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Networked solid oxide fuel cell stacks combined with a gas turbine cycle

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Abstract

An improved design of fuel cells stacks arrangement has been suggested before for MCFC where reactant streams are ducted such that they are fed and recycled among multiple MCFC stacks in series. By networking fuel cell stacks, increased efficiency, improved thermal balance, and higher total reactant utilisation can be achieved. In this study, a combination of networked solid oxide fuel cell (SOFC) stacks and a gas turbine (GT) has been modelled and analysed. In such a combination, the stacks are operating in series with respect to the fuel flow. In previous studies, conducted on hybrid SOFC/GT cycles by the authors, it was shown that the major part of the output of such cycles can be addressed to the fuel cell. In those studies, a single SOFC with parallel gas flows to individual cells were assumed. It can be expected that if the performance of the fuel cell is enhanced by networking, the overall system performance will improve. In the first part of this paper, the benefit of the networked stacks is demonstrated for a stand alone stack while the second part analyses and discusses the impact networking of the stacks has on the SOFC/GT system performance and design. For stacks with both reactant streams in series, a significant increase of system efficiency was found (almost 5% points), which, however, can be explained mainly by an improved thermal management.

Keywords: Solid oxide fuel cell; Combined cycles; Multistage oxidation; Mathematical modelling

1. Introduction

Currently, solid oxide fuel cells (SOFCs) have been demonstrated converting 47% of the supplied fuel energy to electrical power [1]. The only power system in operation today (Siemens–Westinghouse, University of California, Irvine) based on the integration of a pressurised SOFC generator and a gas turbine (GT) achieves an efficiency (net AC/LHV) of 51% although not optimised [2]. The improvement is due to the enhanced performance of the SOFC generator at elevated pressure and to the recovery of SOFC exhaust heat by the GT. Even higher efficiencies have been predicted of pressurised SOFC/GT power systems [3,4,5] by optimising configuration and operational parameters. In this paper, such a configuration is suggested introducing the staged oxidation of fuel in the fuel cell component of the pressurised SOFC/GT cycle.

In a fuel cell, high fuel utilisation and high operating voltage are required in order to obtain high efficiency. However, voltage penalty is paid when operating at very high utilisation due to the fact that the Nernst potential decreases with increasing degree of fuel utilisation. Being dependent on the reactant composition, the Nernst potential, at the cell outlet, will put a limit on the cell operating voltage. This problem can be overcome by either operating the cell with a high recycle ratio of the fuel [6] or by an introduction of the staged oxidation (i.e. a fraction of the total fuel flow is first utilised in a part of the total cell area and then the oxidation is continued in the rest of the cell area). A necessary part of the first alternative is removal of reaction products (H_2O, CO_2) external to the cell requiring additional process equipment and power consumption. The networked fuel cells are a simpler and less costly approach for increase of the system efficiency [6]. The principle has been briefly investigated earlier for MCFC [6,7] and to some extent for SOFC [8].

The present system analysis examines the efficiency enhancement of a pressurised hybrid SOFC/GT power system where the SOFC stack is arranged in network. The process simulation software Aspen Plus® has been used for modelling of the systems. The analysis comprises stack networks with both reactant streams in series and with only the fuel stream in series. Any modelling work on staged fuel cells for hybrid systems have not been performed to any extent previously. However, it was indicated in [6] that a system comprising MCFC and steam bottoming cycle could achieve more than 5% points improvement of cycle efficiency with help of networking of the fuel cell stack.

In the following chapters, the benefit of the networked stacks is demonstrated for a stand alone stack along with

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analysis and discussion of the impact of the networking on the SOFC/GT system performance and design.

2. SOFC network analysis

The basic principle of a fuel cell network is staging of the fuel flow path. This is described as having the fuel pass a number of separate or segmented electrical circuits on its way through the fuel cell array [6]. Fig. 1b illustrates how the reactant streams in a fuel cell network flow in series from stack to stack.

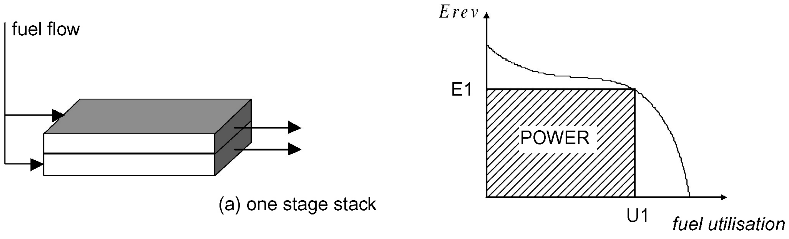
In this way, the partially utilised fuel exhaust stream from one stack becomes the inlet fuel for the next stack. In conventional configurations, the fuel feed is divided into equal streams which flow in parallel through the fuel cell stack (Fig. 1a). Further, in the figure, the maximum power that could be generated by two different SOFC systems having identical feed streams compositions is compared. Each system converts an equal amount of fuel into heat and electrical work and the total stack area is the same in both cases (the air flows either in parallel or as serial flow). For the networked stack, a part of the fuel flow is converted in the first stage at fuel utilisation U^*, while the fuel utilisation of the second stage is chosen such that the total utilisation of the stacks is the same as in the single stage stack. As the diagram indicates, it may be possible, in the networked stacks, to transfer charges at rather higher reversible voltages ($E2$, $E3$) and hence to convert more of free energy directly into electric energy and less into heat. The low voltage associated with high utilisation, which is typical for conventional single stacks, is restricted in the network to stacks which produce only a portion of total power (second stage in Fig. 1b).

A fuel cell model is used to investigate and compare single stage oxidation with two-stage oxidation. The model, based on the finite volume method, has been developed for simulation of a planar SOFC with internal reforming [9]. The model is extensively used in simulation of hybrid SOFC/GT cycles [5,10]. With the model the temperature and current density distribution, the species concentration and the channel flows are calculated. This requires the solution of mass balances of the chemical species and the energy balances of the gases in the gas channels and the solid structure for each volume element. This two-dimensional steady state model was validated against other models by comparing the simulated results obtained for a benchmark test. A standard bench mark test was defined for a flat plate cross flow design and the test input conditions have been set up according to IEA Annex II report [11]. The developed model showed a good agreement with the other model results [9].

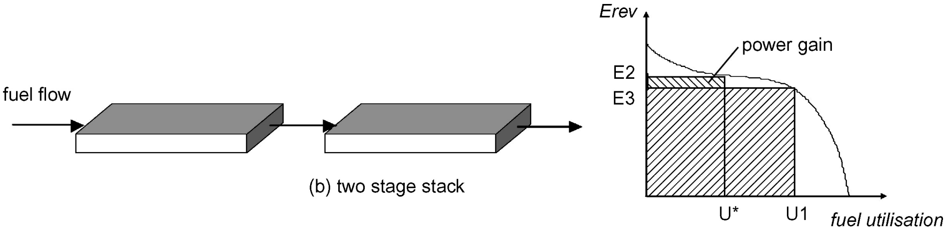
For the analysis, two stack arrangements are chosen, according to Fig. 1a and b, where the single stage stack consists of two cells each receiving the same amount of fuel and air. The fuel and the air flow in each single cell are arranged in cross flow. An advantage of the planar SOFC is that it allows isolation of the fuel and air exhaust streams enabling multistage oxidation. This is especially facilitated by single cell with the gases in cross flow. (However, practical realisation of this would require more leak tight manifolding.) First stack in the network configuration receives the total fuel flow of the single stage stack. The air flow (21% O_2, 79% N_2) has single pass through each of the networked stacks and it is maintained to keep the maximum solid temperature of 1050 °C. This temperature maximum is also defined for the one-stage stack. The other possible configuration of the air flow is in series, which will be investigated in connection to the hybrid system analysis.

Two inlet fuel flow compositions are studied, wet hydrogen (90% H_2, 10% H_2O) and 30% pre-reformed methane fuel. Main operational settings of the SOFC in this analysis are given in Table 1.

There is an increase of power output as a result of staging. The performance of the two different SOFC stack config-



(a) one stage stack



(b) two stage stack

Fig. 1. Schematic representation of fuel flow configurations for (a) one, and (b) two stages stack.

Table 1
Baseline conditions used in the SOFC network studies

Parameter	Value
Total fuel utilisation (%)	85
Pressure (bar)	1
Operating voltage, one-stage stack (V)	
Hydrogen cell	0.697
Methane cell	0.700
Inlet gas temperatures (°C)	900

urations, i.e. the staged one and the single stage stack, are compared in Table 2. The power increase in the table is defined as a ratio of the difference in the total power output of the stacks (ΔP) and the power output of the corresponding single stage cell (P). The cell fuelled with hydrogen has an increase of power output of 2.7%, while the benefit of the staging is lower in the cell fuelled with the methane mixture where an increase of power of only 0.57% is calculated.

The reason for the increase in the performance, in both cases, is that with staging the current density distribution becomes more uniform because the Nernst potential varies by a smaller amount within each stage. (The Nernst voltage variation given in the table refers to values at inlet and outlet of the cell.) More uniform current density lowers the Joule losses and polarisation losses. Further, the voltage gain in the fuel rich stages is greater than the voltage loss in the fuel poor stages resulting in higher mean operating voltage for the staged stacks, as it is shown in the table.

An increased fuel mass flow rate to achieve the net utilisation over multiple stages results in lowering the temperature gradients in the stack. This has a positive effect on the required air flow, which in the case of hydrogen fuel, decreases by 24% compared to the single stage stack. On the other hand, the effect in the cell with internal reforming is the opposite one. A combined cooling effect of the increased fuel mass flow and of the reforming reaction would decrease the solid temperature at the fuel inlet side to the extent when a heating of this part by increased air flow is necessary in order to avoid the cell quenching. In this way, the air flow is increased by 24% compared to the single stage stack.

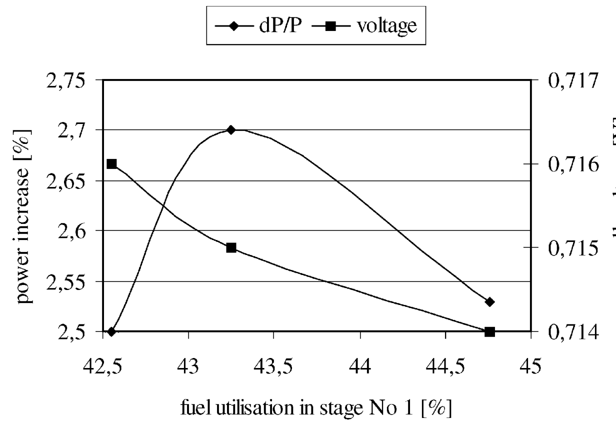


Fig. 2. Impact of degree of the fuel utilisation in the first stage on the total power increase and mean cell voltage for hydrogen fuelled cell.

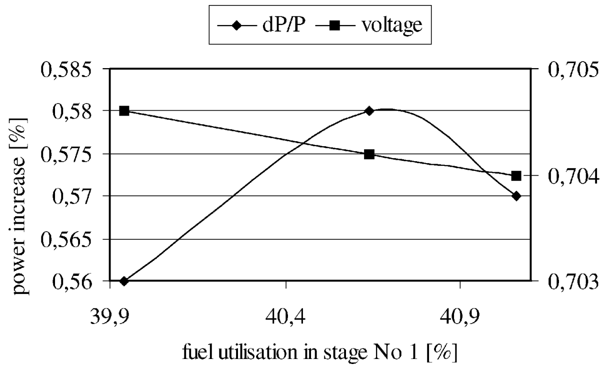


Fig. 3. Impact of degree of the fuel utilisation in the first stage on the total power increase and mean cell voltage for 30% pre-reformed fuel.

Figs. 2 and 3 show the results of the variation of the degree of the fuel utilisation in the first stage of the staged stack. The fuel utilisation in the second stage is allowed to vary in order to obtain the exit fuel utilisation of 85%. Again, the output power is compared, here, to the power of the single stage system at the same fuel utilisation. The figures clearly show that there is an optimum utilisation in the first stage giving the maximum increase of the power output. For the cell with hydrogen the optimum utilisation is 43% (Fig. 2)

Table 2
Effect of staging on SOFC performance

Parameter	Hydrogen cell	30% External reforming
Average operating voltage, one-stage stack, (V)	0.697	0.700
Average operating voltage, two stages stack, (V)	0.715	0.704
Nernst voltage variation, one-stage stack, (%)	8.28	4.9
Nernst voltage variation, 1st stage, (%)	6.03	0.276
Nernst voltage variation 2nd stage, (%)	7.5	7.55
Mean current density, (mA/cm^2)	319	250
Power increase $\Delta P/P$, (%)	2.7	0.58
Electrical efficiency, one-stage stack, [dc %LHV]	47	53
Electrical efficiency, two stages stack, [dc %LHV]	49	53.6

while for the cell with 30% reforming the power maximum is found at 41% fuel utilisation (Fig. 3).

The mean cell voltage represented in the figures is calculated as an average between the two stack stages. It decreases as the electrical load of the upstream stack is increased (i.e. increased fuel utilisation), since the stacks have to maintain a high driving force by a decrease of the operating voltage.

3. Networked SOFC/GT system analysis

3.1. System simulation model

The impact of networking or staging of stacks has to the authors' knowledge not been reported to any extent for a hybrid system. Here, a conceptual SOFC/GT system is suggested with an SOFC topping a recuperated GT cycle. The system features external pre-reforming of the incoming fuel (natural gas) together with steam generation of continuously supplied water, see Fig. 4. This lay-out is somewhat different than a system presented earlier [5] which used anode gas recirculation for the internal supply of water steam. The reference system below uses a single SOFC stack with parallel and uniform gas feed to each cell.

The fuel is first desulphurised before getting mixed with steam in a molar ratio of 2.5, which is high enough to avoid carbon deposition. In the pre-reformer, 30% of the incoming methane and all heavier hydrocarbons are converted. Air is compressed and pre-heated before reaching the cathode side of the fuel cell. Unspent fuel from the SOFC is combusted and hot gases are expanded in the GT. The exhaust is used for providing heat for the pre-reformer, for pre-heating the gas streams and for generating steam. The fuel gas waste heat is finally used in a district heating system. Two high temperature heat exchangers are placed close to the stack to bring SOFC inlet temperatures to 850 °C. An inverter converts the dc produced by the fuel cell to ac.

The SOFC model has been integrated into a process simulation tool, Aspen Plus®, as a user defined model whereas other components constituting the system are standard unit operation models. A system size of around 300 kWe was chosen as an adequate size applicable to the emerging distributed power market. The GT share of the output, around 100 kWe, corresponds to a typical microturbine size which has adequate operating data for these hybrid cycles (low pressure ratio and modest turbine inlet temperature (TIT)). In Table 3, main assumptions for the reference system are given.

A design case, not optimised, was evaluated at a pressure ratio of 4.0 and a TIT of 885 °C, corresponding to a turbine exhaust temperature of around 630 °C. No additional fuel was introduced in the GT combustor, as it would deteriorate the performance. A maximum solid temperature of the SOFC has been set to 1050 °C as in the above stack study. The fuel is Danish natural gas with a molar composition of 91.1% methane, 4.7% ethane, 1.7% propane, 1.4% butane, 0.5% carbon dioxide and 0.6% nitrogen. For a given fuel flow rate of 37.6 kg/h and a stack size of 15,000 cells, a cell voltage of 0.761 V and an air flow rate of 2622 kg/h were needed to meet both the TIT and the fuel cell hot spot requirements. The base case was also evaluated at different stack sizes and pressure ratios.

As was described above, there are two options for networking the stacks, both the air and fuel stream in series or only the fuel stream in series whereas the air stream is divided. Both options have been investigated with two stacks with a total stack area equal to the single stack of the reference system (15,000 cells). Also, fuel flow rate has been kept constant as well as component characteristics according

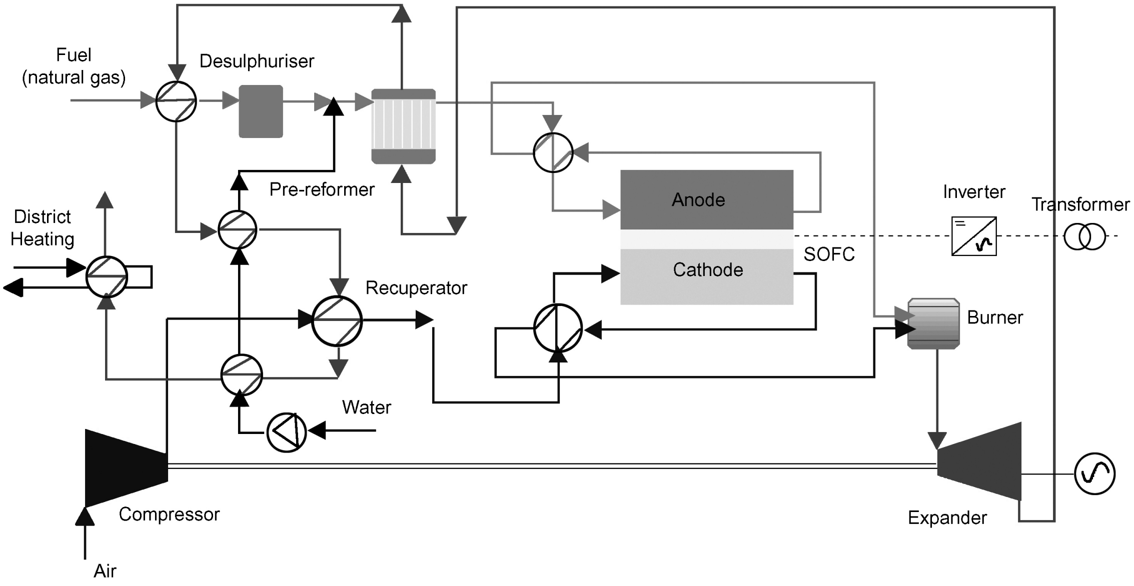


Fig. 4. Reference SOFC/GT system lay-out with a single stack.

Table 3
Design assumptions for the reference system

Assumption	Value
Ambient	ISO air
Fuel entrance temperature	15 °C
Fuel pressure available	30 bar
Heat loss to surrounding (combustor)	1%
Compressors isentropic efficiency	81%
Turbine isentropic efficiency	84%
Generator efficiency	98%
Burner efficiency	99%
Temperature approach in pre-reformer	15 °C
Heat exchangers pinch point	30 °C
Pressure drop in heat exchangers	2%
Pressure drop in combustor	5%
Pressure drop in recuperator (hot side)	4%
dc/ac Converter efficiency	95%
Turbo-machinery mechanical efficiency	99.5%
Desulfurisation temperature	400 °C
Fuel gas stack temperature	80 °C

to Table 2. Cell voltage of the two stacks and air flow rate are, however, adjusted according to above mentioned requirements (TIT and hot spot). For above reasons, the fuel utilisation of the two stacks can not always be identical to the fuel utilisation of the single stack in the reference system. Yielding different current densities, no electrical connection between the stacks can be assumed.

A networked SOFC/GT system with series connected fuel and air streams is shown in Fig. 5. Compared to the reference system the lay-out is similar, except the stack being divided into two subsequent smaller stacks. The outlet gases of the first stack are directly ducted to the second one without mixing or cooling of the streams. If temperatures of the gas streams are high, this could be a problem and some intermediate cooling between the stacks would be necessary. A way of varying the fuel utilisation between the stacks is distributing the total cell area (number of cells) between them. This study will show the impact of optimum cell distribution for the networked fuel cell system.

The second option, fuel stream in series and parallel air streams, is shown in Fig. 6. Here, an implication is dividing a hot air stream before the stacks (alternatively, the air split could be made after the recuperator). An even distribution is assumed so that each cell sees the same air flow rate. This means that an active flow controller would probably not be necessary. For the fuel stream passing between the stacks cooling due to high temperature could again be necessary, however, neglected here.

3.2. System simulation results and discussion

According to simulations, the reference (single stack) SOFC/GT system would achieve 60.5% electric efficiency (LHV) under given conditions. The power output is 305 kWe, of which the GT yield is around 34% or 106 kWe. The fuel utilisation of the stack is rather low (57.5%) due to large cooling demand of the cells leading to a requirement of more unspent fuel for the turbine combustor. This base case has not been optimised. By increasing the stack area or decreasing the pressure ratio larger efficiencies may be obtained. Calculations showed that by increasing the number of cells by 20% and by lowering the pressure ratio to 3.0, efficiency increased by 1.5 and 1.0% points, respectively.

When introducing networked SOFC in the system lay-out, considerable performance improvement was observed for the series connected arrangement (network A), whereas the network B, with only fuel stream in series, showed a

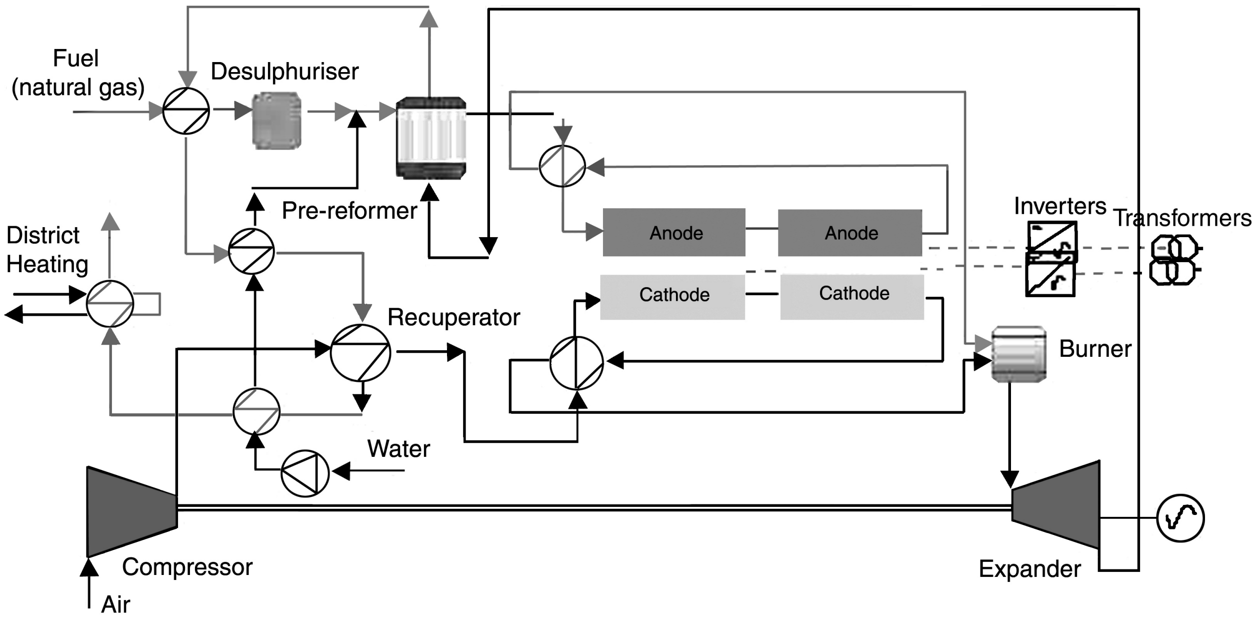


Fig. 5. Networked SOFC/GT system with both reactant streams in series.

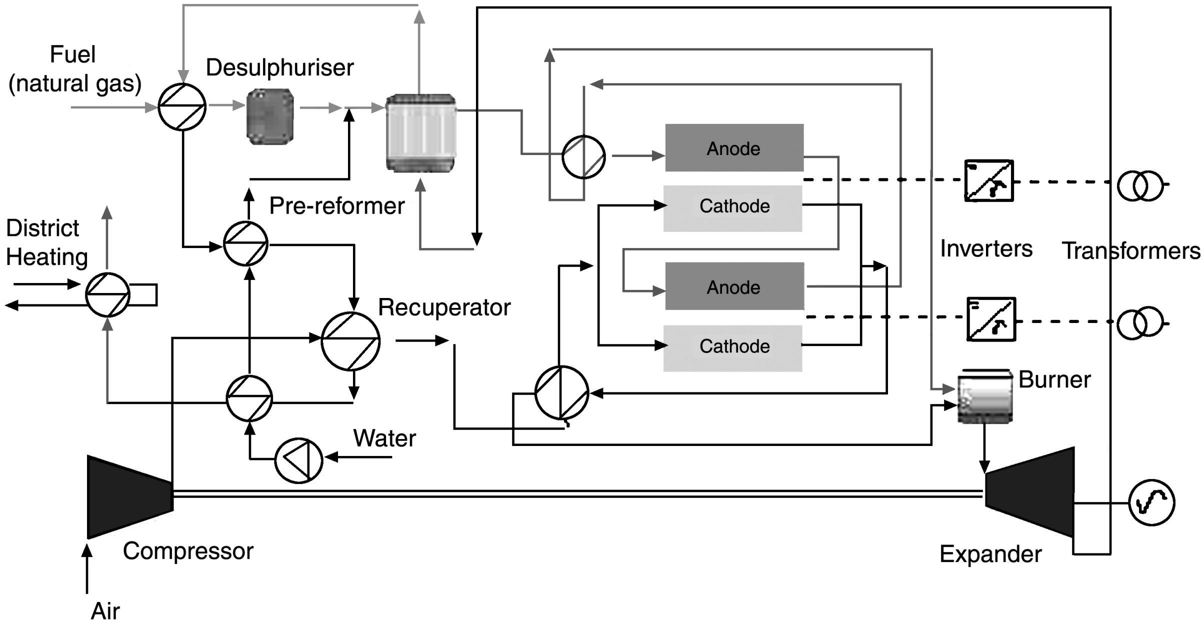


Fig. 6. Networked SOFC/GT system with only fuel stream in series and parallel air streams.

decrease of performance compared to the reference case, see Table 4. Both network configurations contained equal number of cells in each stack.

The large improvement of the performance for the SOFC/GT system of network A (4.7% points) can be explained with more effective cooling (i.e. more uniform temperature profile) as air flows through two subsequent smaller stacks compared to one large stack. This allows reduced cell voltages and still maintaining the hot spot temperature. Consequently, larger power output and larger fuel utilisation of the stacks are possible. Also air flow rate can be decreased which reduces compressor work and also reduces the GT power fraction of the output. For the network configuration B, the consequence of dividing air flow is negative (efficiency is reduced by 1.5% points). The reason is air flow per cell is reduced leading to a larger total air flow rate and higher cell voltages to avoid hot spots. Fuel utilisation of the stacks reduces which will hurt system performance as the increased GT output does not compensate the reduced power of the SOFC stacks.

Above behaviour can be explained with a better thermal balance between the stacks and GT leading to a higher total fuel utilisation for network A and the opposite behaviour for network B compared to the single stack reference system. To study the impact of varying the fuel utilisation between the stacks, as was done in the fuel cell section above, the cell distribution was changed keeping the total number of cells constant. Only network A is studied as it promises better performance. In Fig. 7, fuel utilisation of the first stack and total fuel utilisation are shown together with system efficiency. A flat maximum for the efficiency is found for 60% of the cells in the first stack (9000 cells). This corresponds to a fuel utilisation for the first stack of 52% of the total fuel utilisation.

In the range of around 40–87% of the cells in the first stack, the total fuel utilisation is about the same (72%), see Fig. 7. The efficiency behaviour within this range is due primarily to the air flow which has a minimum close to the maximum efficiency. However, also the staging effect, i.e. the average cell voltage of the cells increases as a consequence of staged stacks, can be recognised. This implies that maximum efficiency is found where air flow rate is low and average cell voltage is high. Compared to the case with equal

Table 4
Overall performance comparison for SOFC/GT system with and without networking

Simulation	Reference	Network A	Network B
Number of cells	15000	7500 + 7500	7500 + 7500
Power SOFCs (kWe)	201.1	238.2	192.9
Power GT (kWe)	106.5	92.4	107.0
System efficiency (%)	60.5	65.2	59.0
Air flow (kg/h)	2622	2201	2648
Mean cell voltage (V)	0.761	0.716	0.768
First stack fuel utilisation (%)	57.52	34.83	25.59
Total fuel utilisation SOFC (%)	57.52	72.35	54.51

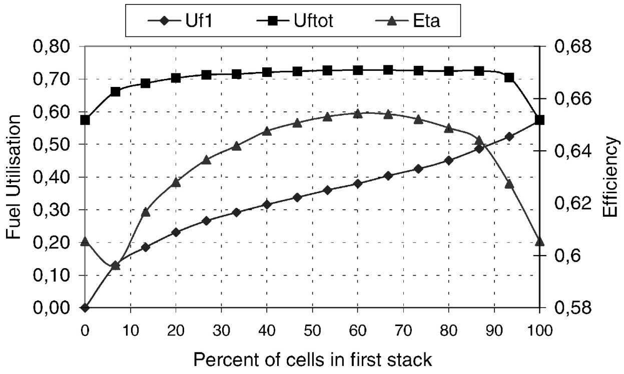


Fig. 7. Effect of cell distribution among stacks for network A (fuel utilisation of first stack, total fuel utilisation with system efficiency).

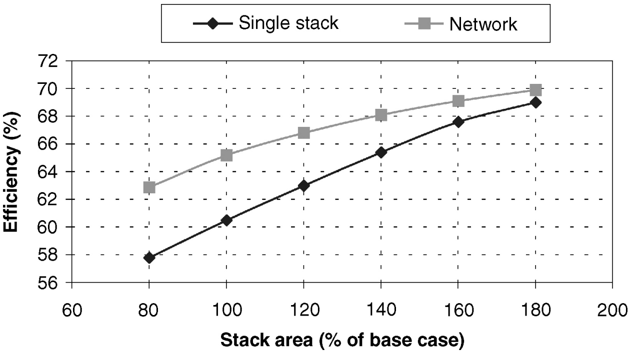


Fig. 8. Effect of stack area on efficiency for reference (single stack) system and network A configuration.

number of cells (50%) the maximum efficiency (found at 60%) is just 0.40% better.

The choice of base case determines the relative size of the fuel cell and GT. As it will be shown, it also can determine the relative improvement of variations of configurations such as the networking of stacks. By increasing the stack area, a more uniform temperature distribution is achieved within the fuel cell which will allow less air flow for cooling. Also, a higher average solid temperature of the fuel cell is possible which will increase power output and fuel utilisation of the stack. The reference system (single stack) and the SOFC/GT system with networked stacks (configuration A) were calculated with different stack sizes (80–180% of the base case), see Fig. 8. It is evident that both systems benefit from increased stack size but the relative difference between them diminishes as stack size increases. This can be explained by the networked stacks configuration improves stack cooling more efficiently in a situation with larger air flow (such as in a system with a smaller stack area).

4. Conclusions

- An SOFC configuration applying the multistage oxidation concept has been analysed. This configuration was shown to increase stack efficiency due to smaller variation in the Nernst voltage across the cell area. The increase was more manifested when hydrogen fuel is used.
- Due to decreased temperature variation in the multistage concept the air flow required to maintain the maximum solid temperature at desired level could be decreased in the case of the hydrogen cell. In the case of partially externally reformed fuel, the air flow was increased. Due to a combined cooling effect of the increased fuel flow and the endothermic reforming reaction, the heating of the fuel cell, fuelled with the methane mixture, by the increased air flow, was required.
- For a case of two-stage oxidation, there was an optimum in the fuel utilisation of the upstream stack giving the maximum of the power output.
- For the networked SOFC/GT systems analysed, it was found that both fuel and air streams fed in series will increase efficiency significantly. This is attributed predominantly to the effect of thermal management decreasing the required air flow and increasing the fuel utilisation of the stacks. For a system with only the fuel stream fed in series, the impact on performance was negative i.e. insufficient cell cooling results from air flow fed in parallel.
- A redistribution of the cells between the stacks for a networked system was found not to be worthwhile. Maximum efficiency was just slightly more than the case with equal amount of cells in the stacks.
- Networked stacks is a better choice for a system with relatively smaller stacks, thanks to the ability to reduce cooling demand of the cells.

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