Solid Oxide Fuel Cell Power Plants with Integrated CO₂ 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 CO₂ emissions. The overall efficiency of a power generation plant is significantly reduced if CO₂ is captured from the flue gas. Technologies available or being considered for CO₂ 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 CO₂ concentration in the fuel exhaust is very high, facilitating an energy efficient up-concentration of the fuel exhaust to consist of CO₂ and water, only.

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 CO₂, 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ in the form of MetalCarbonate with a subsequent desorption of CO₂ 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 CO₂ (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 CO₂ removal. The energy consumption for CO₂ capture is defined as the required energy for pumping pure oxygen into the afterburner as well as the necessary energy to compress the CO₂. 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 CO₂ removal processes, see [2].
For the SOFC power plant the calculated efficiencies are based on the lower heating value (LHV) as defined below.

\[ E_{\text{el}}(\text{DC}) = \frac{P_{\text{el, DC}}}{P_{\text{Fuel IN SYSTEM}}} \quad (1) \]

\[ H_{2\text{-eff}} = \frac{P_{\text{H2 OUT}}}{P_{\text{Fuel IN SYSTEM}}} \quad (2) \]

where \( P_{\text{Fuel IN SYSTEM}} \) is the power (LHV based) of the NET fuel entering the system/s; \( E_{\text{el}}(\text{DC}) \) is the gross fuel-to-DC-electricity efficiency and \( P_{\text{el, DC}} \) is the electrical DC-power output from the SOFC STACKS; \( H_{2\text{-eff}} \) is the fuel-to-hydrogen efficiency and \( P_{\text{H2 OUT}} \) is the power (LHV based) of the produced hydrogen/s.

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

\[ E_{\text{el}}(\text{DC}) = \frac{\text{Equivalents of Electrons}}{\text{mole fuel in STACK}} \times F \times CV \times FU \times \text{mole fuel in STACK} \times \frac{1}{s} \times \frac{\text{1000 kW}}{\text{W}} \approx 60.9\% \]

(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 \( 1.0 \text{ mole CH}_4 \) \((\text{LHV}_{\text{CH}_4} = 802\text{ kJ/mole}[3])\) of which 85\% is used leaving 0.15 \text{ mole CH}_4 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 \((0.4 \times 0.15 \text{ mole/s} \times 802\text{ kJ/mole})\). The net fuel input rate thus amounts to 0.94 mole/s equivalent to 753.88 kW; each mole of \text{CH}_4 will react with 2 moles of \text{O}_2 and each mole of \text{O}_2 will “carry” 4 Equivalence of Electrons (EE) [1,3]. Inserting in Eq. (3) above yields

\[ E_{\text{el}}(\text{DC}) = \left( \frac{\text{EE}}{\text{mole CH}_4 \text{ in STACK}} \times 96487 \times \text{Coulombs} \times \frac{\text{EE}}{\text{mole CH}_4 \text{ in STACK}} \times 0.7 \times 0.85 \times 1.0 \times \frac{\text{mole fuel in STACK}}{s} \times \frac{1}{1000} \frac{\text{kw}}{\text{W}} \right) \]

\[ \approx 60.9\% \]

(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. 6. STACK flow diagram](image)

Fig. 7. Energy balances for SOFC based power plants including CO₂ capture

![Fig. 7. Energy balances for SOFC based power plants including CO₂ capture](image)
Conclusions
Planar SOFC based power plants can offer high electrical efficiencies in combination with energy efficient CO₂ 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 CO₂ capture show significantly higher overall efficiencies than gas turbine based power plants with CO₂ capture.

The base case SOFC power plant with CO₂ 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 CO₂ 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 CO₂ from biomass and still maintain a net electrical efficiency of around 50%.

Based on the potential of SOFC power plants, demonstration plants with integrated CO₂ 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
