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Design and operation of interconnectors for solid oxide fuel cell stacks

W. Winkler, J. Koeppen

Arbeitsbereich Energietechnik, Fachhochschule Hamburg, Berliner Tor 21, 20099 Hamburg, Germany

Abstract

Highly efficient combined cycles with solid oxide fuel cell (SOFC) need an integrated heat exchanger in the stack to reach efficiencies of about 80%. The stack costs must be lower than 1000 DM/kW. A newly developed welded metallic (Haynes HA 230) interconnector with a free stretching planar SOFC and an integrated heat exchanger was tested in thermal cycling operation. The design allowed a cycling of the SOFC without mechanical damage of the electrolyte in several tests. However, more tests and a further design optimization will be necessary. These results could indicate that commercial high-temperature alloys can be used as interconnector material in order to fullfil the cost requirements.

Keywords: Solid oxide fuel cells; Interconnectors; Operation

1. Physical basis for interconnector design

The interconnector is the connection element between a power plant and a single planar solid oxide fuel cell (SOFC) as used in the tests presented. The connections of an electrochemical battery are included in this definition.

All the designs of combined power plants with fuel cells can be generally described by the reversible fuel cell heat cycle [1]. Fig. 1 shows the simplified cycle close to the practical application [2]. The main design principle is the use of the fuel cell as an isothermal heat source for the Carnot cycle representing any heat cycle. This general principle is a very important aspect of the use of high-temperature fuel cells such as the SOFC for improving total plant efficiency. Calculations show a possible efficiency up to 80% for the combined cycle. A SOFC gas-turbine cycle was proposed as a possible practical implementation of the combined cycle [3].

It is important for the design of such cycles to integrate the heat exchangers into the SOFC surroundings for heating the process fluid (flue gas and steam) of the steam injected gas turbine by cooling the SOFC. A very simple way of integrating such a heat exchanger system is the use of interconnectors. But the design of the interconnectors is governed by some important factors which influence the SOFC operation.

Fig. 2 gives an overview. The material of the interconnector must be gas-tight, must show electric conductivity and sufficient high temperature stability. The surface must be chemically stable during the operation time and must have a sufficient electric conductivity. Additionally, the operation of SOFCs includes the heating and cooling process (thermal cycling) during start-up and shut-down periods. Different thermal expansions occur and can destroy the SOFC if the different interconnector materials and the interconnector design are not matched. Materials with an equivalent thermal expansion to the electrolyte material (yttria stabilized zinc oxide) must be used for the tubular SOFC and this expansion problem is solved. But if we look at the number of the requirements mentioned we see that only a few materials are suit-

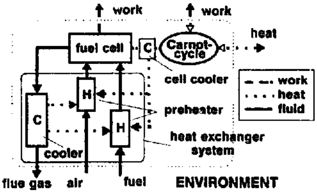

Fig. 1. Simplified fuel cell: heat cycle.

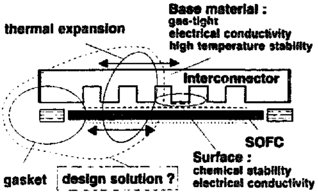

Fig. 2. Design parameters of a SOFC interconnector.

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able to be used [4–6]. It is a useful task for engineers to look for possible design solutions in order to reduce the material requirements of the interconnectors of the planar SOFC. The use of commercial materials will be an important benefit to reach the cost targets. Glass gaskets are mainly used for sealing the planar SOFC.

2. Design and testing of the interconnector

If we analyse the published proposals for interconnectors of planar SOFCs we find two major types of design (Fig. 3) [5,7–9]. The fixed planar SOFC follows the design principles of the tubular SOFC. The thermal expansion of all the materials used must be nearly the same in the range of the operation temperature. The benefit of this design is a good gas-tight sealing of the SOFC that allows cascades on the fuel flow side. The open SOFC allows more freedom in the choice of the interconnector material if different expansions can be absorbed by the contacting [7]. The unused fuel burns outside the SOFC. A combination of both designs mentioned is the free-stretching SOFC used in our test rig.

The first hot tests of our test rig showed that the ceramic material of the SOFC was not destroyed after temperature cycles in a single stack with interconnectors of the high temperature alloy HA 230. Fig. 4 shows the different thermal expansions of some high temperature alloys [10]. HA 230 was used as an available example of the typical thermal expansion characteristics of metallic alloys and not because of any requirements of long-term stability.

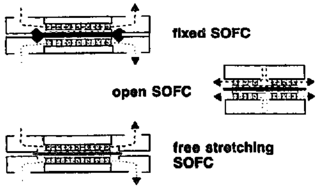

Fig. 3. Interconnectors of a planar SOFC.

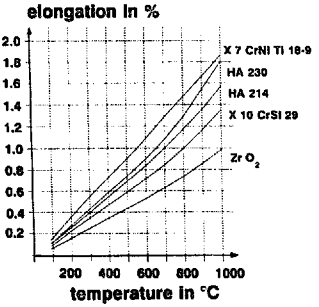

Fig. 4. Thermal expansion of different materials.

Cycling of the SOFC without mechanical damage has been achieved by a matched arrangement of the cell, the glass gaskets and the interconnectors, that allows a free stretching of the SOFC. The free-stretching SOFC seems to be an interesting option, because of the opportunity to use commercial metallic alloys instead of very specialized alloys or ceramics. We hope that this design will allow larger stacks with the option of cascades of the fuel flow too.

Any new power system has to compete with existing technology. Today we see electric efficiencies of nearly 60% for gas-fired combined cycles and of nearly 47% for coal-fired steam cycles as a result of the advanced technologies. The development of combined SOFC cycles gives the opportunity to reach efficiencies of about 20% higher than these developed power plant technologies may obtain [2,3]. Therefore, the development of the SOFC technology for power plant applications is a realistic opportunity to reduce clearly the CO_2 emission of power plants [11]. However, attractive investment costs are necessary for a commercialization of this technology. A study of a 50 MW SOFC gas turbine plant [12] indicates that the cost of this plant will be mainly influenced by the SOFC stack cost. It is easy to calculate the tolerable investment cost of a SOFC gas turbine plant if we assume that the performance of a developed SOFC gas turbine plant is as good as the performance of a combined steam and gas turbine plant and the power production cost will be equal. Fig. 5 shows the relation of the investment cost of a SOFC gas turbine plant (70% efficiency) and the investment cost of a combined steam and gas turbine plant (50% efficiency). The other data used are given in Fig. 5. The investment cost of the SOFC gas turbine plant may be 1.2 to 1.8 times as high as the cost of a combined steam and gas turbine plant depending on the yearly operation time (hours) and the specific investment cost of the combined steam and gas turbine plant (influenced by the size of the plant). This may be possible if we can realize that the specific cost of the SOFC stack are lower than 1000 DM/kW [11,13]. This figure was confirmed by others [14].

The cost of the stack depends mainly on the cost of the SOFC and of the interconnector. The aim of our progamme is the development of power plant cycles and of mechanical components related to the SOFC technology. The develop-

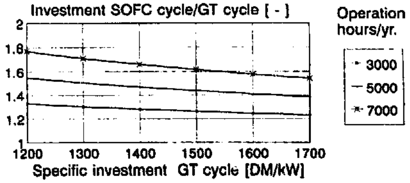

Fig. 5. Possible investment cost of a combined SOFC plant. Efficiencies: GT cycle, 50%; SOFC cycle, 70%; depreciation time, 15 years; rent, 8%; errection time, 2 years; inflation, 4%, and fuel cost, 12 DM/GJ.

ment of the interconnector is included but the development of the SOFC itself is not included. During the design phase of the test rig the interconnector was developed by the following criteria:

(i) use of a welded design applicable for mass production;

(ii) integration of the heat exchanger into the interconnector, and

(iii) possibility of changing the flow direction during SOFC operation.

Fig. 6 shows the first basic design of an application for four 100 mm × 100 mm planar SOFCs at the same voltage level [15]. A version of a single 50 mm × 50 mm SOFC stack was built and tested as a first step of this development. The design consists of five welded layers of sheet metal with a thickness of about 1 mm. The heat exchanger and the flow distribution of the interconnector is integrated into the medium layer. The medium layer is closed by the deck layers. The deck layers carry the contacting naps and are fitted with slits and borings to provide for the flow distribution in the anode and in the cathode chamber and to form the gas supply and removal pipes of the stack. The frame plates fitted with the integrated borings for the gas supply and removal surround the contacting area. Glass strips were used for sealing as mentioned above.

Fig. 7 gives an overview of the developed test rig [16]. The SOFC stack can be placed at the test table inside the electric furnace. The gas supply and removal pipes are arranged under the test table. The electrolyzer is used for the hydrogen supply. The fan is used for the supply of air. A hydrogen bottle and a central air supply (15 bar) can be used alternatively. Nitrogen from a bottle is used to flush the SOFC during start-up and shut-down.

The start-up operation and the temperature control of the furnace is computer-controlled. The control of the gas flows was manual at the beginning and then automated to avoid sharp gradients at certain variations. The main data from the tests such as the voltage and the current were recorded on-line at a PC. The recording of other data, e.g. the actual flow was manual at the beginning and automated in some cases later. The improvement of the on-line data recording and analysis is a still an on-going process. All measurements were done outside the single stack. The results show the performance of the combination of both the interconnectors and the SOFC and can be compared with the later power plant application.

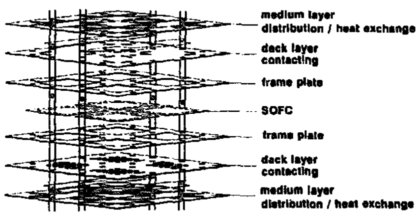

Fig. 6. Selected design of an SOFC interconnector.

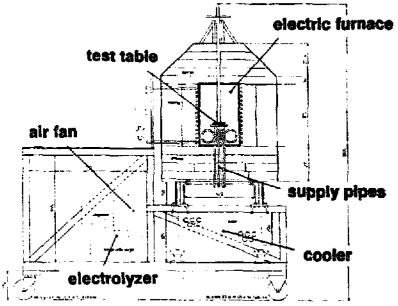

Fig. 7. Test rig.

The flow distribution inside the interconnector is mainly influenced by the shape of contacting that causes the main flow resistances. The contacting with the naps has two main benefits: the flow distribution is regular and the diffusion process within the anode and cathode chambers is less disturbed by the naps than by the channels formed by the contacting strips.

3. Results

The cycling operation of the stack is a main evaluation test for any design of SOFC interconnectors. The tests that succeeded and the tests that failed gave important information for further interconnector development. The use of a single-cell stack for this purpose has the benefit that the damage of only one SOFC during the tests is payable for low budgets and the amount of work to get the stack operative again is small. The start-up and the shut-down operation was one of the most important tests. The start-up time was usually 6 h from cold conditions. This time differs little from the start-up time of a coal-fired boiler. After an operation time of about 6 h (depending on the tests planned) the electric power of the test rig was switched off. The next start-up from cold conditions began usually about 48 h because of the slow

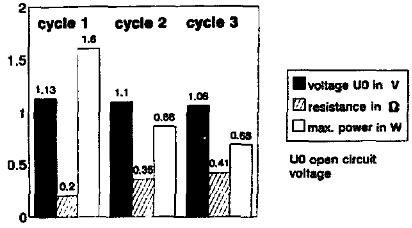

Fig. 8. Results of a single SOFC stack cycling.

cooling of the furnace to ambient temperature. All cycles were performed with cold starts.

Fig. 8 shows the results of a cycling test with three cycles [10]. The influence of cycling on the open-circuit voltage of the stack is about 3% per cycle (from 1.13 to 1.10 V and to 1.06 V). The increase in internal resistance of the stack was another observed result related to stack cycling. The first cycle increased the internal resistance from 0.20 to 0.35 Ω (75%) and the second cycle to 0.41 Ω (17% related to second cycle). The power output decreased from 1.60 to 0.86 W (54%) and finally to 0.68 W (79% related to the second cycle). Overvoltage tests were realized at the end of the third cycle and the cell was finally destroyed by overheating. A comparison with other tests gives an indication for this evident increase in internal resistance. Local ruptures at the contacting area of the electrode layers at the anode and the cathode side have been detected. The design of the naps has to be improved for future tests in order to reduce the internal resistance and to improve the cycling characteristics.

The welded design showed a good performance. Only a few of the cycling tests resulted in a fracture of the SOFC caused by mounting faults. During other tests the anode atmosphere was not controlled well during the critical cooling phase and the anode was destroyed.

4. Conclusions

These first tests indicate that a welded design of interconnectors consisting of high temperature alloys allows a cycling of a single SOFC stack. It seems to be a benefit of the planar SOFC that a design solution of the thermal expansion problems can be indicated. These results confirm the already published results of the open SOFC [7,17]. Contacting by naps seems to be an adequate solution. The integration of a heat exchanger in the interconnector seems to be possible. A simplification for mass production and a weight reduction are necessary to reduce the production cost of the interconnector. The choice of material including the use of coatings must be strictly orientated to the cost targets of < 1000 DM/kW.

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