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Combined solid oxide fuel cell and gas turbine systems for efficient power and heat generation

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Abstract

The Department of Heat and Power Engineering at Lund University in Sweden has been conducting theoretical studies of combined SOFC and gas turbine (SOFC/GT) cycles. The overall goal is an unbiased evaluation of performance prospects and operational behaviour of such systems. The project is part of a Swedish national program on high-temperature fuel cells. Results of continuous studies started earlier by authors are presented. Recent developments in modelling techniques has resulted in a more accurate fuel cell model giving an advantage over previous system studies based on simplified SOFC models. The fuel cell model has been improved by detailed representation of resistive cell losses, reaction kinetics for the reforming reaction and heat conduction through the solid part of the cell. This SOFC model has further been confirmed against the literature and integrated into simulation software, Aspen Plus™. Recent calculations have focused on a system with external pre-reforming and anode gas recirculation for the internal supply of steam. A reference system, sized at 500 kW, has also been analyzed in variants with gas turbine reheat and air compression intercooling. In addition, knowledge of stack and system behaviour has been gained from sensitivity studies. It is shown that the pressure ratio has a large impact on performance and that electrical efficiencies of more than 65% are possible at low pressure ratios.

Keywords: Solid oxide fuel cell; Gas turbine; Combined cycles; Modelling; High efficiency

1. Introduction

A solid oxide fuel cell combined with a gas turbine represents a power cycle suggested in many studies. Unreacted fuel from a topping fuel cell is combusted and the thermal energy is utilised by a bottoming heat engine. Synergy effects of such systems lead to very high electrical efficiencies. Another advantage is the low environmental impact due to high efficiencies and electrochemical oxidation of the fuel. Gas turbine output from a combined SOFC/GT system would typically be 1/3 of total output. Initial system sizes would probably be in the sub-MW to a few MW range, where advantage against competing technology is large. Also, there is a growing market for distributed power generation and for small to medium scale CHP plants. SOFC research around the world has come far but still needs to resolve problems like cost and life-time of stacks. Therefore, a market entry of SOFC/GT systems cannot be expected until a few years more. For evaluation of SOFC/GT systems, reliable computer models and tools are essential.

2. SOFC/GT cycle component modelling

2.1. Fuel cell model

A two dimensional steady-state stack model of a planar solid oxide fuel cell of cross-flow design has been developed. The stack model is based on earlier work by the authors [6] and now improved by detailed representation of resistive losses of the cell stack, introduction of reaction kinetics for reforming reaction and, most importantly, heat conduction through the solid part of the cell stack. Cell geometry was discretised by applying the finite volume method and by formulating constitutive laws for the solid parts and for the gas phase. In this way, behaviour of single cell plates at different operating conditions can be

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Table 1
Base case parameters

Input parameter	Value	Input parameter	Value
Geometry	Crossflow	Cell voltage	0.658 V
Cell dimensions	10×10 cm^2	Mean current density	3000 A/m^2
Anode thickness	50 E-6 m	Pressure	1 bar
Cathode thickness	50 E-6 m	Fuel feed	0.6421 mol/h
Electrolyte thickness	150 E-6 m	Air feed	10.445 mol/h
Interconnect thickness	50 E-6 m	Air composition O_2, N_2	21%, 79%
Number of fuel channels	18	Fuel composition	30% reformed CH_4
Number of air channels	18	Excess air	7
Temperature of fuel feed	875°C	Fuel utilisation	85%
Temperature of air feed	875°C		

obtained, that is, gas utilisation, power density, efficiency and also current and temperature profiles. The SOFC model is based upon the following assumptions:

1. Two dimensional model with axial coordinates (x,y) of the cell.
2. Cell dimensions and material characteristics as in Ref. [4].
3. Uniform distribution of feed gases among various channels and cells of the stack.
4. Cell losses caused essentially by electrical resistance to current through cell components and activation polarisation phenomena.
5. Current collectors considered as equipotential plates.
6. Uniform cell voltage.
7. No heat transfer by radiation between gases and solid.
8. All exterior walls adiabatic.
9. In direction of gas flow, only convective heat transport assumed.
10. Pressure drops along the channels neglected.

The model considers mass balances with flow rate variations due to chemical reactions: oxidation of hydrogen (overall cell reaction), reforming of methane and water–gas shift reaction of carbon monoxide. The rate of the reforming reaction is modelled with an expression from the work of Achenbach [4]. According to Faraday's law, the amount of hydrogen and oxygen consumed is related to the local electric current produced in the cell. The shift reaction is always assumed to be at equilibrium. The internal electrical resistance and activation polarisation have been determined according to a procedure proposed by Karoliussen [1]. The reversible potential is calculated on the basis of Nernst's equation applied to the oxidation of hydrogen.

In the energy balance equation, three temperatures are unknown for each volume element. These are the temperature of the solid part (electrolyte + electrodes + interconnect), T_s, and the temperature of the fuel gas out and air out of each volume element, T_f and T_a. The temperature gradient in the flow direction is assumed to

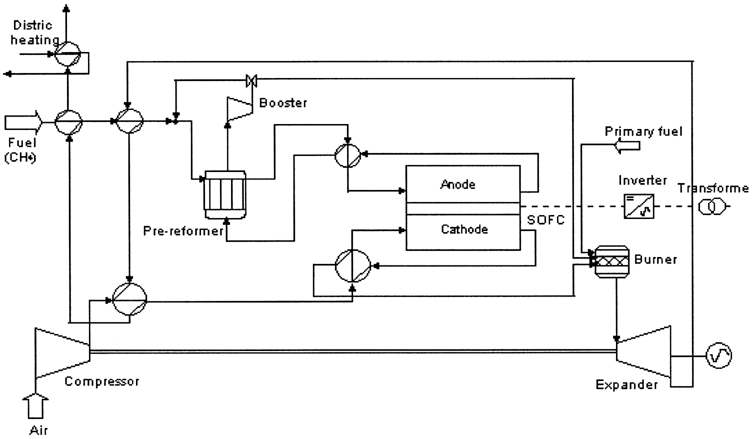

Fig. 1. Reference system configuration.

Table 2
Assumptions for the reference system

Assumption	Value	Assumption	Value
Air temperature and pressure	ISO air (15°C, 1.013 bar)	Pressure drop in burners	5%
Air to system	4820 kg/h	Pressure drop in recuperator	4%
Fuel temperature	15°C	Pressure drop in SOFC (anode/cathode)	10 mbar
Fuel pressure	30 bar	Pinch point for recuperator and reformer	30°C
Fuel to system (CH4)	58 kg/h	Turbine and Reheat temperatures	883°C
Heat loss to surrounding	0%	Temperature after intercooling	40°C
Compressors polytropic efficiency	84%	Final gas leaving temperature	80°C
Turbine polytropic efficiency	82%	Number of cells in the cell stack	16 000
Generator efficiency	98%	Cell voltage	0.695 V
Burner efficiency	100%	DC/AC converter efficiency	95%
Pressure drop in heat exchangers and intercooler	2%	Turb/compr. mech. Efficiency	99.5%
		Maximum solid temperature of SOFC	1100°C

depend only on convectional heat transfer from the channel walls to the bulk of the gases. The energy balance for the fuel and air channel for each control volume is given by:

$$\sum_i \frac{\mathrm{d}(n_i \times \mathrm{cp}_i \times T_\mathrm{f})}{\mathrm{d}x} - A_\mathrm{f} \times \alpha_\mathrm{f} \times (T_\mathrm{s} - T_\mathrm{f}) = 0 \qquad (1)$$

$$\sum_i \frac{\mathrm{d}(n_i \times \mathrm{cp}_i \times T_\mathrm{a})}{\mathrm{d}y} - A_\mathrm{a} \times \alpha_\mathrm{a} \times (T_\mathrm{s} - T_\mathrm{a}) = 0 \qquad (2)$$

where cp_i is the specific heat capacity of the fuel and air and n_i denotes the molar flows of the gases. Subscripts f and a refer to the fuel and air channel, respectively. Calculation of heat transfer coefficients α_f and α_a is based on a constant Nusselt number of 4.0 [5], determined from laminar flow conditions. The area over which convective heat transfer takes place, A_a and A_f, is assumed to be the whole hydraulic diameter of the channels [3]. The energy balance of the solid part describes steady heat conduction in a quasi-homogeneous structure. For the solid part of the cell, the energy balance equation is given by:

$$k_i \times \frac{\partial^2 T_\mathrm{s}}{\partial x^2} + k_j \times \frac{\partial^2 T_\mathrm{s}}{\partial y^2} + A_\mathrm{f} \times \alpha_\mathrm{f} \times (T_\mathrm{s} - T_\mathrm{f}) + A_\mathrm{a} \times \alpha_\mathrm{a} \times (T_\mathrm{s} - T_\mathrm{a}) = Q + W \qquad (3)$$

The convective heat, reaction enthalpies, Joule heat from ohmic resistance as well as electrical work produced by the cell occur as source terms $(Q + W)$. The effective thermal conductivities of the solid structure k_i and k_j are calculated by a procedure given in Ref. [2].

For sensitivity analysis of a stand-alone SOFC, a base case, unoptimised, was selected (Table 1), and then one parameter at a time was varied.

Important cell operational parameters are the fuel utilisation factor U_f and electrical efficiency η of the cell, defined as;

$$U_\mathrm{f} = \frac{n_\mathrm{f}^\mathrm{in} - n_\mathrm{f}^\mathrm{out}}{n_\mathrm{f}^\mathrm{in}} \qquad (4)$$

$$n_\mathrm{f} = 2 \times n_{\mathrm{H}_2} + 2 \times n_\mathrm{CO} + 8 \times n_{\mathrm{CH}_4} \qquad (5)$$

$$\eta = \frac{P_\mathrm{el}}{\mathrm{LHV}} \qquad (6)$$

In the formulae, n denotes molar flow rate, subscript ''in'' is for inlet and ''out'' is for outlet. P_el is the electrical effect delivered by the cell and LHV is the lower heating value of the fuel mixture at the cell inlet. Selected parametric studies are presented in the following section.

2.2. System simulation model

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 modelled as standard unit operation models. A reference SOFC/GT system was developed according to Fig. 1. In

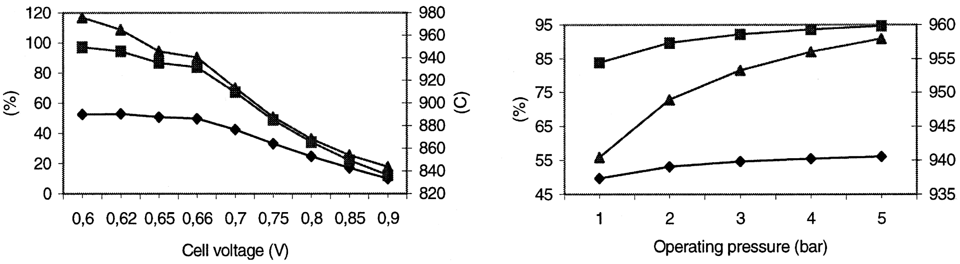

Fig. 2. Influence of operating cell voltage and operating pressure on stack performance and mean solid temperature.

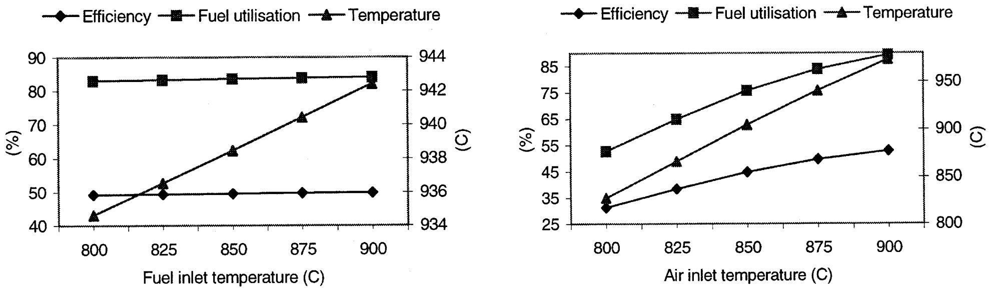

Fig. 3. Influence of fuel and air feed temperature on stack performance and mean solid temperature.

this system, effluent from the anode is partially recycled in order to provide steam and heat for external reforming of the fuel; the remains is burned in the gas turbine combustor together with cathode off-gas. The concept of anode gas recirculation has been proposed elsewhere [7] and has the advantage of providing an internal steam supply. The feedback ratio of the recirculation loop is controlled by a valve to meet an S/C ratio of 2.5. The degree of external pre-reforming is set to 30% which determines the reformer temperature and amount of heat required. For this reason, fuel inlet temperature and flow to the SOFC cannot be chosen independently, but are determined from the reformer requirements. The hot gases are expanded in a gas turbine and the exhaust is utilized for pre-heating the fuel and compressor discharge as well as to supply heat to a district heating system. Additional primary fuel is used for increasing the turbine inlet temperature (TIT). Two high temperature heat exchangers are placed close to the stack to bring inlet temperatures to 900°C.

A system size of around 500 kW was chosen as an adequate size for demonstrations and for market entry units. This would translate into assumptions given in Table 2. Sensitivity studies have been performed to understand the impact of the pressure ratio, turbine inlet temperature and cell voltage. Variants of the reference SOFC/GT system have been analysed with respect to two gas turbine design features, that is, intercooled air compression and gas turbine reheat.

A system base case, unoptimised, was evaluated for a pressure ratio of 4 and a turbine inlet temperature of 883°C, corresponding to an exhaust temperature of 630°C. Additional primary fuel, corresponding to 30% of the total fuel to the system, was needed to boost the TIT. In the sensitivity studies fuel flow to the system was kept constant; exceptions were in the reheat case with an increased fuel flow, and, at low pressure ratios, with a reduced flow. All calculations are design point calculations, however, with SOFC geometry and stack size fixed.

3. Results and discussion

3.1. Parametric study of the SOFC

Comparison of the fuel cell model with similar models found in literature shows good agreement. Results have been compared to those obtained from an earlier developed SOFC model. Output parameters such as cell efficiency, fuel utilisation, cell effect and mean outlet temperatures of the gases differed by about 3%. In addition, extreme values of solid temperature and current density were clearly overestimated by the earlier model. Improved accuracy of the present model results in better control over operational parameters.

The influence of cell voltage and operating pressure on fuel cell performance and mean solid temperature is shown in Fig. 2. When decreasing the operating voltage, the difference between the reversible cell voltage and operating voltage becomes larger resulting in higher current densities. The solid temperature increases in proportion to the current density at lower cell voltages. The efficiency reaches a maximum for a particular combination of cell voltages and fuel utilisations and then decreases at higher cell voltages.

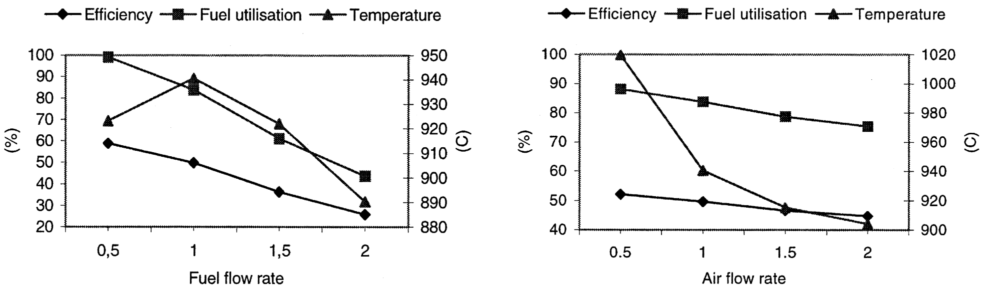

Fig. 4. Influence of fuel flow rate and air flow rate on stack performance and mean solid temperature.

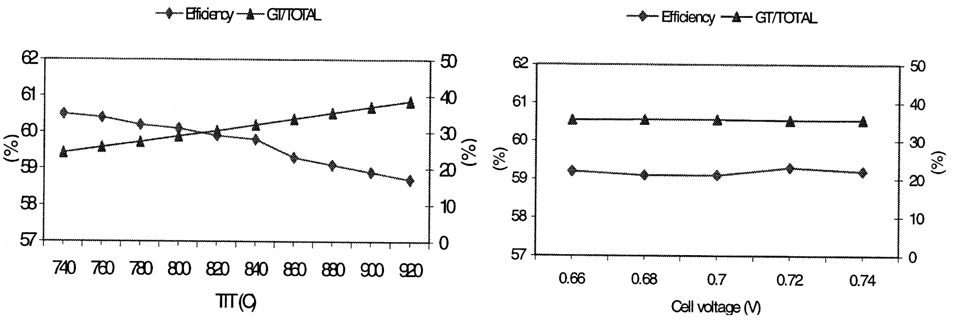

Fig. 5. Influence of turbine inlet temperature and operating voltage on system performance and mean solid temperature of the SOFC.

3.1.1. Cell voltage and operating pressure

A pressure increase causes partial pressure changes of reacting substances leading to an increase of reversible cell voltage. This influences the cell performance favourably because the difference between reversible voltage and operating voltage increases yielding higher current densities. Enhancement of this parameter is restricted by the operating temperature range of the cell.

3.1.2. Air and fuel inlet temperature

The effect of air and fuel inlet temperature on cell performance is shown in Fig. 3. Here, the feed temperature of air is held constant and the fuel temperature is varied. The same procedure is repeated with the air feed temperature while holding the fuel temperature constant. In this way, the impact of both parameters can be studied separately. There is a minor influence only on cell performance when the fuel feed temperature is varied due to the low convective heat transfer between the solid and the fuel gas. Air feed temperature has a larger effect on cell performance owing to a relatively larger flow and, consequently, convective heat transfer. The increase of solid temperature is considerable when increasing the air inlet temperature. Keeping the solid temperature within a reasonable constraint puts a limitation on the feed temperature. For optimising the feed temperatures the following parameters should be taken into consideration: solid temperature, fuel utilisation, as well as energy required for preheating the feed gases.

3.1.3. Air and fuel flow rates

Keeping the air flow constant, the fuel flow rate is varied from one half to double the flow (Fig. 4). The mean temperature of the solid decreases when halving the fuel flow due to a decreasing amount of fuel oxidised. This lowers the cell current since ohmic resistance increases with reduced temperature.

When doubling the fuel flow, a higher amount of fuel can be oxidised but the convective cooling effect is larger resulting in a decreasing solid temperature. The highest electrical efficiency is not obtained at the highest cell current since electrical efficiency is directly proportional to fuel utilisation. Highest fuel utilisation occurs at a lower fuel flow when sufficient cell area is available. At higher fuel flow, fuel utilisation consequently decreases. The impact of reducing air flow is similar to reducing fuel flow on efficiency, and on fuel utilisation. Cooling of the cell is pronounced by the large amount of air decreasing the cell temperature and, consequently, decreasing the current density.

3.2. Parametric study of the SOFC / GT system

The reference system base case described above yields an electrical efficiency of nearly 60%, a total efficiency of 86% and specific work around 350 kW/kg/s air. Output from the SOFC and gas turbine generator were 311 kW and 173 kW, respectively, corresponding to 36% gas turbine of total output. Average and maximum solid tempera-

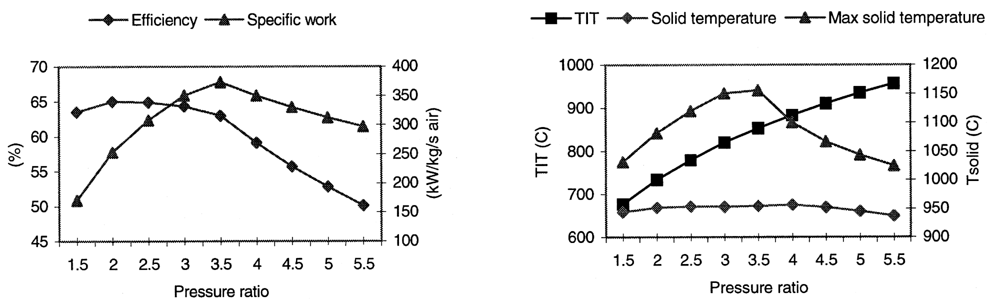

Fig. 6. Influence of pressure ratio on system performance, mean and maximum solid temperature of the SOFC and turbine inlet temperature.

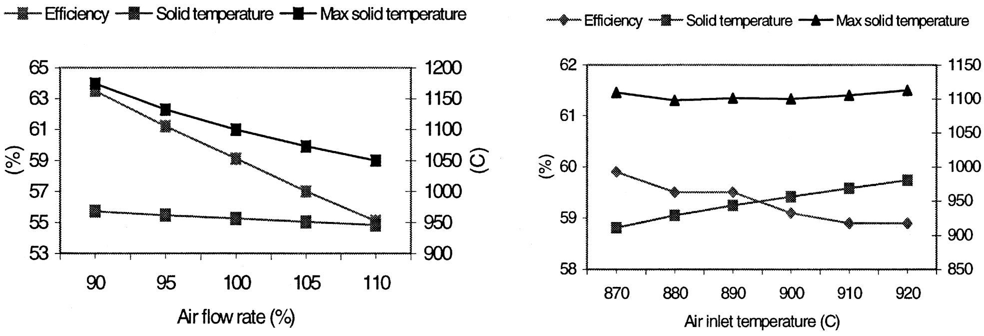

Fig. 7. Influence of air flow and air inlet temperature on system performance, mean and maximum solid temperature of the SOFC.

tures of the fuel cell was 956°C and 1100°C, fuel utilisation 0.77, outlet fuel and air temperatures 1000°C and current density 3100 A/m^2.

3.2.1. Turbine inlet temperature and cell voltage

The influence of turbine inlet temperature and cell voltage on system performance is shown in Fig. 5. Increasing the TIT does not lead to an improvement of efficiency and specific work. At higher inlet temperatures more fuel is being consumed in the gas turbine, decreasing the fuel flow to the SOFC unit. At 728°C, no primary fuel is added and the gas turbine output is 24% of net output. As illustrated, a small portion of the gas turbine work to net output is better for overall performance.

The cell voltage shows virtually no impact on system performance. A voltage range between 0.66 and 0.74 V was studied, corresponding to a fuel utilisation between 0.94 and 0.40. The reason performance does not change is the same as described above, that is, the portion of gas turbine to total output is constant (36%). At high cell voltages relatively more fuel can be directed to the SOFC unit and less to the gas turbine, thus compensating for the low fuel utilisation. The solid temperature follows the fuel utilisation trend, decreasing with increasing voltage.

3.2.2. Compressor pressure

The most interesting parameter is compressor pressure, due to its large impact on system performance (Fig. 6). At lower pressure ratios, primary fuel in the gas turbine must be reduced to meet a constant exhaust temperature, and more fuel can be sent to the SOFC. This means less output from the gas turbine and more from the SOFC increasing efficiency with decreasing pressure. At a pressure ratio of 3.5 and below, fuel to the system must be reduced for the same reason and the specific work reaches an optimum. At a pressure ratio of 2 and below, the gas turbine output is close to zero and the system is working as a stand alone SOFC. A maximum efficiency of 65% was found at this pressure ratio. At higher pressures, the TIT increases to maintain the exhaust gas temperature and the gas turbine net output increases. The maximum solid temperature follows the specific work trend, decreasing below and above a pressure ratio of 3.5. Only at pressure ratios below 2, and above 4 is the solid temperature constraint of 1100°C met.

3.2.3. Air flow rate and air inlet temperature

Increasing the air flow can be necessary for reducing the solid temperature; however, performance deteriorates as shown in Fig. 7. When reducing the maximum solid temperature from 1100°C to 1050°C, 110% air flow is needed causing an efficiency drop by four percentage points. Increasing the air inlet temperature raises the solid temperature of the SOFC. In spite of this efficiency slightly decreases with air inlet temperature, owing to a higher fuel utilisation when returning less hydrogen in the anode gas feedback loop; this decreases the Nernst cell potential and, therefore the current density.

3.2.4. Cycle variants

Air compression intercooling improves electrical efficiency by 1.5 percentage points but decreases the total efficiency nearly ten percentage points over the base case. Reheat of the gas turbine decreases efficiency slightly and increases exhaust temperature rapidly. Both variants boost the specific work by more than two percentage points each and nearly five percentage points jointly.

4. Conclusions

A two-dimensional, steady-state SOFC model has been developed and confirmed against the literature. A recent model has been integrated into the Aspen Plus™ simulation tool for SOFC/GT system analysis. The accuracy and applicability of this tool shows an advantage over many system studies based on a simplified SOFC model or performance curves. A system featuring external pre-reforming and recirculation of anode gases was proposed. A maximum efficiency of 65% was found at a pressure ratio of 2, whereas the specific work had a little higher optimum value. The TIT and cell voltage did not show a big impact on system performance. Intercooling of air compression and gas turbine reheat would not be worthwhile as the gain in performance is relatively small, especially for the reheat case.

A parametric study of a stand-alone SOFC was also performed showing operating parameters having a noticeable influence on electrical efficiency and fuel utilisation of the cell. These parameters were cell voltage, air inlet temperature and flow rates of fuel and air. The efficiency increased when cell voltage and flow rates of fuel and air decreased and when air inlet temperature increased. The fuel utilisation of the cell was raised by decreasing the operating voltage, decreasing the fuel flow rate and by increasing the air inlet temperature.

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