water after condensing the steam [7]. The main stack parameter values of the four cases discussed below are given in Table 3.

A certain steam/carbon ratio at the prereformer inlet is required to overcome the carbon formation limits. As in the base case a ratio of $H_2O/C = 2.5$ was chosen for case 2. This ratio defines the recycle ratio. It was assumed that the pressure drop is 70 mbar in the gas loop (50 mbar in prereformer, 20 mbar in stack). An analysis of the calculated results shows that many peripheral and stack operation parameters are influenced, when plant design is changed to anode gas recycling. The main advantages are:

1. no external steam production;
2. stack fuel utilization (one pass through the stack) is reduced from 80% to about 60% (the value of plant fuel utilization remains fixed at 80%), thus the cell area is lowered by about 25%;
3. the exhaust gas has a lower steam concentration, so that the unusable heat content (last cooling step between about 80°C and room temperature) is lower and consequently the total plant efficiency (including useful heat) is higher.

The disadvantage is that a higher compression energy for the natural gas driven injector operation is necessary. All these effects result in COE reductions of 7% for case 2a compared to the base case 1a (see Table 4).

The influence of anode gas (water) recycling on the heat balance and the total efficiency of the plant is illustrated in Figs. 7 and 8. In a plant concept with external steam generation (case 1a) the exhaust gas contains this excess steam in addition to the produced steam. Much heat is unused, since condensation takes place outside the plant below 80°C. Anode gas recycling (case 2a) provides an internal steam circuit. Therefore, the steam concentration in the

Table 3

Stack parameter values and air ratio for the four discussed cases with and without anode gas (water) recycling

Case	1a	2a	2b	3
	Base case		Anode gas recycling	Water recycling
Degree of internal reforming (%)	50	50	50	100
Air temperature increase (stack) (K)	100	200	200	200
Air ratio	7	7	3.6	1.5

Table 4
Plant optimization by anode or cathode gas recycling

	Air ratio	Heat exchanged in air preheater kW, normalized[a]	Electric plant efficiency (%)	Total efficiency (%)	Cost of electricity normalized
Pressure drop in stack = 20 mbar					
Basic plant concept	7.1	208	43	67	100
Anode gas recycling (pressure drop in prereformer = 50 mbar)	6.9	202	40	82	93
Cathode gas recycling					
With hot gas fans	1.5	19	49	78	90
With injector	1.7	33	46	76	83
Pressure drop in stack = 50 mbar					
Cathode gas recycling with injector	2.0		40	76	93

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

exhaust gas and the corresponding heat loss is reduced. Furthermore, the temperature increase in the afterburner is higher in case of lower steam contents in the fuel cell outlet gases, so that the ratio of the unused to the used temperature range of the exhaust gas becomes smaller (Fig. 7). Both effects result in a higher total plant efficiency of 81% instead of 67% in the base case.

Further reduction of unused heat is obtained, when the air ratio and consequently the amount of exhaust gas is reduced. In case 2b with an air ratio of 3.6 a total plant efficiency of 89% is calculated. In case 3 with complete internal reforming the air ratio is reduced to 1.5. This low amount of air leads to a very high temperature increase in the afterburner (Fig. 7), so that at least the portion of unused heat becomes very small. The total plant efficiency reaches 93%.

4. Heat supply at high temperature levels

Starting from the base case (case 1a), in which heat of the exhaust gas is utilized in a temperature range between 168 and 80°C, in cases 1b, 1c and 1d (Fig. 9) the heat is taken out between the different recuperative heat exchangers. In all cases the amount of useful heat is chosen to a fixed value of 94 kW (23.5 kW related to 100 kW LHV of the natural gas). The heat is taken out from the exhaust gas at the following positions within the heat exchange network:

1. case 1a: behind the boiler 168–80°C;
2. case 1b: behind the air preheater 224–136°C;
3. case 1c: behind the reformer 934–859°C;
4. case 1d: behind the afterburner 1028–953°C.

For the base case the driving temperature differences of the recuperative heat exchangers are about 120 K or higher (in the reformer) as listed in Table 5. For the cases 1b, 1c and 1d the result of the plant simulations is, that the driving temperature differences in all subsequent heat exchangers (downstream the heat exchanger for the useful heat supply) are reduced by about 80 K, so that about 40 K remain for the air preheater and the boiler. Consequently, the heat exchangers are enlarged by a factor of about 3 and, therefore, the investment costs are much higher than in the base case.

These plant simulations show that, in principle, useful heat can be supplied at temperature levels up to about 900°C (so that the heat contains much energy). On the other hand such plant concepts require larger heat exchangers (low energy loss inside the plant). This influence on the heat balance of SOFC plants results in higher investment costs, which have to be compensated by higher useful heat credits, if the COE should be unchanged.

5. Conclusions

For a combined heat and power plant with a 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

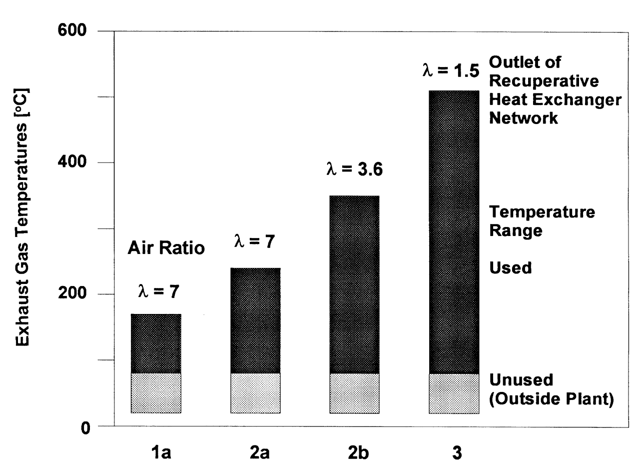

Fig. 7. Influence of anode gas (water) recycling and of subsequent reduction of the air ratio (case 2b and 3) on the temperature ranges of the exhaust gas available for heat production.

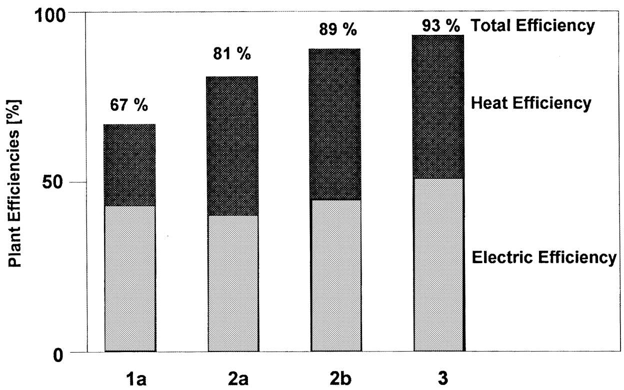

Fig. 8. Total plant efficiencies of the four discussed cases.

gas processing periphery, and by analysis of investment and operational costs a sensitivity study of flowsheet variants with respect to 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 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 the plant concept in relation to the simple flowsheet without gas recycling (base case) has strong influences. The flowsheet simulations with cathode gas recycling demonstrate that for pressure drops of 20 mbar in the SOFC stack the COE can be reduced by about 10%, when hot gas fans are used, and by about 20%, when an injector (jet pump) is used.

Anode gas recycling is also very advantageous, especially with respect to high total plant efficiencies. The COE are reduced by about 10%, when an injector is used.

Removal of useful heat at higher temperature levels diminishes the driving temperature differences and enlarges the heat exchange area of the recuperative heat exchangers located downstream. The increased investment costs have to be compensated by a 3.5 times higher heat credit (900°C), if the COE should be unchanged.

Especially for applications with high temperature heat supply plant concepts have to be developed with an as small as possible network of recuperative heat exchangers (low air ratio, anode gas recycling).

Including the results of part I it can be concluded, that research and development work should concentrate on the following issues:

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. gas flow inside the stack and in external loops with low pressure drop, so that gas recycling with jet pumps will be attractive (manifold and cell design);
4. reduction of internal resistances in the solid oxide fuel cell (electrochemistry, material development, stack design).

In general the advantages of SOFC cogeneration systems can clearly be seen.

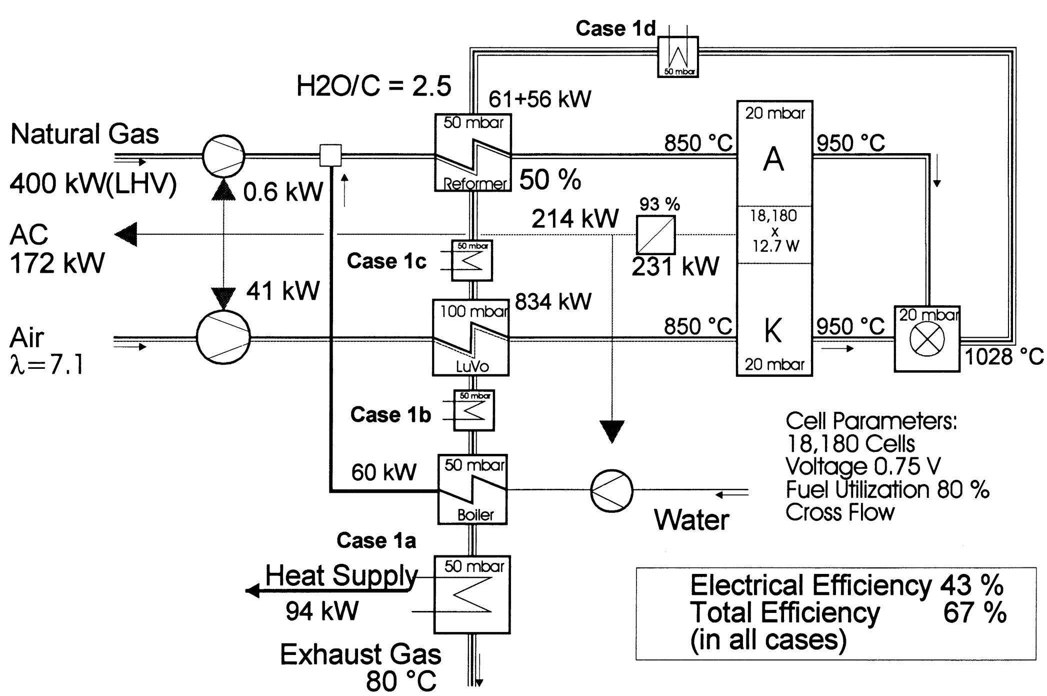

Fig. 9. Removal of useful heat at different temperature levels starting from the base case (94 kW in each case).

Table 5

Temperature differences, heat exchange areas and investment cost of the heat exchangers

Case	1a	1b	1c	1d
Temperature level heat supply (°C)	60	120	800	900
Mean log temperature difference ΔT (hot side–cold side) (K)				
Heat removal	–	–	–	79
Prereformer	268	268	268	189
Heat removal	–	–	79	–
Air preheater	117	117	38	38
Heat removal	–	79	–	–
Boiler	122	34	34	34
Heat removal	79	–	–	–
Sum heat exchange areas (m^2/kW_{el})	2.09	2.24	5.85	5.90
Sum investment cost ($\$/kW_{el}$)	690	870	1630	1660
Heat credit (base case and required for unchanged COE) (cent/kWh)	27	47	92	96

The broad flexibility in gas processing and plant design allows:

1. further reduction of COE;
2. adaptation to user requirements with respect to the quality and the quantity of heat;
3. flexible specification of the SOFC system to match special issues for different applications.

References

[1] L. Blomen and M. Mugerwa, *Fuel Cell Systems*, Plenum, New York 1993.

[2] P. Costamagna, E. Arato, E. Achenbach and U. Reus, *J. Power Sources, 52* (1994) 243.

[3] E. Riensche, U. Stimming and G. Unverzagt, *J. Power Sources, 71(1–2)* (1998) 306.

[4] Solid oxide fuel cell systems study, prepared by TNO, Apeldoorn, The Netherlands, *Comm. Europ. Commun.*, Rep. 88–315, July 1989.

[5] A system study for a 200 kWe combined heat and power package, prepared by British Gas plc, *ETSU Rep. FCR-008/010*, March 1994.

[6] H.P Schlag, Experimentelle und theoretische Untersuchungen zur Berechnung der Kennlinien von gasbetriebenen Einphaseninjektoren und Gutaufgabeinjektoren, *VDI-Fortschrittsberichte, Reihe 3, Nr. 313*, Düsseldorf, 1993 (in German).

[7] W. Drenckhahn and A. Lezuo, *Fuel Cells for Decentralized Cogeneration Plants*, Siemens AG, Erlangen, Germany, paper based on a lecture held at Power Gen Europe ’96, Budapest.