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Environmental analysis of solid oxide fuel cells

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Abstract

Nowadays, for a new technology to be successfully introduced, it should compete not only in terms of economy, but also in terms of ecology. Therefore, end-of-pipe treatments are no longer sufficient, but precautionary environmental protection is also necessary. The aim of the present work is an environmental analysis of the solid oxide fuel cell (SOFC) technology using the 'Environmental Precaution Study'. Constituent materials, energy and emission flows are determined and evaluated throughout the entire life cycle. Cradle to grave considerations embrace the production of raw materials and technical equipment, respectively, operation and dismantling. A reference SOFC cell of the planar cell type, based on the current fuel cell programme of the Research Centre Jülich, has been compared with a conventional technology in the form of a 10 MW gas turbine. The latter has been chosen as the competitive conventional technology, because the power output is similar to the expected SOFC power output and the use of the same fuel, natural gas, facilitates the comparison.

Keywords: Solid oxide fuel cells; Environment

1. Introduction

In many countries environmental issues on both a global and a national scale have created an increasing awareness of the need for an active environmental protection policy. Industrialized countries have a particular responsibility for environmental protection, because they have created the potential of full exploitation of the earth's resources. Advantages in science and technology have increased prosperity levels but at the same time allow a more intensive use of natural resources.

The discussion on environmental protection is no longer limited to modifications of the present technology, but has been directed to precautionary measures. Yet, an international standard unit for environmental relevance does not exist. Therefore, comparison of results from different precautionary studies is therefore not possible in most cases. To use the benefit of one technique against an other, it is necessary to consider them from the same point of view and under the same conditions. The entire life cycle including production, operation and dismantling has to be determined and evaluated. The 'Environmental Precaution Study', developed in Germany, reconsiders these points by collection of relevant input and output data (material, energy and emission), data of persistence and accumulation, and levels of toxicity over the entire life cycle. A comprehensive compilation of these data allows a comparison of different technologies. Furthermore, the 'Environmental Precaution Study' enables researchers to prevent faults in early stages of development of new technologies. In this way, modification during initial research can also yield an economical advantage.

In this paper, the SOFC technology, still in a developing stage, is compared with a conventional technology. The gas turbine is chosen to represent power producing systems. The main reasons are the similar size of typical power output (1–10 MW) and the use of the same fuel, natural gas, which reduces the adaptation expense during comparison.

2. Production and operation of SOFCs

The application of SOFC units in the future power production will involve more processes than the simple operation of the unit. Fig. 1 gives a survey of production and operation processes involved in an SOFC application. The process chain of the first level includes only processes during operation of the unit. At the second level upstream processes are represented. For SOFC power production these are the production of the fuel cell unit itself and the production of H_2 or CH_4 converters. This work includes only the fuel cell production processes, because, as mentioned above, the gas turbine uses the same fuel.

3. Production processes of SOFCs

At the beginning of the collection of data, a reference SOFC cell has been defined, based on the current fuel cell

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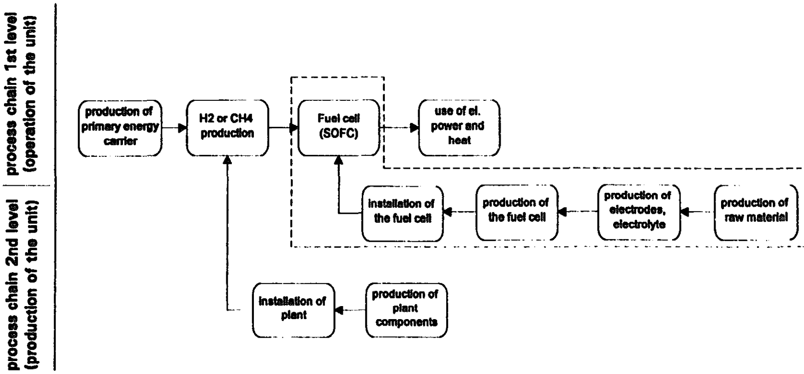

Fig. 1. Structure of production and operation steps of an SOFC.

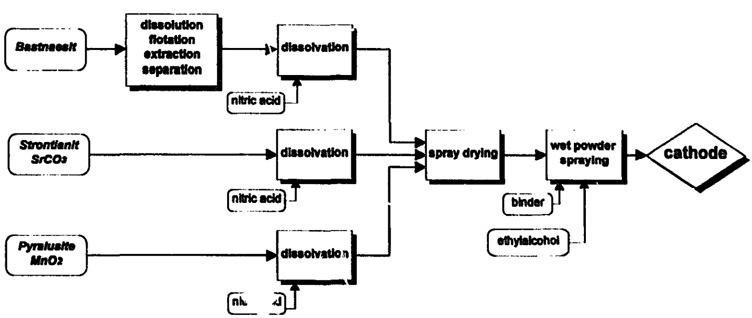

Fig. 2. Cathode production line.

programme of the Research Centre Jülich (KFA). The SOFC developed at that time was a planar fuel cell, where the components were processed in different production lines.

The carrier sheet is the electrolyte, produced from yttrium stabilised zirconium oxide by tape casting [1]. The electrodes, the LaSrMn–perovskite cathode and the NiO cermet anode, are applied onto the electrolyte by a wet powder spraying production process (WPS) [2]; two types of interconnectors, the metallic (Cr, Fe, Y_2O_3) and the ceramic (LaSrCrO) were also examined [3]. The metallic interconnector is formed using hot isostatic pressure (HIP); the ceramic one obtains its shape through calcination of the powder, followed by a pressure process and mechanical treatment.

For all cell components, the production line, from the production of raw material through the production of the powders to the production of the component itself, has been set up. Fig. 2 shows the production line for the cathode.

Parent materials are bastneasite, strontianite, $SrCo_3$, and pyralusite, MnO_2. After mining, the ore is dissolved in nitric acid to separate the materials and to obtain the nitrates of the substances [4]. The parent powder for the production of the cathode sheet is prepared by WPS. Along this production line, the amounts of the materials necessary for the production of one cathode layer are evaluated stoichiometrically. Knowing the power output of a single cell it is possible to calculate the material input per kW, see Table 1. Considering a typical 50% scrap rate for ceramic production processes, the amounts must be doubled. Similar calculations exist also for the other materials used.

Table 1
Nitrates required for the cathode production of a 1 kW plant

Substance	Amount (kg/kW)
$La(NO_3)_3$	8.6×10^{-4}
$Sr(NO_3)_2$	0.8×10^{-4}
$Mn(NO_3)_2$	5.9×10^{-4}

4. Operation

Data for operation cannot been given at the present early stage of development. Nevertheless, the expected high efficiency of the SOFCs allows the prediction that the emission per electricity output unit will be less high than those of conventional technologies.

The operation of PAFCs have already shown a considerable decrease in emission compared with technologies used today [5]. Yet, the results obtained from PAFC measurements can only serve as a pointer. At high operation temperatures, such as 1000 °C for SOFCs, the formation of NO_x from N_2 and atomic oxygen increases. However, today the production of NO_x is neglected in most of the models that try to simulate SOFC operation.

Serious validation of the result from simulation models can only be given by results obtained in field tests done in the future.

5. Dismantling

Even after successful operation, dismantling of the unit remains an important part of the entire cycle life. Prevention and reduction and re-use of waste products are key elements in the material management, that has to be planned before introducing a new technology. For SOFC technology, little is known about handling waste products; some problems, however, are already known.

1. Fuel cells are connected in series. In the present concept, a malfunction of a single cell leads to the replacement of the whole stack.
2. Ceramic materials possess a high sensitivity to stress. During disconnection of a stack, this susceptibility can lead to individual cells developing cracks. The process of separating cells is therefore complicated.
3. Disconnection of a cell into its components is impossible due to production method.
4. Substances can be only be regained during powder production. The ceramic powders of the cathode and interconnector can be integrated into the parent materials.
5. No process to dissolve yttrium from YSZ are known. In order to decrease the amount of YSZ waste, the use of the latter as an inert material has been suggested in other sectors of industry.

The increasing interest in waste management will yield a higher demand for research in the field of dismantling SOFC.

6. The competing conventional technology

In future fuel cells will compete still developing technologies being already on the market, such as gas or steam turbines, or alternative energy generation technologies such as solar and wind energy. However, market forces will decide where fuel cells will be most applicable and with which technology they will compete in different market segments. In the smaller size range (1 kW–1 MW) the presently used technology are reciprocating engines and gas motors. Gas turbines are used for power generation in the 1 MW–10 MW range. For the production of several hundreds of MW combined steam and gas turbine cycles with already high efficiency of 58% [6] are in severe competition.

To evaluate the benefits or disadvantages of SOFC technology the collected data must be compared with those of

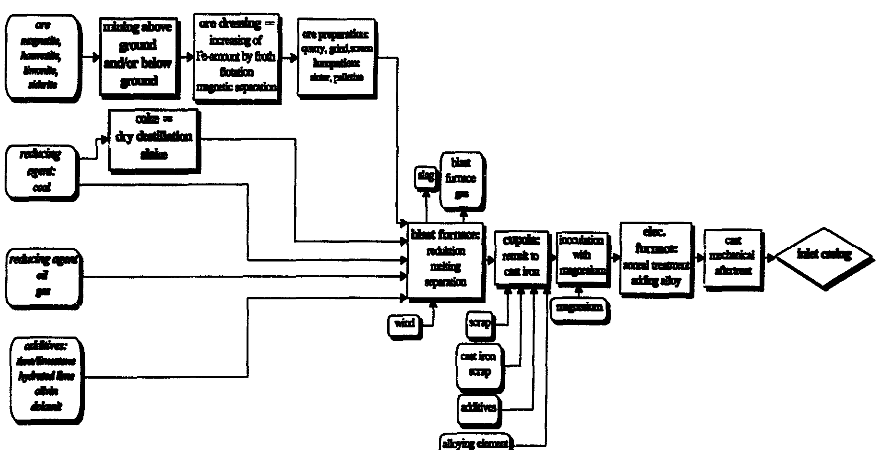

Fig. 3. Production line for the inlet casing.

Table 2
Material balance for the production of 1 tonne pig iron [7]

a) *Addition*	
Ore and additives (kg)	1650
Coke (kg)	450–500
Wind (kg)	1500–2500
(m^3)	1200
b) *Removal*	
Pig iron (kg)	1000
Slag (kg)	310
Blast furnace and dust (kg)	3000–3500

conventional technologies. In this paper, a gas turbine has been chosen as the competing technology, because a market penetration for SOFC in small units of the range 1–10 MW is most likely. A second reason is the use of the same fuel, natural gas, which facilitates the comparison of both technologies.

The gas turbine chosen has an electrical power output of 9435 kW and has been put onto the market recently. This means that this technology is of a modern standard. The heavy-duty machine has 23 different components consisting of 16 different materials. Fig. 3 shows the production line for an air inlet casing produced from spherical graphite cast iron.

The entire material balance for the gas turbine has not yet been completed. However, Table 2 [7] shows the material balance for the production of 1 tonne of pig iron. This Table shows the data for the basic production step of most steel types; different data for alloying, casting and shaping of the specific products should be added in order to give a complete data balance.

7. Conclusion

The ecological evaluation of a developing technology is obtained by comparison with already common technologies. The SOFC technology is still in an early stage of development. The prospected power output range for high temperature fuel cells is 1 MW–10 MW, with market segments where gas turbines produce the electrical power today. Therefore, the entire life cycles of both technologies have to be evaluated and compared. At the current stage, data for operation and dismantling of SOFCs are not yet available. Results from field tests and data from other fuel cell types can serve as reference. The collection of the gas turbine data has to be completed in order to determine and evaluate the entire life cycle. Benefits and disadvantages of one or other technology can be pointed out be a direct comparison of both technologies. Conclusions from this study enables changes in the development during the initial stage.

References

[1] H. Jansen, Hertsellungsverfahren und Eigenschaften von Komponenten für die Hochtemperaturbrennstoffzelle, *Thesis*, Technical University Aachen, 1993.
[2] A. Ruder, H.P. Buchkremer, H. Jansen, W. Mallener and D. Stöver, *Surf. Coat. Technol.*, *53* (1992) 71–74.
[3] Z. Li and D. Stöver, *Internal paper*, Research Centre Jülich, 1993.
[4] *Ullmann's Encyclopaedia of Industrial Chemistry*, Verlag Chemie, Weinheim, Germany, 1993.
[5] H. Nymoen, *J. Power Sources*, *49* (1994) 63–76.
[6] Anonymous, New Frontiers in gas turbine technology, *Diesel and Gas Turbine Worldwide*, (June) (95) 58–73.
[7] A.K. Bolbrinker, *Stahl und Eisen*, 1989.