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Engineering aspects and hardware verification of a volume producable solid oxide fuel cell stack design for diesel auxiliary power units

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Abstract

A solid oxide fuel cell (SOFC) stack module is presented that is designed for operation on diesel reformate in an auxiliary power unit (APU). The stack was designed using a top-down approach, based on a specification of an APU system that is installed on board of vehicles. The stack design is planar, modular and scalable with stamped sheet metal interconnectors. It features thin membrane electrode assemblies (MEAs), such as electrolyte supported cells (ESC) and operates at elevated temperatures around 800 °C. The stack has a low pressure drop in both the anode and the cathode to facilitate a simple system layout. An overview of the technical targets met so far is given. A stack power density of 0.2 kW l^{-1} has been demonstrated in a fully integrated, thermally self-sustaining APU prototype running with diesel and without an external water supply.

Keywords: SOFC stack; Auxiliary power unit; Diesel reformate

1. Introduction

Recent advances in solid oxide fuel cell (SOFC) technology have made SOFCs a reasonable choice for fuel cell auxiliary power units (APUs). Such units combine the advantages of conventional, internal combustion engine-based generator technology (e.g. usage of fuels with a well established infrastructure like diesel or gasoline) with the specifics of fuel cells, such as:

- relatively high efficiency of power conversion;
- low maintenance;
- silent operation;
- scalability.

APUs can be employed in a broad range of applications, ranging from vehicle and recreational usage to military applications. In the recent years, by far the most attention has been paid to the automotive application of fuel cell APUs, for numerous reasons:

- APUs are seen as a key technology to meet future energy demands on board of passenger and commercial vehicles. In passenger cars, the increasing electrification of vehicle functions owing to customer demands and environmental regulations have led to a situation where the old 12 V lead acid start, light, ignition (SLI) battery in combination with an alternator is at its limits and starts to constrain future innovation. In commercial vehicles, mainly in heavy trucks, an engine independent power source is needed as an alternative to idling the truck's main engine.
- The automotive industry was the main driver behind the commercialization of PEM fuel cells. Originally started as a technology to revolutionarize the passenger vehicle's drive train, PEM fuel cells turned out to be still not cost efficient and reliable enough to be used as the main power plant on board of vehicles. In turn, the enormous amount of knowledge about PEM stacks and fuel processing that was generated by many industrial and academic researchers was directed towards alternative PEM applications on board of vehicles, with APUs being the most important.
- It was demonstrated that fuel cell APUs can be based on SOFCs, and that they can in principle be integrated into vehicles [1].

Abbreviations: APU, auxiliary power unit; ASC, anode supported cell; CPOX, catalytic partial oxidation; DC, direct current; ESC, electrolyte supported cell; FEM, finite elements mechanics; LSM, lanthanum strontium manganite; MEA, membrane electrode assembly; *n*, number of cells in the stack; OCV, open cell voltage; P_C, failure rate of one repetitive unit [0, . . ., 1]; PEM, polymer electrolyte membrane; P_S, failure rate of the stack [0, . . ., 1]; RU, repetitive unit; SOFC, solid oxide fuel cell; SPC, statistical process control; YSZ, yttria stabilized zirconia

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2. SOFC stack design constraints

SOFC-based APUs offer significant advantages over PEM-based systems, as discussed elsewhere (e.g. in [2]). Nevertheless, an SOFC stack for APU usage has to fulfill the common automotive industry criteria:

- mass producable design;
- stable and controllable fabrication methods and processes;
- tight mechanical and process integration into the APU system;
- lightweight, high power density;
- resistance to shock and vibration.

The design should be adapted to the requirements of future high power DC grids on board of vehicles, such as 42 V grids. Furthermore, typical scenarios of APU usage should be considered and respected.

In the following sections, the engineering aspects leading to the design of an APU stack are highlighted.

2.1. Power output and stack configuration

A typical vehicle integrated APU will have a net power output of about 2–5 kW electrical, which has to be delivered by the stack. In addition, the stack has to power the parasitic loads in the APU, such as system components or ohmic losses in cables and connectors. Depending on the actual system configuration, a parasitic loss of ca. 10–20% has to be expected.

Several options exist for the stack geometry, the most important being tubular and planar. Configurations other than planar were excluded in the early design phase, because it was not believed that tubular designs can meet the requirements with respect to power density, mechanical robustness, and operating temperature.

For planar stack configurations, the main parameters are cell count and cell area. The cell count determines the stack voltage. In the following sections, several criteria affecting the number of cells in a stack are highlighted.

2.1.1. Optimum cell count—influence factors

2.1.1.1. 42 V compatibility. Current power systems on board of vehicles deliver a DC voltage of 12 or 24 V. Thus, a 5 kW APU at full load would generate 417 A net current if run in a 12 V grid, which is not desirable due to high ohmic losses, necessarily large cable cross-sections, and the high electromagnetic field that is generated. Thus, a higher output voltage is needed. 42 V was accepted as a compromise between voltage and conductor cross-section among the automotive industry.

The raw stack voltage will vary with the load that is applied, therefore, a DC/DC converter is needed to guarantee a stable output voltage. Modern step down DC/DC converters require a voltage buffer of ca. 5 V, thus the stack voltage has to be above 47 V at full load.

2.1.1.2. Single cell voltage. Depending on the oxygen partial pressure in the reformate and the operating temperature, Ni components in the anode compartment can be oxidized to NiO. Assuming an O_2 partial pressure of 1×10^{-8} Pa in the reformate, the Ni oxidation at 850 °C occurs below 680 mV at OCV. As a result, the single cell voltage under full load should not significantly drop under 680 mV, otherwise the stack degradation rate will increase due to inhomogeneous voltage distribution. Furthermore, the conversion efficiency will drop to unacceptable levels.

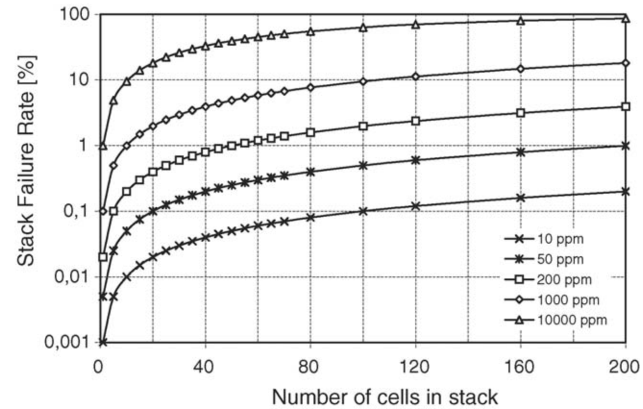

Fig. 1. Stack failure rate as function of cell count and RU failure rate.

2.1.1.3. Degradation reserve. Any SOFC stack will degrade under load when operated for several thousand hours. A realistic estimate is a degradation rate of ca. 1% per thousand hours of operation. A typical scenario on board of vehicles implies a stack lifetime of ca. 5000–10,000 h. Thus, a voltage reserve of 10% in any operating point should be available at the beginning of the stack life.

2.1.1.4. Reliability. Although it is advantageous from an electrical point of view to have a high cell count in the stack, reliability issues counteract the usage of stacks with many cells in series. Considering a single stack, a catastrophic failure of one single repetitive unit (RU) translates to the failure of the complete stack. In a single stack, potential failures of single repetitive units can be treated as independent events. Thus, the initial statistic failure rate of a complete stack can be calculated from the failure rates of the respective RUs according to Eq. (1), where P_S is the failure rate of the stack, P_C the failure rate of one RU and n is the number of cells in the stack:

$$P_S = 1 - (1 - P_C)^n \quad (1)$$

Typical failure rates of mass produced parts (>100,000 units per year) are in the range of 50 ppm. In Fig. 1, a sample calculation according to Eq. (1) is presented. It is obvious that even with an RU failure rate of less than 50 ppm, a 60-cell stack will fail with a probability of 0.3%. This value is not acceptable in high volume production of APU systems. Thus, the reliability of the RU production process has to be increased, i.e. by automated parameter observation (statistical process control, SPC). Nevertheless, a 60-cell stack seems to be volume producable with reasonable effort.

2.1.2. Optimum cell type and area

2.1.2.1. ESC versus ASC. The cell active area, in combination with the cell power density, eventually determines the stack power.

Several options exist for SOFC cells that can be used in planar stacks. The oldest technology is electrolyte supported cells (ESC), characterized by their mechanical robustness, but relatively low power density and high operating temperature.

To overcome power density problems and to lower operating temperatures, anode supported cells (ASC) were developed. They deliver power densities of approximately half an order of magnitude higher than ESC at operating temperatures of about 200 K lower than ESC. The penalty, however, is the relative mechanical weakness and the significantly higher usage of raw material.

A third technology is in a predevelopment stage that is hoped to combine the mechanical robustness of ESC with the lowered operating temperature and higher power density of ASC. In this so-called metal substrate concept, the mechanical integrity of the cell is delivered by an external metal mesh or felt, on which the layers forming the cell are applied. Several layer build-up techniques have been described, such as vacuum plasma spaying.

The decision on the cell type is not only determined by the maturity of the technology, but also heavily influenced by system aspects and cost considerations in a relatively broad context. To deal with this complexity, a decision matrix scheme and scenario analysis was carried out (see below).

Two cell technologies were estimated to have the maturity for SOFC APU usage: anode supported cells and electrolyte supported cells.

2.1.2.2. MEA active area. Based on sample geometry, several geometrical options including ASC and ESC were investigated. Only the core stack was calculated without end plates or a compression system. The shape of the MEA was assumed to be square. At least the cathode was assumed to be 10 mm shorter in length than the electrolyte on both sides to give space for a seal. It was assumed that for thermomechanical reasons dimensions of more that 150 mm × 150 mm for a single cell cannot be reached. A hollow steel cassette was assumed as an interconnector plate, including seal and contact mesh or grid. Densities for representative materials, such as steel, YSZ, NiO and LSM were taken from the literature, with an assumed average anode porosity of 30% for ESC and 40% for ASC. Cost projections and scale effects of all materials were also included, but are not subject of detailed discussion here. Some typical results of the analysis are presented in Table 1.

Table 1
Sample stack geometries and weight for various cell types

	ESC 1	ESC 2	ESC 3	ASC 1	ASC 2
Anode area (cm^2)	81	196	81	90	225
Anode thickness (μm)	100	100	70	1000	1000
Electrolyte area (cm^2)	100	225	100	90	225
Electrolyte thickness (μm)	120	120	90	10	10
Cathode area (cm^2)	81	196	81	81	196
Cathode thickness (μm)	100	100	70	100	100
Interconnector area[a] (cm^2)	350	600	350	350	600
Steel sheet thickness (mm)	0.5	0.5	0.5	0.5	0.5
Sealant area (cm^2)	40	80	40	40	80
Sealant thickness (mm)	0.3	0.3	0.3	0.3	0.3
MEA weight (g)	11.5	26.6	9.2	42.8	107.0
RU weight (g)	151.2	267.1	148.9	185.8	347.4

ESC 1: typical geometry of today's state of the art ESC; ESC 2: ESC with outer (i.e. electrolyte) dimensions of 150 mm × 150 mm; ESC 3: advanced ESC with thin electrodes and electrolyte; ASC 1: typical geometry of today's state of the art ASC; ASC 2: ASC with outer (i.e. anode and electrolyte) dimensions of 150 mm × 150 mm.

[a] Interconnector area includes double layered portions of the hollow cassette.

From Table 1, it becomes clear that a stack consisting of ASC has an intrinsic disadvantage in weight when compared to a geometrically similar stack consisting of ESC. The ASC stack in the sample geometry will be heavier by a factor of 1.2–1.3 if 0.5 mm steel sheets are used as the interconnector. The effect obviously is more pronounced if thinner interconnector material is used. Higher active MEA areas per RU increase the ESC advantage, since less interconnector material is wasted in non-active areas. The volumetric effect also cannot be neglected, since the cell pitch will be increased by ca. 0.6 mm when moved from current ESC to current ASC.

The weight and volume disadvantages of ASC stacks are compensated by the higher power density of ASC. Typically, up to twice the power output as compared to ESC is reported for ASC under comparable operating conditions.

In addition to effects discussed above, other effects influence the cell decision:

- ASC mechanically are less robust than ESC, thus often require more rigid or better TEC adapted interconnectors or external compression systems.
- ASC require the usage of relatively large amounts Nickel for mechanical integrity, which does not add to power density. Hence, ASC have an intrinsic material cost disadvantage.
- ESC stacks have a low weight to volume ratio, thus can be heated up rapidly via the gas interfaces without building up too much thermomechanical stress.
- ESC and ASC have different optimum operating temperatures, thus the cell should be chosen with respect to system complexity (i.e. additional heat exchangers should be avoided).

In the design presented here, ESC were chosen for their better system compatibility.

3. Bipolar plates

3.1. Bipolar plate material—engineering aspects

Numerous options exist for planar interconnector plates in SOFC stacks: full ceramic plates, net shape pressed chromium alloy-based plates and interconnectors manufactured from sheets of iron or nickel-based alloys have been described. Although full ceramic plates in many cases offer superior thermomechanical properties, this path was not pursued in the present approach, mainly because ceramic plates in a stack require elaborate external auxiliaries to make the stack shock and vibration resistant, and due to cost considerations.

Any bipolar plate raw material, in addition to its material cost, requires mechanical processing. In a volume production context, mechanical processing to a large extend defines the final stack cost. Multiple cost blocks have to be considered:

- Loss of raw material: It is obvious that process steps that do not waste raw material are the most cost efficient. Thus, on a relative scale, net shaping processes like powder pressing are superior to milling from raw parts: net shaping > stamping, cutting > milling.
- Cost of the process step itself: This includes machine times, wear of tools, cost of supplementary and filler materials, and handling cost. Typically, mass manufacturing processes like automated stamping and cutting from steel sheet coils or powder pressing have a very low per-part cost, because these processes are very fast and do not require additional chemicals. In contrast, the necessary stamping or pressing tools are very expensive and virtually not changeable, once the geometry is fixed. Thus, high part counts of up to several 10,000 and above are necessary to make such tools commercially viable. This effect is often overseen in current SOFC R&D, since the high tooling cost, wide mechanical tolerances and low flexibility of stamped parts hinder small and fast optimization of stack components. A solution to this dilemma for the design approach described here was the use of rapid prototyping techniques and modular tools for sheet metal forming.
- Cost of quality: As described above, the failure rate in the production process of the complete RU has to be in the ppm range for automotive and similar applications. Even in a moderate cost calculation, there is no room for a 100% inspection, that is a complete examination of all parts that are produced. Thus, production processes have to be very stable and reliable to allow for statistic process control. A major prerequisite for such methods is, that all production steps can be characterized by parameters that can easily be monitored and recorded with statistical significance and that the relationship between these process parameters and product performance is understood. This does not hold yet for all SOFC production methods that are currently investigated, but the lack of such control parameters will exclude even promising production methods from being introduced into volume production. In the design presented here, stamping was chosen also for its well-known and secure process control.

It is obvious that any bipolar plate material also has to withstand the operating conditions that are defined by the cell and the feed gases, with the most prominent parameter being the temperature. If ESC are chosen, operating temperatures of 850 °C and above are reached. The specific properties of alloy-based interconnect materials are not subject of this paper and discussed elsewhere [3].

In the design presented here, a bipolar plate produced by stamping and welding processes from ferritic sheet metal was chosen as the best compromise between cost, performance, and reproducible quality. Several advanced ferritic alloys were tested in material verifiers under stack operating conditions for up to 1000 h prior to the design decision. They were found to be suitable, although apparently at the upper limit of their usable temperature range.

3.2. Bipolar plate geometrical layout

Many bipolar plate geometries have been proposed for planar designs. Modern interconnectors are not merely gas separators, but include several or all of the following sub-functions:

- separate gas streams in the active area;
- separate gas streams outside the active area;
- provide means for gas distribution within the RU (i.e. flowfields);
- provide means for gas distribution within the stack (manifolds);
- provide temperature distribution functions;
- provide current conducting functions;
- include sealing and gasketing functions;
- include means to mechanically support the cell or active area;
- provide means to mechanically integrate the stack (clamps, tie rods).

In the following sections, several non-trivial functions are discussed with respect to the APU stack design.

3.2.1. Separation of gas streams outside the active area

Anode off gas in diesel reformate operation under full load still has a considerable heating value. It is, therefore, burnt to provide heat to endothermic reactions elsewhere in the APU system. Due to the low water content in CPOX diesel reformate, virtually no endothermic steam reforming takes place in the stack. Thus, the cooling effect of the steam reforming reaction does not contribute to the stack's thermal balance like it does in the case in methane/steam operation as seen in many stationary systems. Hence, the anode off gas must not be burnt within the stack or at its outer rim to prevent the stack from overheating. In an APU configuration, off gas streams have to be separated. In the design discussed here, this was achieved by using a hollow cassette enclosing the anode space.

3.2.2. Gas distribution within the stack and bipolar plate—manifold layout

An efficient stack requires an even feed gas distribution to each cell to achieve high overall fuel utilization rates. Cells with poor gas supply have low cell voltages, and thus poor performance. The main influence on gas distribution in a stack can be attributed to pressure effects related to viscous dissipation and to mixing and demixing in the manifolds.

Pressure drops in gas ducts and manifolds are approximately proportional to gas velocity squared. The velocity in the manifold itself is affected by the gas usage per cell, the number of cells stacked together, the cross-section of the manifold and the temperature. Assumed that the gas usage per cell and the temperature are fixed values, there are two degrees of freedom to

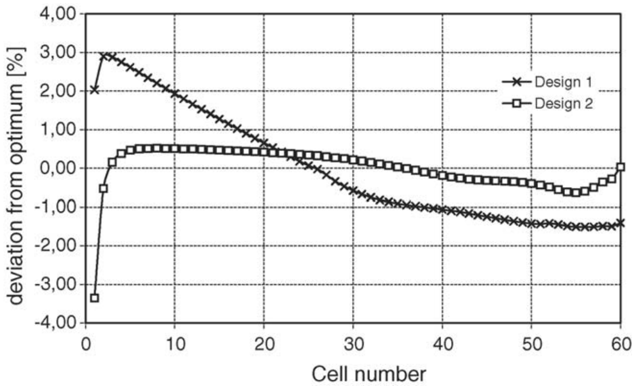

Fig. 2. Calculated deviation of the gas flow to each cell from the optimum value (in %) for two RU designs in a 60-cell stack. The relatively large deviation of cell 1 in designs 1 and 2 is due to the boundary conditions of the CFD model. The influence of the gas feed line was not taken into account for this calculation, although it is known there will be an effect.

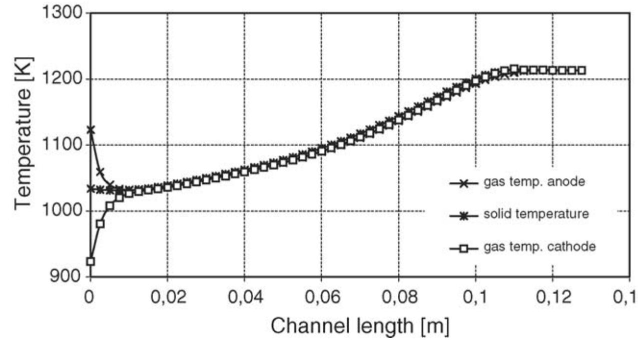

Fig. 3. 1D-simulated temperature distribution in an assumed channel parallel to the direction of the gas flow in a sample stack, co-flow case.

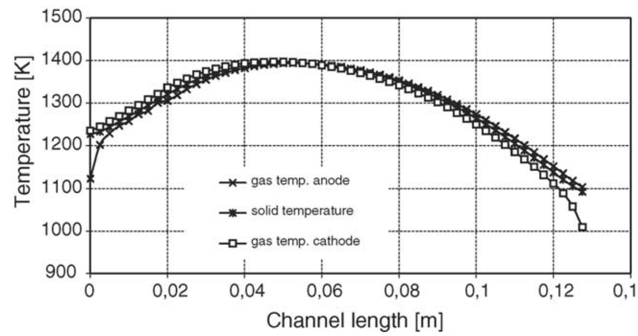

Fig. 4. 1D-simulated temperature distribution in an assumed channel parallel to the direction of the gas flow in a sample stack, counter-flow case.

reduce the velocity, and thus the pressure effects (i.e. pressure drops): the size of the manifold and the number of cells vertically stacked together.

The cross-section of the manifold is determined by the cross-section of the openings in the RU. As the RU is supposed to be a mass produced part with the same shape throughout the stack, the only degree of freedom is the size of the inlet and outlet manifold; hence, the size of the openings in the bipolar plate. For reasons of good usage of the available area per RU, a prismatic manifold had been chosen.

Even slight design variations of these openings in the RU, and under the restrictions described above, can have a pronounced effect on the gas distribution along the stack, as shown in Fig. 2.

The system specification imposes a limit on the maximum allowable pressure drop along the stack, thus also defines the maximum gas velocity along the stack internal manifolds. Once this maximum velocity is set, the cross-section of the manifold has to be varied with the number of RUs stacked up. The higher the stack, the larger the openings in each individual RU have to be in order to not exceed the maximum gas velocity. As manifolds are part of the passive area of a stack they have to be as small as possible to reach an optimized volumetric power density.

3.2.3. *Temperature distribution in the bipolar plate*

In every individual RU, several heat sinks and sources have to be managed, such as chemical reactions and gas streams. The primary means of heat distribution within the RU is the bipolar plate. A number of restrictions apply, such as the necessity of a well adjusted stack thermal balance, the avoidance of hot spots or cold spots and the avoidance of excess thermal stress on the RU components.

Temperature distribution in possible RU geometries was investigated by simulation. Localized temperature measurements for planar SOFC stacks with adequate resolution are in the development phase and were used to support the simulation.

Three principal geometries are possible for planar SOFCs: co-flow and counter-flow (reformate and air flow direction parallel or antiparallel, respectively) and cross-flow (flow directions perpendicular). It is known from previous reports that cross-flow configurations lead to pronounced hot spots especially under dry feed gas operation, as is the case with CPOX reformers. Thus, cross-flow configurations were excluded from the investigation, although cross-flow stacks typically have the most compact designs.

Co-flow and counter-flow configurations were investigated by one-dimensional finite elements mechanics (FEM) simulations using MATLAB/FEMLAB. In Figs. 3 and 4, simulation results of the temperature distribution along an assumed channel for the anode gas phase (T_a), the cathode gas phase (T_c) and the solid phase (T_S) are presented.

Consistent with the system simulation, inlet temperatures of 650 °C for the cathode air and 850 °C for the anode gas (equilibrium composition of Diesel reformate at 850 °C; H_2 22%, CO 20%, CO_2 2%, H_2O 3%, CH_4 0.1%, N_2 52.9%) were used as parameters. The simulation was performed under constant current conditions assuming an average current density of 250 mA cm^{-2}. The cooling air flow was adjusted to high utilization and the reformate flow was set to only 25% utilization to make the distribution effects clearer.

To allow adaption of gas temperatures to the solid temperature in the RU without affecting the MEA, an electrochemically inactive area was included in the RU upstream and downstream of the cell. This inactive area was also included in the geometric model.

3.2.3.1. Simulation for co-flow case. In co-flow operation, the temperature steadily rises towards the end of the channel. The temperature difference between the inlet and the outlet of the cell reaches values of about 150 K, which is equivalent to about 17 K cm^{-1}.

3.2.3.2. Simulation for counter-flow case. In counter-flow operation, the resulting temperature distribution features a prominent peak ($T > 1100\,°C$) close to the center of the gas channel. This effect leads to high temperature gradients of more than 33 K cm^{-1} along the channel.

It cannot be concluded from the simulation, which version of flow direction is preferable in a stack. Whereas in the case of co-flow the overall temperature gradients along the MEA are smaller than with counter-flow, the steadily rising temperature profile along the gas channel leads to a non-uniform temperature profile in the stack assembly. In the counter-flow case, gradients along the MEA are higher, but the temperatures at the terminal points are almost equal.

The simulated temperature profiles furthermore show that the inactive area upstream and downstream of the MEA indeed leads to an equalization of gas and solid temperatures in both cases. Thus, thermomechanical stress across the MEA and its fixation to the metal plate is reduced.

As a result, the stack assembly is designed to be used with both versions of air flow directions. The influence of each version are subject to present investigations on stacks in a system context. The symmetry of the bipolar plate will be lifted at a later point in time.

3.2.4. Sealing and gasketing function

Seals and gaskets are a critical component in any fuel cell stack. Failure of one single gasket often translates into severe power loss or complete failure of the stack.

In Section 3.2.1, it was concluded that gas streams have to be separated at the inlet and outlet of the stack. Anode feed gas and off gas both are toxic and flammable, and thus have to be tightly enclosed throughout the stack and the respective ducting. Since the off gas has to be collected within the stack, the bipolar plate has to have at least two openings for reformate: one for distributing the feed gas to the RUs and one for collecting the off gas.

Air, in contrast, has a much lower risk potential, thus does not necessarily have to be confined in gas tight ducts. Moreover, air can be completely externally manifolded. In this so-called open cathode configuration, air is blown through the stack from the outside directly onto the cathodes of the MEAs. The cells are not addressed individually. This configuration has several advantages: no special gasket for air is needed, and the risk of a vertically uneven temperature distribution within the stack is minimized, especially under part load or transient operation.

Following these considerations, a bipolar plate with an open cathode and two openings for reformate manifolding is the simplest configuration that is applicable in a diesel reformate SOFC stack, since it has the lowest number of openings to seal. It, therefore, was chosen for the stack described here. The bipolar plate assembly is depicted in Fig. 5.

Fig. 5. Complete, laser welded bipolar plate assembly.

4. Results—stack integration

4.1. Summary of technical details

Based on the analyses described above, the following technical decisions were made as a technical basis for the first proof-of-concept prototypes of APU SOFC stacks that can be operated on diesel reformate:

- cell count: 60 cells, series connected, single stack;
- electrolyte supported cells;
- cell area 81 cm^2;
- operating temperature 850 °C;
- sheet metal bipolar plates, stamped and laser welded. Optionally, specific features can be introduced by milling the plate from raw parts;
- two openings – one for reformate feed gas and one for off gas – per plate;
- stack integrated temperature control elements;
- open cathode.

A cell count of 30–60 cells was chosen as a good compromise between usable power output, availability and reliability of parts and manufacturing processes, and stack shape. The latter is close to cubic, which minimizes radiation losses.

ESCs, mainly selected for their advantageous properties discussed above, can be mounted very easily to the cassettes by means of a proprietary flat gasket technique. The flexible design of the anode and cathode current pick up allows for flexible usage of ESCs of varying layer thickness and chemical composition. Furthermore, metal substrate cells can be integrated into the stack without design changes.

Fig. 6. Completely assembled 60-cell SOFC module with light compression system.

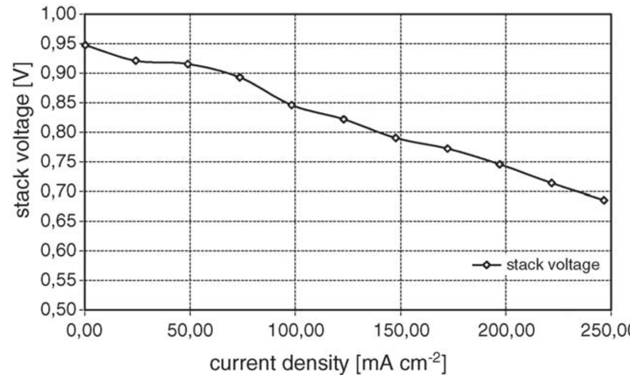

Fig. 7. UI curve of the stack module with a 30-cell stack in dry CPOX diesel reformate operation.

An operating temperature close to 850 °C is fundamental for current ESCs. Thus, materials and joining techniques were chosen to be compatible with this temperature. The number of different materials was limited to the minimum. As an example, laser welding was chosen over brazing for the joint between the two parts of the bipolar plate, since it does not require additives that might contaminate the active parts of the cells. Operating temperature of 850 °C was chosen for a second effect. At this temperature, a typical dry CPOX reformate does not form solid carbon. In contrast, this is the case with lower temperatures, as was shown with simulations and experiments.

The stack requires a light external compression system. The complete 60-cell module is depicted in Fig. 6.

4.2. System integration of the stack

To prove the concept, the stack module as 10- and 30-cell version was incorporated into a diesel APU prototype. The APU system is described in detail in a separate paper [4].

The stacks were directly connected to the CPOX reformer exhaust, thus the anode inlet temperature was close to the reformate temperature. Temperature management was accomplished via the air side. The cathode gas was preheated in the system afterburner and then directed to the stack's open cathode area via low pressure drop air ducts. The flow rate was adjusted to be in a range where the stack is not sensitive to changes in flow rate ($\lambda > 3$ to prevent oxygen starvation). The stack's internal heat management prevented the occurrence of cold spots (which would lead to soot formation) or the build up of excess thermomechanical stress.

Some specific design details of the stack could successfully be demonstrated:

The 30-cell stack showed a good volumetric power density of more than 0.2 kW l^{-1} at 850 °C with diesel reformate over a period of several hours. During the tests, it went through more than 15 full thermal and redox cycles. No purge gas or any other means of chemical stack protection was used. Degradation or soot formation in the stack was not observed. Thus, the huge potential of ESC for simple and robust SOFC APU systems was clearly demonstrated. Furthermore, it was shown that ESC do not have to lack power density by an order of magnitude when compared to ASC. The cells used in the experiments were mechanically robust standard products and not yet optimized for higher power densities.

Ferritic alloy bipolar plates can be used at operating temperatures around 850 °C without any short-term degradation that would prevent these alloys from being used in APUs. The specific hollow plate design, leading to an open cathode and complete internal distribution of anode gas, led to a very uniform temperature and cell voltage distribution under full load, as can be seen in Fig. 7.

The stack internal heat management allowed for a complete temperature control of the stack via the air side in reformate operation. Due to the low pressure drop in the cathodes (<10 mbar) the stack could be operated in low oxygen utilization mode without the need of an overdimensioned air compressor, thus paving the way for a simple system. The relative bulkiness of the low pressure drop design is overcompensated by this lack of heavy external components. During the tests, no electric heating elements were used, i.e. also the heat up and cool down of the stack was performed via the gas side plus external radiation and convection.

5. Conclusion

A stack design has been presented that is suitable for diesel operated SOFC APUs on board of vehicles. The design is based on electrolyte supported cells and ferritic alloy bipolar plates. It features an open cathode with low pressure drop, simplified bipolar plate layout, and internal heat management.

It was demonstrated that the design has to obey certain serious restrictions to allow for mass fabrication. It was also shown that an APU stack design has to be derived from a clear system specification.

A sample stack layout was set up from the design criteria that were developed. The stack modules, consisting of 10 and 30 cells, were tested in an APU prototype. It was demonstrated that the stack design fulfills the most critical criteria. It was possible to operate the stack fully self-sustainable, to go through multiple full thermal and redox cycles, and to perform the complete thermal management inside the stack without degradation.

ESC have turned out to be an attractive choice for SOFC APUs. The availability of advanced ferritic alloys have made it possible to operate APU stacks at 850 °C without a significant disadvantage over ASC-based stacks. The relatively high operating temperature was shown to be not much of a problem. Instead, it is helpful in terms of simple system setup and soot prevention.

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