Second Nordic Minisymposium on Carbon Dioxide Capture and Storage, Göteborg, October 26, 2001.
available at http://www.entek.chalmers.se/~anly/symp/symp2001.html

Solid Oxide Fuel Cell Power Plants with Integrated CO_2 capture

Asle Lygre, Matteo Cé, Arild Vik and Jan Byrknes, Prototech AS, P.O.Box 6034 Postterminalen, N-5892 Bergen, Norway. Tel + 47 55 57 41 10, firmapost@prototech.no.

Introduction

The power generation sector is a major source of CO_2 emissions. The overall efficiency of a power generation plant is significantly reduced if CO_2 is captured from the flue gas. Technologies available or being considered for CO_2 capture are:

- Adsorption of the gas by use of molecular sieves
- Physical and chemical absorption
- Cryogenic processes
- Membranes

of which absorption processes are the most likely candidate to gain current wide spread use.

In a power plant based on planar solid oxide fuel cells (SOFC) the air and fuel streams are kept separated through the energy conversion process, see Fig.1. Accordingly, the CO_2 concentration in the fuel exhaust is very high, facilitating an energy efficient up-concentration of the fuel exhaust to consist of CO_2 and water, only.

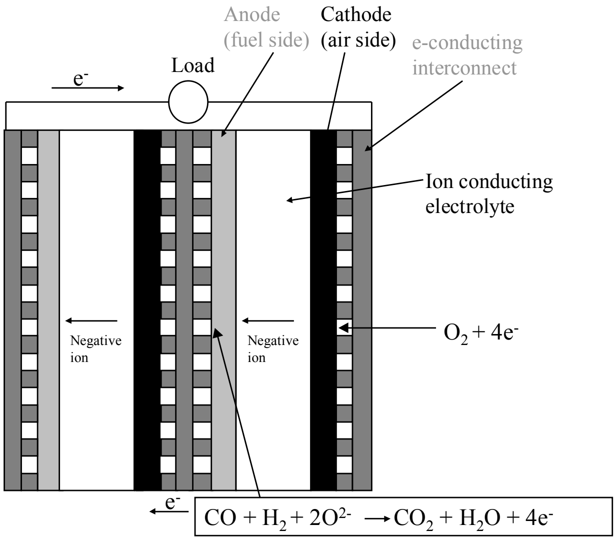

Fig.1. Planar SOFC STACK operating principle. Oxygen "diffuses" from the air side (cathode) and reacts with the fuel, H_2 and CO, produced by reforming natural gas. The air exhaust is hot oxygen depleted-air, and the fuel exhaust consists of steam, CO_2 and unburned fuel whose respective concentrations depend on the inlet fuel used and on the fuel utilization. Note, the STACK elements are not drawn to scale.

The rest fuel not utilized in the STACK, will be partly recycled and partly burned in the *afterburner* which will be fed with pure oxygen in order to produce exhaust composed of water and CO_2, only. A more detailed description of fuel cells can be found in i.e. [1].

In this paper various SOFC power plant concepts will be briefly analyzed with emphasis on energy efficient CO_2 capture. The work was carried out as a part of a collaborative project between the Institute for Energy Research (IFE), Christian Michelsen Research and Prototech with the objective to develop technology for production of electricity and hydrogen from natural gas with integrated CO_2 capture (The Future Energy Plants Project).

SOFC technology at Prototech

A number of groups in e.g. US, Europe and Australia are working on development of high temperature SOFC technology [1]. Prototech has been engaged for more than 10 years in development, system design and testing of planar SOFC power generation systems. In 1997 Prototech in collaboration with Statoil, developed, designed & manufactured a "10kW class system", including all major balance of plant components, which was successfully demonstrated on natural gas for a period of 3 months (Fig.2).

At the moment Prototech participates in the on-going PROCON EU-funded SOFC-project and is a partner in the Future Energy Plant project, see above.

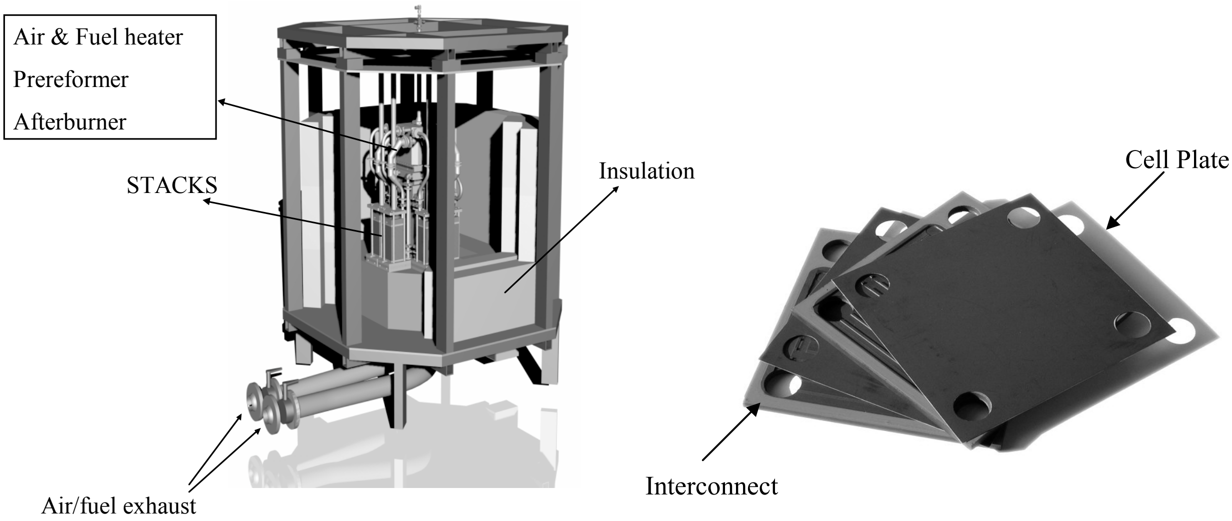

Fig.2. The Mjøllner 10 kW SOFC system. The pilot plant with STACKS and integrated balance of plant components (left). Cell plates and interconnects (right).

SOFC power plants with CO_2 capture

A basic SOFC power plant, excluding the power electronics, is mainly composed by 5 sub-systems, see Fig.3:

- Air preheater
- Prereformer
- SOFC STACKS
- Afterburner
- Water heat exchanger

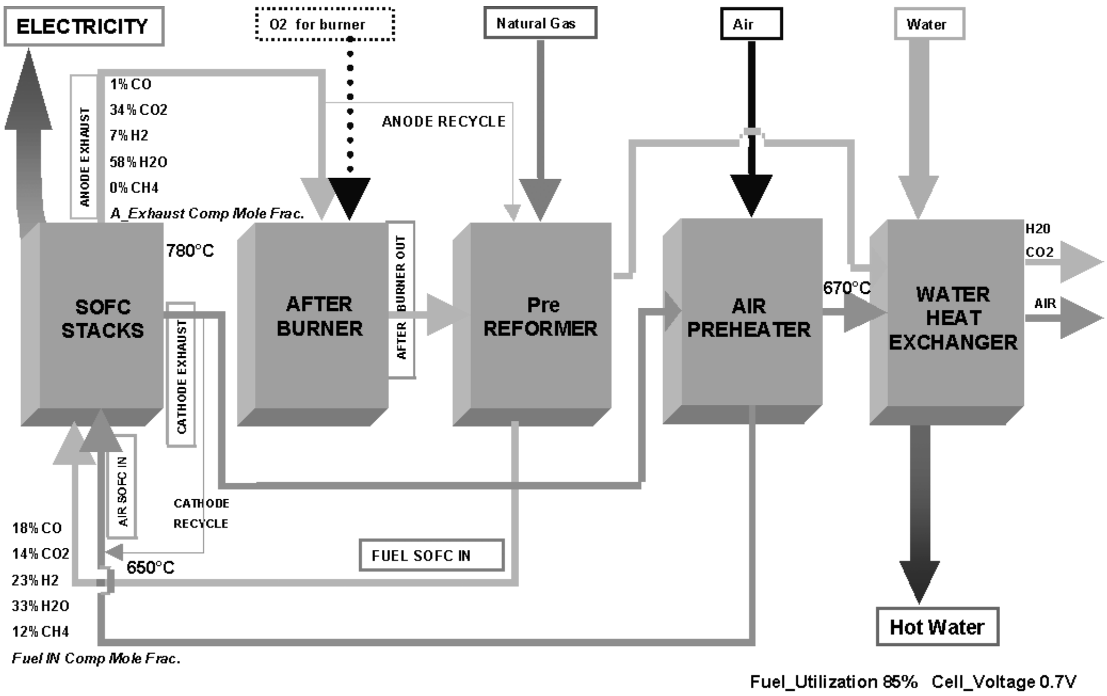

Fig.3: Basic SOFC Power Plant - combined heat & power

The operating temperature of the system displayed in Fig.3 is around 800°C, i.e. a low temperature SOFC. Recycling the cathode exhaust reduces the inlet airflow. Accordingly, less pre-heating is required. Recycling the anode exhaust increases the fuel utilization and makes it possible to avoid the installation of a dedicated steamer for the reforming process. Thus, the efficiency of the plant is increased. The heat produced by the SOFC is used to preheat the inlet air while the heat produced from the afterburner is used for the prereforming. The residual heat may be used for the production of hot water. Alternatively, the waste heat can be effectively utilized by integrating the SOFC plant with other endothermic processes. A cell voltage of 0.7V and a STACK fuel utilization of 85% are considered as being realistic for this type of power plant, see below.

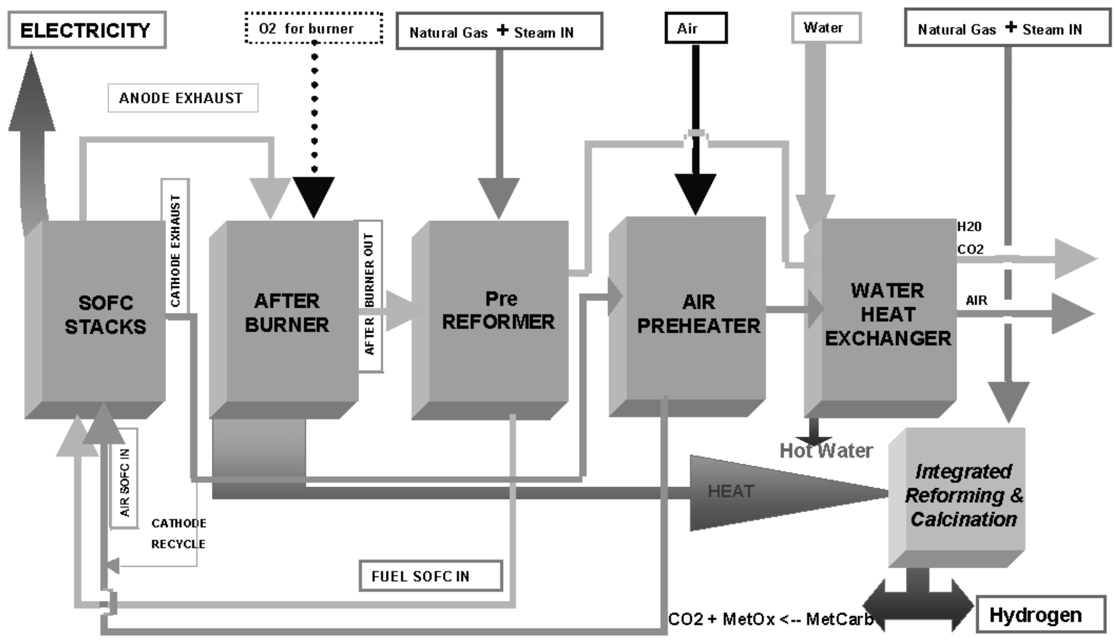

Fig.4. SOFC Power Plant – combined hydrogen & power production

Fig.4 displays the SOFC power plant concept where waste heat produced by the SOFC, is used to produce hydrogen. The plant also comprises a cyclic process where MetalOxide is used to capture CO_2 in the form of MetalCarbonate with a subsequent desorption of CO_2 and reuse of the oxide. This process is being developed by IFE.

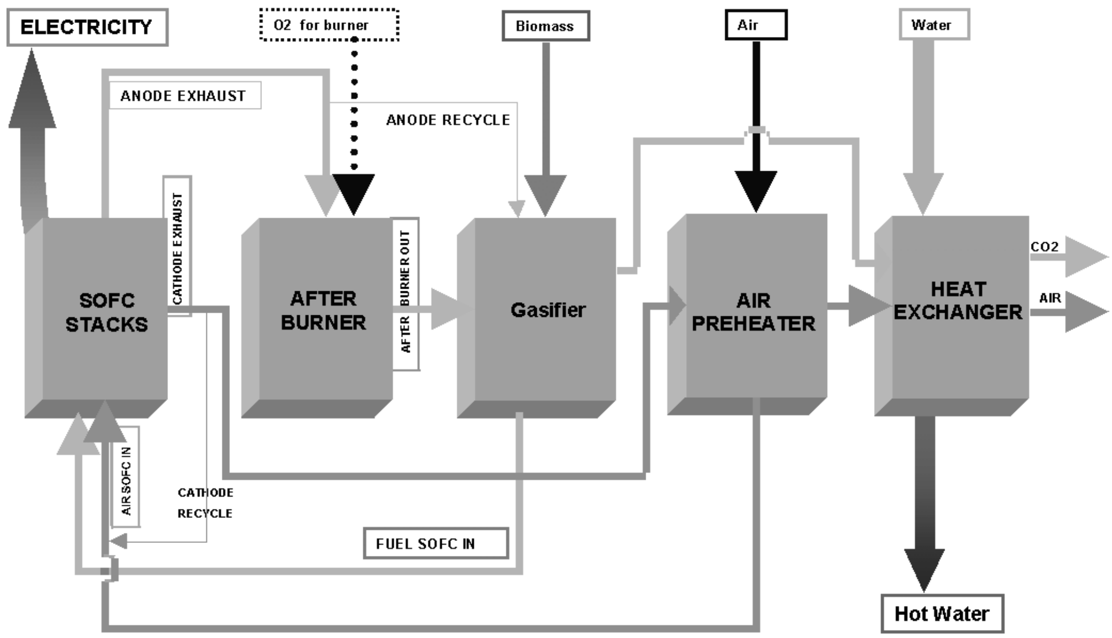

Fig.5. SOFC power plant - power production from biomass

Fig. 5 shows a SOFC power plant concept where waste heat produced by the SOFC is used to gasify biomass, e.g. char coal. In this concept the prereformer unit is replaced by a gasifier. The process is based on a patented process comprising a gasification cycle utilizing CO_2 (from anode recycle) as a gasifying agent and feeding the SOFC with a CO-rich gas.

Energy balances

For the three concepts described above, energy balances have been calculated based on system simulations including CO_2 removal. The energy consumption for CO_2 capture is defined as the required energy for pumping pure oxygen into the afterburner as well as the necessary energy to compress the CO_2. The oxygen pump is based on proprietary technology developed by Prototech. The performances of the three SOFC based power plants have been compared to a combined gas turbine steam turbine power plant with three different CO_2 removal processes, see [2].

For the SOFC power plant the calculated efficiencies are based on the lower heating value (LHV) as defined below.

- $$El\_eff(DC) = \frac{P_{el\_DC}}{P_{Fuel\_IN\_SYSTEM}} \quad (1)$$
- $$H_2\_eff = \frac{P_{H_2\_OUT}}{P_{Fuel\_IN\_SYSTEM}} \quad (2)$$

where $P_{Fuel\_IN\_SYSTEM}$ is the power (LHV based) of the NET fuel entering the system/s; *El_eff(DC)* is the gross fuel-to-DC-electricity efficiency and P_{el_DC} is the electrical DC-power output from the SOFC STACKS; *H_2_eff* is the fuel-to-hydrogen efficiency and P_{H2_OUT} is the power (LHV based) of the produced hydrogen/s.

In the simulations an *El_eff (DC)* of 61% has been estimated as explained in the following. *El_eff (DC)* is determined by the fuel utilization (FU) and the cell voltage (CV) according to [1]

$$El\_eff(DC) = \frac{\dfrac{Equivalence\_of\_Electrons}{mole_{fuel\_IN\_STACK}} * F * CV * FU * \dfrac{mole_{fuel\_IN\_STACK}}{s}}{P_{Fuel\_IN\_SYSTEM}} \quad (3)$$

where F is Faraday's constant, CV the Cell Voltage and FU the Fuel Utilization. Based on laboratory experiments FU can be set to 0.85 and CV to 0.7V. We assume for simplicity that the fuel flow through the STACK, including re-circulation of anode exhaust, amounts to $1.0\frac{mole_{CH4}}{s}$ (LHV_$CH_4 \cong$ 802 kJ/mole [3]) of which 85% is used leaving $0.15\frac{mole_{CH4}}{s}$ in the anode exhaust upstream of the re-circulation off-take. The re-circulation rate is set to 40% equivalent to a power of 48.12 kW (0.4 x 0.15 mole/s x 802 kJ/mole). The net fuel input rate thus amounts to 0.94 mole/s equivalent to 753.88 kW; each mole of CH_4 will react with 2 moles of O_2 and each mole of O_2 will "carry" 4 Equivalence of Electrons (EE) [1,3]. Inserting in Eq. (3) above yields

$$El\_eff(DC) = \frac{8\left[\dfrac{EE}{mole_{CH4\_IN\_STACK}}\right] * 96487\left[\dfrac{Coulombs}{EE}\right] * 0.7[V] * 0.85 * 1.0\left[\dfrac{mole_{fuel\_IN\_STACK}}{s}\right] * \dfrac{1}{1000}\left[\dfrac{kW}{W}\right]}{753.88[kW]} \cong 60.9\% \quad (3a)$$

A flow diagram of the STACK showing the re-circulation and the process streams is displayed in Fig.6 below.

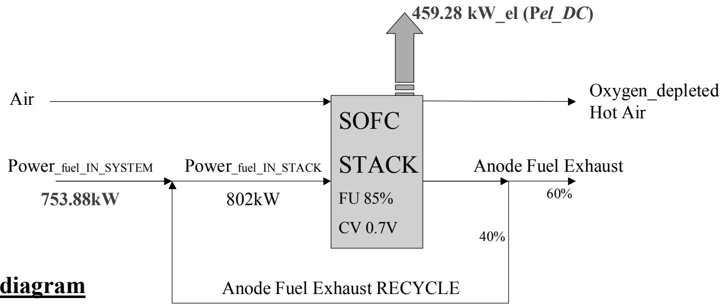

Fig.6. STACK flow diagram

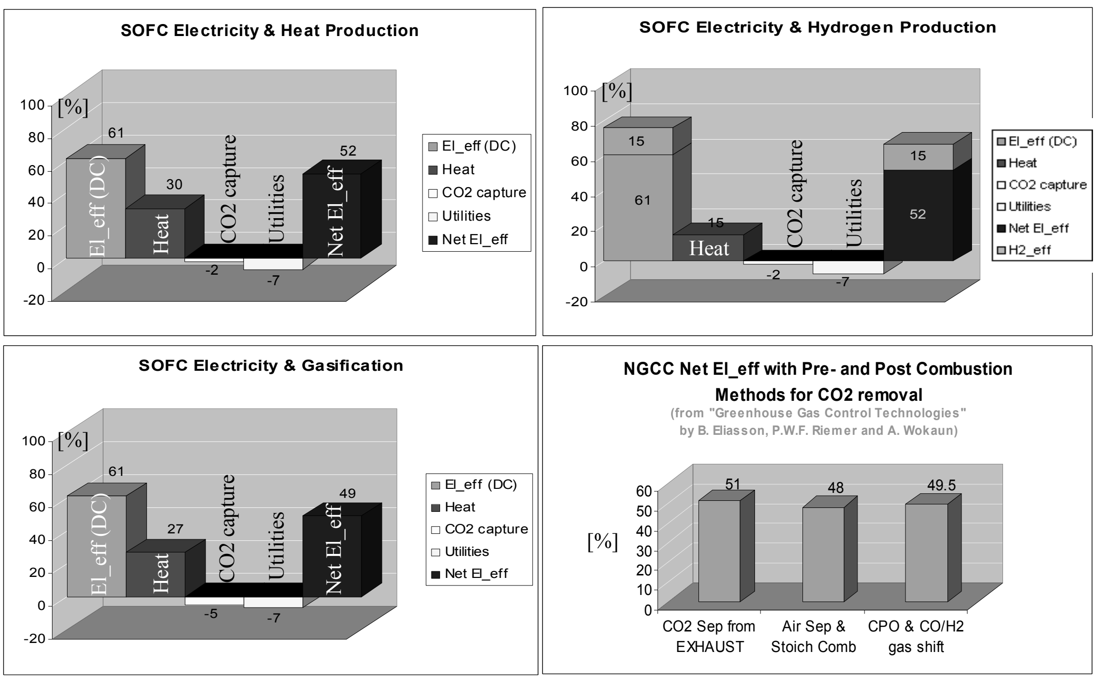

Fig.7. Energy balances for SOFC based power plants including CO_2 capture

Conclusions

Planar SOFC based power plants can offer high electrical efficiencies in combination with energy efficient CO_2 capture, mainly due to the fact that the fuel and air streams are kept separated in the fuel cell.

System analyses of power plants based on SOFC with integrated CO_2 capture show significantly higher overall efficiencies than gas turbine based power plants with CO_2 capture.

The base case SOFC power plant with CO_2 capture, producing combined heat and power, has a net electrical efficiency of 52%. If the waste heat is used in a combined steam cycle, the net electrical efficiency will be larger than 60%.

Combining hydrogen production from natural gas with a natural gas fed SOFC power plant with integrated CO_2 capture, gives an overall efficiency of 67% which can be further increased.

Integrating a biomass gasifier with a SOFC power plant and feeding the fuel cells with CO-rich gas makes it possible to capture the neutral CO_2 from biomass and still maintain a net electrical efficiency of around 50%.

Based on the potential of SOFC power plants, demonstration plants with integrated CO_2 capture should now be designed and built both in order to obtain operating experience and take one step further towards commercialization**.**

It is important to keep in mind that the SOFC is not a mature technology as opposed to i.e. gas turbines. Thus, the potential still exists to further increase the energy efficiencies beyond the levels discussed in this paper.

Acknowledgements

This paper was prepared with support from the KLIMATEK-program operated by the Norwegian Research Council.

References

[1] Hirschenofer J.H., Stauffer D.B., Engelman R.R. and Klett M.G.. **Fuel Cell Handbook**. Fourth edition, November 1998, Parsons Corporation, Reading, PA 19607, US. DOE/FETC-99/1076.

[2] Olav Bolland and Henriette Undrum. **Removal of CO_2 from Gas Turbine Power Plants: Evaluation of Pre- and Postcombustion Methods**; Ref. Balduer Eliasson, Pierce Riemer, Alexander Wokaun, 1999, Proceedings of the 4th International Conference on Greenhouse Gas Control Technologies, 30 August – 2 September 1998, Interlaken, Switzerland. First Edition, 1999, PERGAMON.

[3] Ulf G. Bossel. **Final Report on SOFC Data - FACTS & FIGURES**. International Energy Agency SOFC Task Report, Berne, April 1992.