

# Thermal start-up behaviour and thermal management of SOFC's

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## Abstract

Solid oxide fuel cells (SOFCs) have many attractive features for widespread applications. The high operating temperature provides a valuable heat source and in contrast to low temperature fuel cells they not only tolerate substances such as CO but can even use them as fuel. Thus, reforming of hydrocarbon fuels for SOFCs can be done without additional gas purification. As both stack and hydrocarbon reformer unit have to be operated at high temperatures (700–1000 °C), thermal management plays an important role in the successful operation of SOFC systems. As the SOFC system contains ceramic components, both large thermal gradients in the system and thermal expansion coefficient (TEC) mismatch must be avoided.

Matching TECs is done by selecting the suitable materials. Avoiding high temperature gradients is done by selecting the right system design and control strategies. In order to achieve both, we have built a finite element simulation for a complete SOFC systems which allows to study system parameters both during steady operation and during transients. Examples of the thermal start-up behaviour for several system configurations are given for selected components as well as internal temperatures of the SOFC-stack during start-up. The simulation model includes also the option to simulate the effects of internal methane reformation in the SOFC stack.

As the minimum operation temperature is high, cooling down of the system has to be avoided if instant operation is desired. This can be achieved either passively by selecting suitable thermal insulation materials and/or actively by adopting a strategy for maintaining the temperature.

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## 1. Introduction

Solid oxide fuel cells (SOFCs) are one of the important fuel cell technologies. The operating temperature of 800–1000 °C of the conventional SOFC technology puts high demands both on materials, cell and system designs and on the strategies of thermal management. In the following chapter, we report on various cell designs which have been established with special emphasis placed on their thermal behaviour. The next chapter describes thermal aspects of SOFC stacks embedded in a whole system with additional components like reformer, heat exchanger and catalytic burner. Chapter 4 is addressed to the thermal properties of the used materials, while the last chapter gives a comparison of several strategies for the thermal management of a SOFC systems.

## 2. SOFC configurations and performances

Due to the rigid structure (ceramics) the cells can be shaped into arbitrary structures, each with corresponding advantages, disadvantages and demands on the rest of the system. In the moment SOFC designs concentrate on three shapes: planar, tubular and undulated cells.

Today most companies develop planar cells. Planar SOFC's are further differentiated by the mechanically supporting element: anode supported cells (with the anode being the support), electrolyte supported cells (with the electrolyte supporting the electrodes) or interconnector supported cells. The differences are illustrated in Fig. 1.

In anode supported cells (ASC) the electrolyte layer is typically around 10–40 μm. The internal resistance of the electrolyte allows operating temperatures below 800 °C with standard YSZ as electrolyte material. The supporting anode is a 300–800 μm thick, porous cermet made of Ni-YSZ. The cathode of perovskite oxides is screen-printed on top of the electrolyte.

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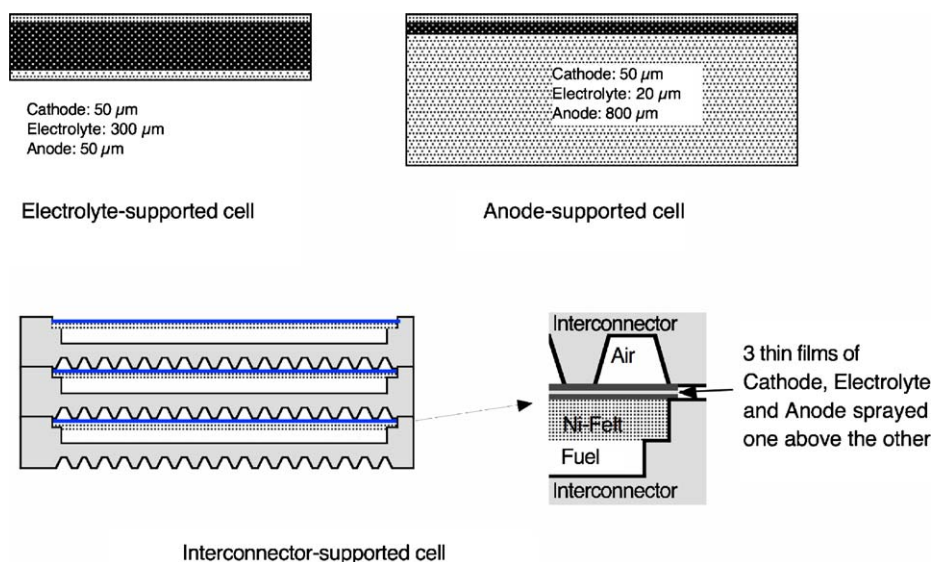


Fig. 1. Comparison of planar fuel cells. Upper row: left electrolyte supported cell, right anode supported cell. Bottom row: interconnector supported cell.

Table 1  
Summary of performances of SOFC stacks of various manufacturers

Company	Cell type	Mechanical carrier	Power density (W cm <sup>-1</sup> )	At fu <sup>a</sup> (%)	Temperature (°C)	Stoic <sup>b</sup>	Fuel	Reference
DLR	Coated <sup>c</sup>	Interconnector	0.2 <sup>b</sup>	10	800	4	H <sub>2</sub> + N <sub>2</sub>	[6]
Risø	Planar	Anode	0.8 <sup>b</sup>	25	750	2	H <sub>2</sub>	[7]
Global TE	Planar	Anode	0.5 <sup>b</sup>	80	750	–	H <sub>2</sub> + N <sub>2</sub>	[8]
CFCL	Planar	Electrolyte	0.06 <sup>b</sup>	–	850	–	Natural gas + steam	[9]
Chubu–Mitsubishi	MOLB <sup>d</sup>	Ceramic interconnectoras carrier	0.25 <sup>b</sup>	77	–	3	H <sub>2</sub>	[10]
Siemens–Westinghouse <sup>e</sup>	Tubular	Cathode	0.25 <sup>b</sup>	85	1000	2	Reformed natural gas	[11]
AIST	Single chamber <sup>f</sup>	Electrolyte	0.48 <sup>b</sup>	–	500	1	CH <sub>4</sub>	[12]

<sup>a</sup> The percentage of available fuel used in the cell.

<sup>b</sup> Fuel cells are run with surplus air, stoic resembles  $\lambda$  in ICE's.

<sup>c</sup> The interconnector is coated with the active layers by plasma-spraying.

<sup>d</sup> Mono-block layer-build (see Fig. 4).

<sup>e</sup> 100 kW system in Arnhem, NL.

<sup>f</sup> Anode and cathode in the same compartment.

The main advantage of the cell is the high power output at relative low temperatures due to the thin electrolyte and a further lowering of the temperature is possible by reducing the thickness of the electrolyte. The main disadvantage is the high amount of raw material needed for the cell. The cell can reach performances of more than 1 W cm<sup>-2</sup> at temperatures below 800 °C. Interconnector materials can be stainless steels.

The electrolyte supported cells (ESC) are thinner than the ASC's: the dense sintered electrolyte is much more stable than the porous anodes so the thickness of the mechanically supporting structure may be reduced down to 150 μm. However, the resistance of a 150 μm layer of YSZ is too high for reasonable power densities at temperatures below 900 °C. An advantage of the higher temperatures of the ESC's is the increased sulphur tolerance of the cell. The higher working temperature reduces the variety of interconnector materials to ceramics or coated high temperature alloys.

'Interconnector supported cells' (ISC)<sup>1</sup>: In this concept the active materials (anode, electrolyte and cathode) are plasma-sprayed onto a fine mesh within the interconnector which provides the supporting structure. The ISC concept theoretically does not need seals between anode and cathode head space (the electrolyte provides the seal) and might be advantageous in terms of volumetric power density. Right now it is still a R&D type cell. The expectation is that the assembly of thin ceramic layers can survive fast heating and cooling cycles which are an requirement in some remote and automotive applications. Power densities are comparable to those of ASC's (see Table 1) while the material costs for the functional layers are minimized.

The main drawback of all the aforementioned designs is the need for a high-temperature seal which has to resist the

<sup>1</sup> Please note this is not an officially recognized term by now and is used in absence of a better designation.

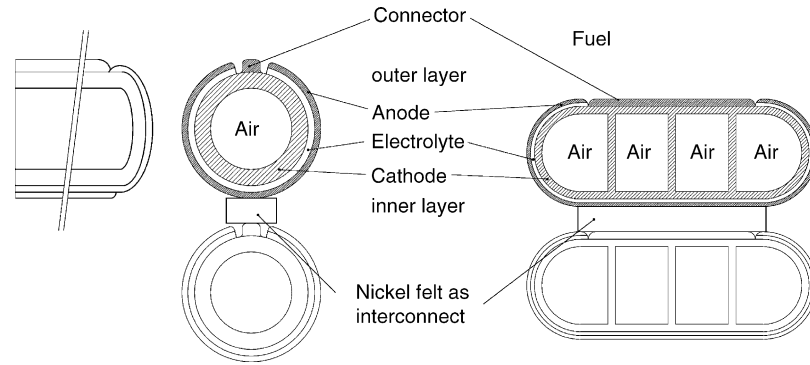


Fig. 2. Designs from Siemens–Westinghouse: (a) state-of-the-art tubular SOFC; (b) enhanced power density design (flattened tubes).

temperatures, both oxidizing and reducing atmospheres and has to remain gastight after several temperature cycles.

One possibility to avoid high temperature seals are tubular cell designs such as the Siemens–Westinghouse (SWPC) concept (Fig. 2).

However, the electrical power density of the tubes is limited by the long current pathway through the thin electrode layers and is far behind the performance of the anode supported cells, even at their working temperature between 900 and 1000 °C. The last enhancement at SWPC was the design of the so-called HPD-tubes (Fig. 2b) where the transverse section of the cells is flattened which shortened the current paths within the cathode and increased the measured power densities to 0.4 W cm<sup>-2</sup> in the cell modules.

Another attempt to increase the power densities of tubular cell arrangements is to reduce the empty voids within and around the cells by reducing the diameter to several millimeters. Due to the small inner diameter of those cells it is impossible to retain the sealless design of SWPC and the seal becomes an issue again.

A further possibility to reduce the internal ohmic losses, especially contact resistance to the interconnects and power lines is to separate the cells into several smaller units which are connected in series (Fig. 3). Dividing a given cell area into e.g. 10 smaller cells connected in series will reduce the current flow by the factor 10, the power loss due to connector resistances  $W = R \times I^2$  by the factor 100.

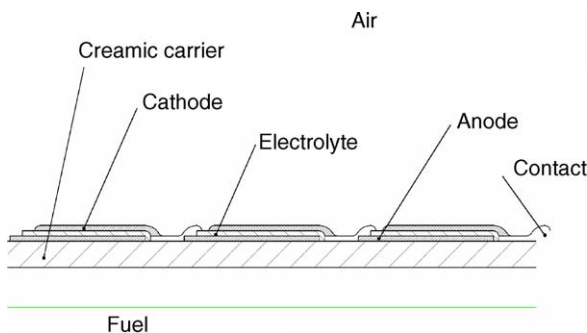


Fig. 3. Series arrangement of cells on one support: tubular, MHI; planar, Rolls Royce.

There are several designs for series connection: in the EPDC/MHI concept the cells are placed on an inert carrier tube [1]. A planar version of the series connection is the so called integrated planar SOFC concept at Rolls Royce. Power densities are in the range of planar cells.

In the so called mono-layer-block design waved structures are used to create a self supporting SOFC cell with low layer thicknesses (Fig. 4). The 3-D structure of the cell is supposed to be less susceptible to thermal stress as the structure allows the cell to bend reducing mechanical stress on the stack assembly. Furthermore, the gas supply channels are integrated into the ceramic cells which allows for flat metal foils or ceramic plates as interconnects. Stack sizes of ‘several 10 kW’ are tested today. Operating temperatures are not mentioned but may be estimated as approximately 1000 °C.

The last—somewhat special—design type is a single chamber cell in which the cell is placed into a single chamber containing both fuel (methane) and air. The setup works by using the low activity of LSM to prevent methane reforming on the cathode and thus generating a local concentration difference between the anode and the cathode of the cell. Main advantage of the design is the omission of the troublesome seal between anode and cathode. Main disadvantage is a certain efficiency loss due to parasitic oxidation of the fuel and reformat diffusion to the cathode.

Table 1 summarizes the publicized performance of some cell developers.

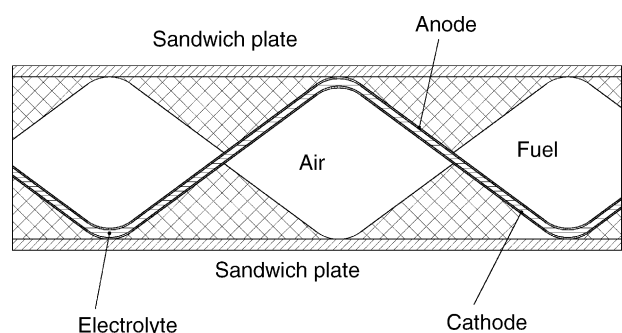


Fig. 4. Mono-block layer-build (MOLB)-SOFC's are developed by Chubu and MHI since 1990.

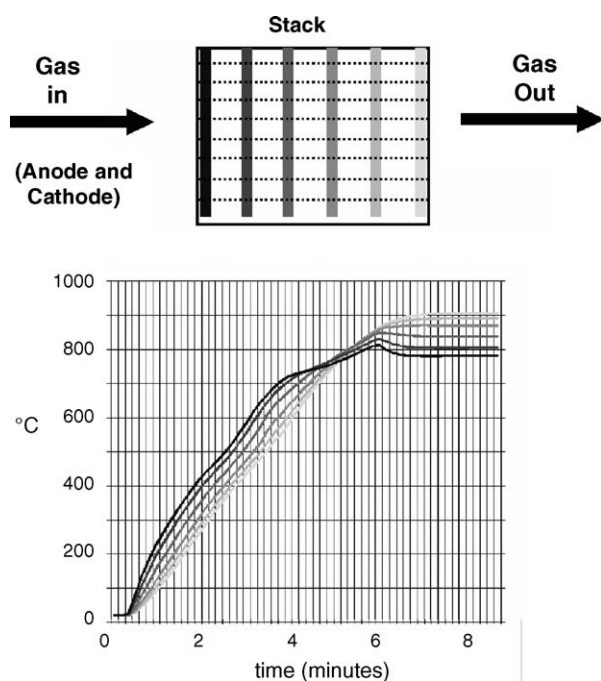


Fig. 5. Internal temperature distribution in a planar 5 kW SOFC-stack for start-up and steady state operation.

### 3. SOFC system concepts, designs and thermal start-up behaviour

As mentioned above, the optimal operational temperature of a SOFC stack is—depending on the stack technology—in the temperature range between 700 and 1000 °C. Below, electrical efficiency and power density are drastically reduced. Therefore, the stack has to be heated up after long periods of standstill from ambient temperatures to the minimum operating temperature of about 700 °C. For most applications this has to be done as quick as possible without thermally damaging the stack. As thermal conductivity is low the stack has to be heated up internally by hot gases (burner offgas) in the cathode and/or anode flowfield channels leading to thermal gradients between gas inlet and outlet. Apart from the thermal power of the peripheral burner the tolerable thermal gradients within the stack strongly influence the achievable start-up times.

In contrast to the situation of heating up the stack has to be cooled at normal operation to dissipate the internal heat production. This is done in most system designs by the cathode (or anode) gas streams which are entering the stack at temperatures below the stack temperature. High temperature gradients have to be avoided here as well. This is usually done by adjusting the cathode air flow.

Fig. 5 shows the result of a finite element simulation for the start-up process of a 5 kW planar SOFC stack for cathode and anode co-flow conditions. At heating-up (12 kW thermal burner power and 0.5 mol s<sup>-1</sup> hot gas flow) the maximum internal stack temperature is at the stack inlet with a maximum temperature drop over the whole stack of about 150 °C for the chosen conditions (stack mass = 8 kg, heat capacity = 450 J kg<sup>-1</sup> K<sup>-1</sup> and a mean thermal conductivity of the stack material parallel to the

gas flow of 20 W m<sup>-1</sup> K<sup>-1</sup>). After reaching the minimum operational temperature electrochemical conversion starts in each segment of the stack producing additional internal heat. When the mean internal temperature is at the nominal stack temperature, the system control unit switches to stack cooling by increasing the cathode air flow and decreasing the cathode air temperature. Accordingly, the internal temperature distribution reverses.

Under operation, mainly the internal heat has to be dissipated by the anode and cathode gas streams, while heat loss due to heat conduction and surface radiation play only a minor role. As the anode volume flow, given by the electric demand, is too low for sufficient cooling most of the waste heat has to be transported out of the stack by the cooling power of the cathode air

$$P_{\text{cool}} = \Delta T V_{\text{cath}} \quad \text{with} \quad \Delta T = T_{\text{out}} - T_{\text{in}} \quad (1)$$

$T_{\text{out}}$  is approximately given by the stack bulk temperature at the cathode outlet. To avoid thermal tensions in the stack care must be taken to avoid too high  $\Delta T$  values (some 100 K). Therefore, increasing the cooling power can only be done by increasing  $V_{\text{cath}}$ . The resulting values for  $V_{\text{cath}}$  normally exceed the stoichiometric air demand for the electrochemically process by a factor  $\lambda = 4$ –10. This unfortunately means high electric demand for the auxiliary blowers and large heat exchanger areas for pre-heating the fresh cathode air.

To avoid high  $\lambda$ -values internal reforming of methane can be used in future SOFC systems. As the steam-reforming reaction is endothermal and is easily catalysed at the high internal temperatures in the SOFC, some fractions of methane and eventually water steam in the anode feed decreases the cooling demand of the stack. Fig. 6 shows this effect for a pure methane/water steam mixture (b) in comparison to totally reformed methane (a). All stack parameters are according to Fig. 5 except for the anode and cathode gas flow directions which now are in counterflow condition. In both simulation runs the anode gas flow has been adjusted to get a fuel utilisation of 85%. The cathode gas flow has been adjusted to get a stack temperature of 800 °C (measured by the anode outlet gas). In the simulation the stack is divided along the direction of gas flow in 20 finite elements, and the kinetic limitation for the internal reforming is approximately accounted for by assuming, that 75% of the remaining methane fraction is reformed in each segment of the 20 finite element stack. The results show a clear reduction of the overall temperature gradients in the stack. Moreover the simulation results show that due to the internal reforming the cathode airflow can be reduced from 8.7 to 5.5 in terms of  $\lambda$ -value.

As a SOFC can use both H<sub>2</sub> and CO as fuel its application is most suitable in fuel cell systems which use hydrocarbons such as gasoline or diesel as fuels. These systems are equipped with a reformer unit which produces a CO containing gas. Regarding existing fuel infrastructure SOFC systems will thus be a promising system for mobile applications (APU, traction) [2,3]. Fig. 7 shows the most simple system design with a pure POX-reformer which converts gasoline by partial oxidation with oxygen to a H<sub>2</sub> and CO rich reformat. This reformat is electrochemical converted in the SOFC stack with a typical fuel utilization of

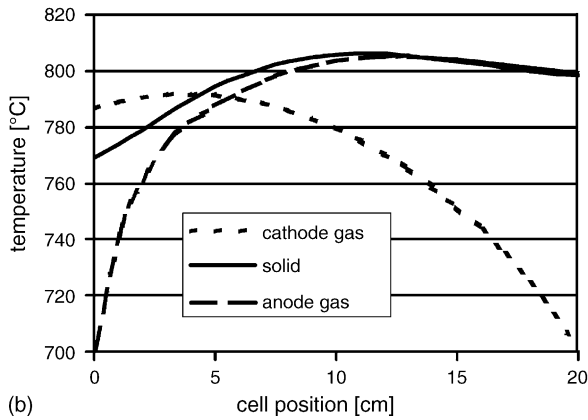
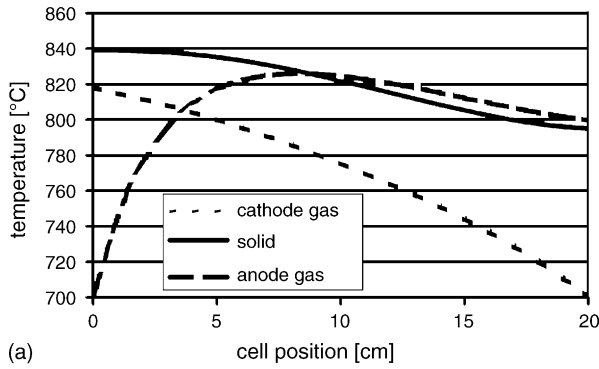


Fig. 6. Internal temperature distribution in a planar 5 kW SOFC-stack (counterflow) for different anode gas compositions: (a) totally reformed methane and (b) methane/steam = 2/3.

80%. The rest is catalytically oxidized in the burner module. Also shown are typical gas temperatures after some period of operation. As indicated in Fig. 8, however, this simple system design never reaches a stable steady state operation. Without any active cooling of the reformer it gets too hot due to the exothermal partial oxidation reaction. As a consequence the control unit has to increase the cathode air flow to keep the stack temperature at a constant level.

To avoid overheating endothermal steam reforming can be used. However, steam reforming requires an additional water tank which has to be refilled regularly by the car driver. A more sophisticated system design for mobile application may use the water content in the anode offgas for steam reforming, e.g. by adding an anode gas recirculation to the system as indicated in

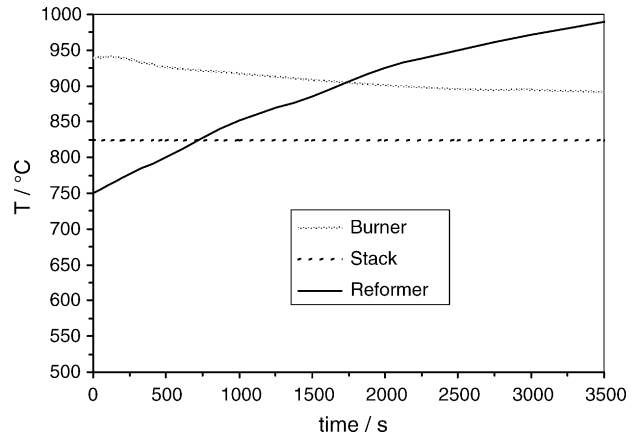


Fig. 8. SOFC System I: temperature of main components.

Fig. 9: an additional heat exchanger is placed near the stack inlet to equilibrate anode and cathode feed before entering the stack. Simulation results for this system configuration show, that even for a recirculation rate of 10% the temperatures of the main components have stable, acceptable values (Fig. 10).

#### 4. Materials and components resistant to thermal shock

A single SOFC unit consists of two electrodes (an anode and cathode) separated by the electrolyte. Fuel (usually hydrogen, H<sub>2</sub>, or methane, CH<sub>4</sub>) arrives at the anode, where it gets oxidized releasing electrons (e<sup>-</sup>) to the external circuit and recombines with oxide ions from the electrolyte. On the other side of the fuel cell, oxidant (usually O<sub>2</sub> or air) is fed to the cathode, where it supplies the oxide ions (O<sup>2-</sup>) for the electrolyte by accepting electrons from the external circuit. The electrolyte conducts these ions between the electrodes, maintaining overall electrical charge balance. The flow of electrons in the external circuit provides electric power. To generate a reasonable voltage, interconnectors are necessary to combine single cells to form stacks by connecting the cathode material of one cell to the anode material of the adjacent one. Today's technology employs several ceramic materials as the active SOFC components. The anode is typically formed from an electronically conducting nickel/yttria-stabilised zirconia (Ni/YSZ) cermet (i.e., a ceramic/metal composite). The cathode is based on a mixed (i.e., both electronic and ionic) conducting perovskite, lanthanum

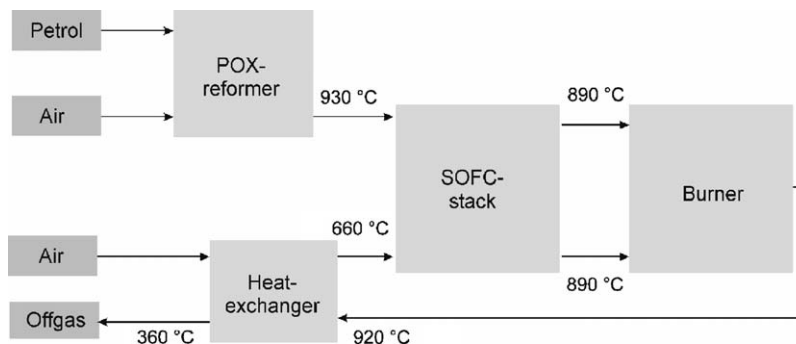


Fig. 7. SOFC System I: simplified design with POX-reformer.



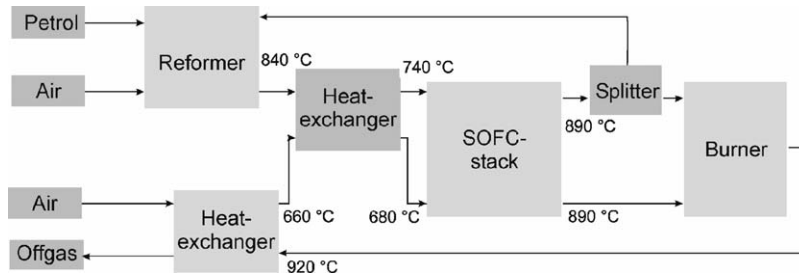


Fig. 9. SOFC System II: advanced design with anode recirculation.

Table 2  
Thermal expansion coefficients (CTE) of SOFC component materials (between r.t. and 1000 °C)

Component	Material	CTE ( $10^{-6} \text{ K}^{-1}$ )
Cathode	(La,Sr)MnO <sub>3</sub>	11–14
Electrolyte	Yttria-stabilized ZrO <sub>2</sub> (YSZ)	10.5
Anode	Ni-YSZ-Cermet	11–12
Interconnection	(La,Sr)CrO <sub>3</sub>	11
	Cr-based ODS alloy	9–10
	Ferritic steel	10–15

manganate (LaMnO<sub>3</sub>). Yttria-stabilised zirconia (YSZ) is used for the oxide-ion-conducting electrolyte. Ceramic, perovskite type materials on the basis of La-chromite have been shown to possess the property combination required for interconnector materials at high temperatures (900–1000 °C). Surface treated oxide dispersion strengthened (ODS) chromium base alloys have been also been developed for interconnector materials which can be used in this temperature regime as well. Ferritic steels can be used below 800–850 °C. Table 2 lists thermal expansion coefficients (TEC's) of these materials, Fig. 11 shows TEC's of several materials over temperature.

When the operating temperature of SOFCs reduces to below 800 °C, the use of inexpensive materials such as stainless steel for manifold, piping, heat exchangers, blowers, etc., can be achieved. Lower operating temperature of SOFCs would also reduce the thermal stress in the active ceramic structures, leading to a longer service life for the system. Anode-supported

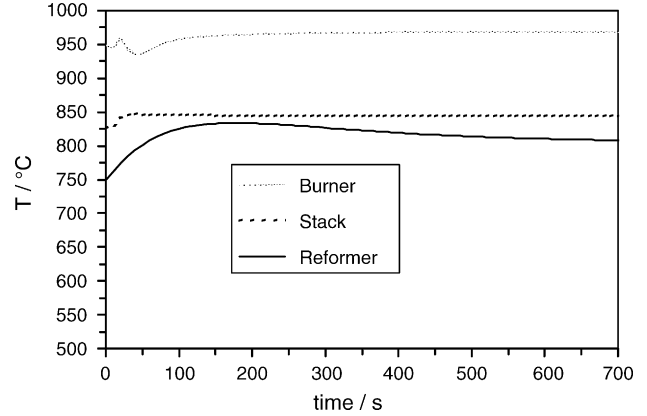


Fig. 10. SOFC System II: temperature of main components.

SOFCs have attracted a great deal of attention for some years because of their high performance at intermediate temperatures. As shown in Table 2, the anode supported cell has the advantage of matching CTE to a ferritic steel.

Planar SOFC designs have significant advantages when compared to tubular designs, including low cost processing methods and higher power densities. One of the critical issues in designing and fabricating planar SOFC stack is the development of the appropriate materials and techniques for hermetically sealing the metal and ceramic components. Current state-of-the-art sealing concepts utilizing glass or glass-ceramic materials have been largely successful in meeting performance requirements in the short-term. The viscous, wetting behaviour of glass

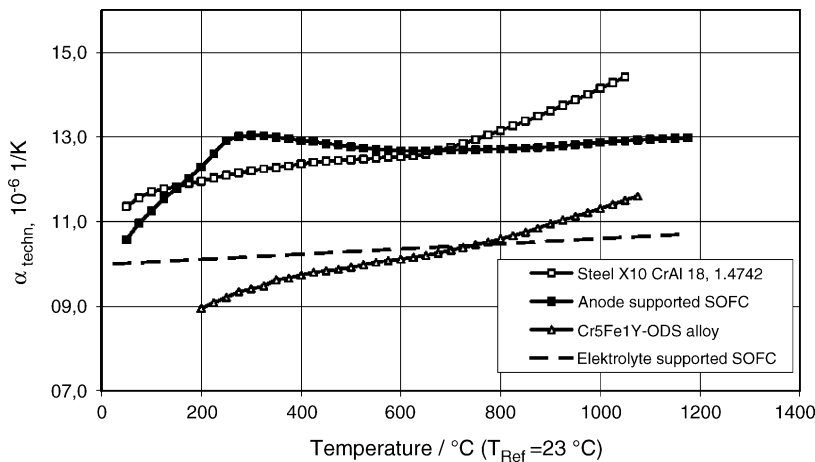


Fig. 11. Thermal expansion behaviour of stack materials.

facilitates hermetic sealing, and glass-ceramics avoid viscous flow and uncontrolled, progressive crystallisation during operation. However, long-term performance of the bonded and rigid seals under thermal cycling has been unsatisfactory. Glasses and glass-ceramics are brittle; consequently, thermal stress-induced bulk microcracking of the seal resulting from start-up/shut-down/start-up cycles may cause reactant leakage. Furthermore, these stresses are affected by the cell/interconnect/seal geometry and the component material properties of the particular SOFC stack design. A possible alternative to glasses is the use of compressive, non-bonding seals where the individual stack components are free to expand and contract during thermal cycling. Compressive seals utilize materials such as sheet-structure silicates, which do not bond to the adjacent component. The sealing is achieved by applying a compressive force to the stack. In this aspect, muscovite and phlogopite micas have been assessed as SOFC seals at 800 °C. Mica papers indicate very poor sealing characteristics requiring extremely high compressive stresses primarily due to the surface roughness resulting from small mica particles pressed together [4]. However, single crystal mica materials with significantly smoother surfaces exhibit lower leak rates than the mica paper may be potentially viable sealing materials.

Joints are required both within the stack, between internal support structures, and externally between auxiliary equipment in SOFC systems. The technologies including brazing and glass-ceramics can be used in the fabrication of SOFCs [5]. Brazing is an established techniques for joining ceramics and metals. When brazing ceramics, particularly to materials with dissimilar CTE, the design of the joint must be carefully considered, and the brazing pastes must be specifically developed. Brazing ceramics can be difficult due to poor wetting of the ceramic surface. The main industrial processes for improving wettability are metallisation and active metal brazing. Glass-ceramics can be a viable joining solution. While they are brittle in nature, their composition can be modified to provide a wide range of CTEs. They can make for ideal interlayer materials, which can be employed to reduce the strain gradient of the joint. A graded structure is achieved by controlled compositional changes in the chosen glass-ceramics to bridge between the components. If joining to a metal, an oxidation layer on the metal surface is important in order to achieve a successful joint. The reaction between the oxide on the metal surface and glass-ceramics will facilitate bonding.

## 5. Strategies of thermal management

Depending on the cell design and the materials used the SOFC stack can be operated within a distinct temperature range in which the upper limit is given by the material properties and the lower limit by the ionic conductivity of the electrolyte. Usually the nominal operating temperature is well above the minimum operating temperature, the stack stays ready for operation for a while also after shut down. To prolongate this time span the stack has to be properly isolated. Fig. 12 shows a variety of present available high temperature isolation materials. The lowest thermal conductivity of commercially available materials is about  $20 \text{ mW m}^{-1} \text{ K}$  at room temperature. In Fig. 13, we show the

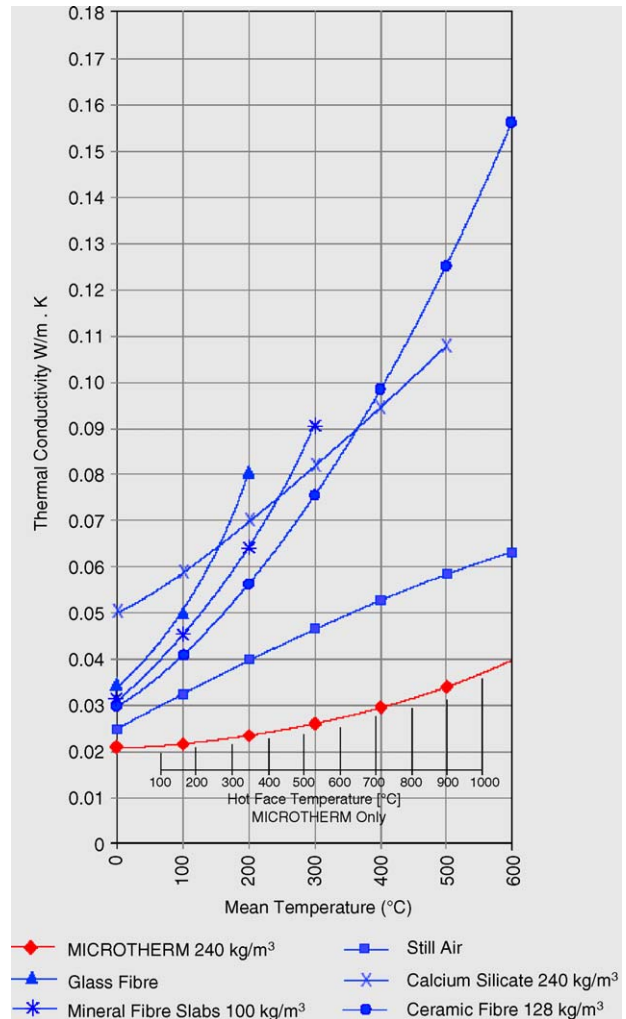


Fig. 12. High temperature isolation materials for SOFC. The isolation material faces to the cold side (lower temperature in the surrounding) and the hot side (higher temperature in the working region, SOFC stack for example). The “Hot-face-temperature” corresponds to the temperature at the hot side of the isolation material. The lower scale represents the mean temperature for all materials including MICROTHERM  $240 \text{ kg m}^{-3}$ . The higher scale represents the Hot-face-temperature just for MICROTHERM  $240 \text{ kg m}^{-3}$ .

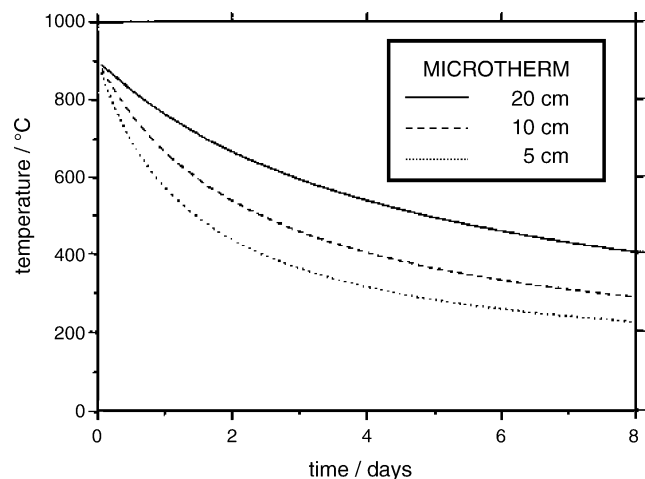


Fig. 13. Cooling down of a 50 kW SOFC-stack for three different values for the insulation thickness.

cool down characteristics of a 50 kW Stack isolated with Microtherm (MICROTEK International Ltd.), which is a microporous high temperature isolation material with pore sizes below the mean free path of the gas molecules. In dependence of the chosen isolation thickness and the minimum operating temperature, the stack can be held ready for operation for several hours or even a few days.

For longer periods of standstill different strategies for the thermal management of the SOFC stack are possible depending on the specific requirements of the particular application regarding energy efficiency, start-up times, long term degrada-

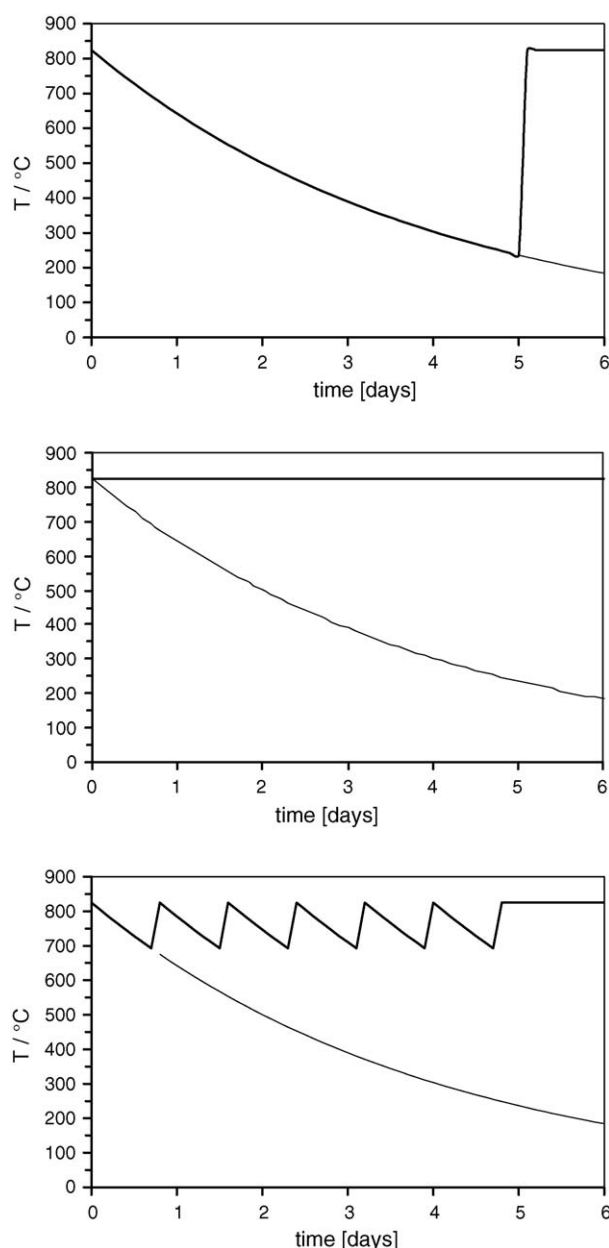


Fig. 14. Different system strategies for prolonged periods of standstill. Top to bottom—only passive insulation: no additional energy needed, but long start-up time; active heating to maintain temperature: additional energy needed, instant operation possible; short reheat cycles: less energy needed, instant operation still possible, reheat time may be matched to probable time of operation.

tion and other constraints. Fig. 14 shows schematically three different routes for thermal management. The first strategy (a) is to allow the system to cool down as slowly as possible by applying only a good inactive isolation. No active components have to be operated, the whole system is completely shut-down. For this strategy the overall thermal losses are minimized as the mean temperature difference between stack and ambient is lower than for the other two cases. In the shown example, the stack temperature is below 300 °C after a standstill period of 5 days. Therefore, the stack has to be heated up before restarting the system which takes some time due to limited thermal power of the used burner and the necessity of avoiding thermal stress in the stack. Dependent on the details of the stack (especially its specific weight) and burner power (which should reasonably be in the same order of magnitude as the stack electric power) the start-up process will take several minutes which may be too long in a mobile, customer-friendly system. In order to avoid this, the stack can be held at its operating temperature by continuously heating as indicated in Fig. 14b. As thermal losses through the isolation are very low this means partial load operation for one of the existing components (reformer, burner, see Fig. 9). Moreover, a continuously active system at 800–1000 °C may be problematic regarding safety aspects and customer acceptance. Therefore, strategy (c) will be a good compromise combining the advantages both of cases (a) and (b): the system is completely shut down for e.g. 24 h and then reheated periodically (e.g. each morning at 6 a.m.) using one of the existing components at its nominal power. Isolation thickness and reheating period are chosen in such a way that the SOFC stack is always above the minimum operating temperature. Therefore, applying strategy (c) the whole system can always be started instantaneously, while it is completely shut down most of the time during standstill.

Regarding the decrease of efficiency due to thermal losses strategies (b) and (c) are similar as the mean temperature difference between stack and ambient is comparable (about 800 °C). Table 3 gives a rough estimate of the fuel input for the compensation of the thermal losses in comparison to the fuel input for operating the stack at its nominal power. As can be seen the additional amount of energy needed to keep the system at or near working temperature (strategy (b) or (c))—when compared to the energy needed to reheat the system to working temperature (strategy (a))—is low (12% in a scenario where 1 h

Table 3

Comparison of fuel consumption due to thermal losses and due to electricity production for the strategies of thermal management as indicated in Fig. 14

Strategy	Fuel to compensate thermal loss during 6 days	Fuel for operation for given period		
		1 h	5 h	24 h
(a)	11.4			
(b)	17.9	45	225	1080
(c)	19.4			

All data are given in MJ upper heating value. Assumed stack data: nominal power, 5 kW el.; specific heat capacity, 3.2 kJ kW<sup>-1</sup> K; SOFC system efficiency, 50%; burner efficiency, 80%.



operation is followed by a week standstill) and may be acceptable as the additional power consumption reduces the number of heatup/cooldown cycles.

## 6. Summary

There are several competing SOFC system designs. While the materials used in these designs differ greatly, one aspect of all the systems remains constant: the number of start-up cycles of the designs is well below 100. While this is not a problem in stationary applications with one or two shutdowns per year it is clearly insufficient for mobile applications with possible daily start-ups and shutdowns.

This obstacle may be circumvented by increasing the system isolation. Especially in cases where start-ups occur daily shutdown times are short as well and 5–10 cm isolation will keep the system at operating temperatures during such short times. The system itself therefore experiences only a few ambient—operating temperature—ambient cycles although it is frequently switched on and off.

For longer times a passive isolation alone may not be sufficient. For longer periods keeping the system on (nearly) working temperature by active heating may be a possibility. An estimate for the additional fuel consumption depending on the overall system strategy is given in Table 3.

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