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# Gas separation membranes for zero-emission fossil power plants: MEM-BRAIN

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ABSTRACT

The objective of the "MEM-BRAIN" project is the development and integration of ceramic and polymeric gas separation membranes for zero-emission fossil power plants. This will be achieved using membranes with a high permeability and selectivity for either $CO_2$, $O_2$ or $H_2$, for the three $CO_2$ capture process routes in power plants, thus enabling $CO_2$ to be captured with high-purity in a readily condensable form.

For the pre-combustion process, we have developed ceramic microporous membranes that operate at intermediate temperatures (≤400 °C) for $H_2/CO_2$ separation. For the oxyfuel process, we have developed dense ceramic mixed oxygen ionic-electronic conducting membranes that operate at 800–1000 °C for $O_2/N_2$ separation. The perovskite-type oxide $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF5582) was taken as the reference material for this application. For the post-combustion process, polymeric and organic/inorganic hybrid membranes have been developed for $CO_2/N_2$ separation at temperatures up to 200 °C.

In addition to the development of membranes, we consider the integration of the membranes into power plants by modelling and optimization. Finally, specific technical, economic and environmental properties of $CO_2$ capture as a component in a CCS process chain are assessed, analysing the energy supply system as a whole.



## 1. Introduction

$CO_2$ is one of the greenhouse gases that contributes significantly to global climate warming. Therefore, the reduction or elimination of $CO_2$ emissions from power plants fuelled by coal or gas is a major target in the current socio-economic, environmental and political discussion. Scenarios about the future global energy requirements forecast an increasing demand for electricity, with 44% of power plants using coal as fuel in 2030 [1]. Today, power plants account for more than 40% of global anthropogenic $CO_2$ emissions [1]; they are by far the biggest point sources of $CO_2$ production and are therefore the main focus of $CO_2$ capture and storage technologies (CCS) [2]. Current energy scenarios of the International Energy Agency (IEA) show an increasing importance of CCS technology within global $CO_2$ mitigation strategies [3]. For several years, the development, improvement and adaptation of CCS technologies have received considerable attention [2]. The technical maturity of specific CCS components varies greatly. Some technologies are extensively deployed in mature markets, primarily in the oil and gas industry. For electricity production, most CCS components are still in the research, development or demonstration phase. The major problems associated with this technology are a sizable reduction in efficiency connected with an increase in power generation costs. Capture technologies using solvents face additional environmental problems due to degradation of solvents. No experience with capture facilities at power plant scale exists. However, existing demo-plants lead to the conclusion that a scale-up to modern power plant sizes will give rise to huge, additional capture plants.

One option to overcome all of these challenges is the development and improvement of membranes for gas separation. However, there are several technical hurdles which have to be overcome first [4,5]. The key scientific and technological challenges associated with membrane systems are ensuring high permeability, specific selectivity and long-term stability up to 100,000 h. The use of membrane technology is expected to cause significantly lower efficiency losses compared to conventional separation technologies. Membranes that are already used for gas separation in other fields (e.g. the chemical industry) are still far from suitable for large-scale industrial applications, as necessary in power production. Strategies for novel membranes bring materials science and technology into the main focus of research and technology development. Examples include functional layers and porous structures in the

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nanometre range, as well as the development of mixed-conducting oxides by means of theoretical materials design approaches and the design of components under operating conditions based on their physico-chemical and mechanical properties. The optimized integration of membrane systems into power plants, as well as the analysis of the entire system, encourages these efforts.

To address this mission, the integrated "MEM-BRAIN" project was started in October 2007 as part of the Alliance Programme of the German Helmholtz Association (HGF). The principle advantage of the project is the parallel, networked (iterative) development of membrane materials by (i) design of components and equipment, (ii) integration into power plants and the related process engineering, and (iii) energy systems analysis.

The Helmholtz Alliance "MEM-BRAIN" consists of 12 research organizations: Forschungszentrum Jülich (FZJ, D), GKSS-Forschungszentrum Geesthacht (GKSS, D), DESY/HASYLAB (D), Helmholtz Zentrum Berlin (HZB, D) and Ernst Ruska-Centre (ER-C, D), Hermsdorf Institute of Technical Ceramics (HITK, D), Flemish Institute for Technological Research (VITO, B), Consejo Superior de Investigationes Cientificas (CSIC, E), and the universities of Aachen (RWTH, D), Bochum (RUB, D), Karlsruhe (KIT, D), and Twente (UT, NL). Five industrial partners ensure that the results are applied in an industrial context: EnBW (D), GMT (D), Plansee SE (A), Shell (NL), and Siemens (D). The project is meeting a long-term scientific and technological challenge with a time horizon for significant commercialization after 2020.

## 2. The four research topics of MEM-BRAIN

A breakdown of the membrane research targets by MEM-BRAIN programme is displayed in Fig. 1. It can be seen that membranes must be engineered to suit different gas streams as listed below:

- post-combustion ($CO_2/N_2$ separation),
- pre-combustion ($H_2/CO_2$ separation) and
- oxyfuel combustion ($O_2/N_2$ separation) (Fig. 1).

To address the needs of the target research processes in Fig. 1, it is important to focus on membranes that can be designed for each specific application. Bearing this in mind, full consideration has been given to the following membranes:

- Polymeric membranes working at temperatures of up to 200 °C are candidates for pre-combustion and in particular post-combustion processes.

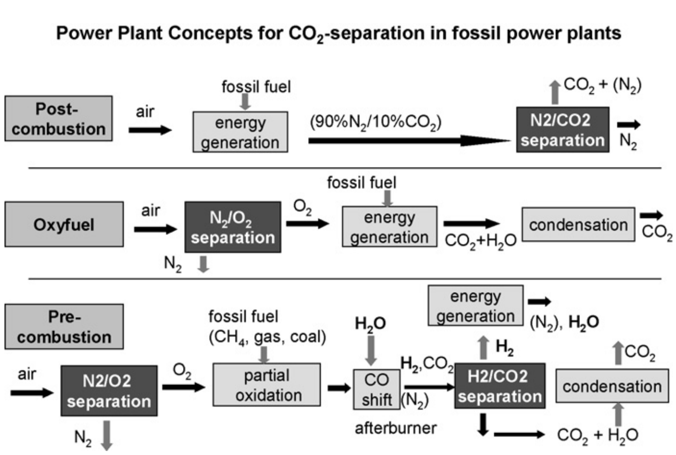


**Fig. 1.** The three $CO_2$ capture concepts.

- Microporous ceramic membranes operating at temperatures of up to 400 °C can be used for pre-combustion and possibly for post-combustion capture.
- Dense ceramic membranes are necessary for oxyfuel processes working at temperatures between 800 and 1000 °C (mixed ionic-electronic conductors, MIEC) and are possible candidates for pre-combustion operation at temperatures above 600 °C (mixed proton-electronic conductors).

To address the described challenges, the work of the Alliance has been structured into four research topics. The technical basis is provided by two of the topics in the field of materials science, one developing ceramic membranes, and the other developing polymeric membranes. The main scientific challenge is the development and manufacture of novel membrane systems with high permeability, specific selectivity and long-term stability under operating conditions. These systems must be incorporated into power plants and an energy system defining additional boundary conditions. It must be shown that membrane systems cause less energy losses than competing capture technologies at a comparable cost. The membrane area must be kept to a minimum to avoid significant increases in capital costs. Close cooperation with systems analysis groups is necessary to identify optimum operating conditions with low environmental impacts. Two topics consider the integration of capture techniques into the power plant and the energy supply system as a whole [6].

### *2.1. High- and intermediate-temperature ceramic membranes*

One research field consists of material synthesis and processing, as well as the characterization and modelling of the performance of ceramic membranes. The overall aim is the identification and further development of promising candidate membrane materials for the separation of $H_2/CO_2$, $O_2/N_2$ and possibly $CO_2/N_2$ and others. The information required to select the most promising options for integrating membranes into power plant process scenarios aimed at $CO_2$ capture will be provided.

Important research goals to be addressed include:

- Development and characterization of ceramic molecular sieving membranes, including zeolite and sol–gel derived membranes, for $H_2/CO_2$ separation.
- Development and characterization of dense ceramic proton conducting and mixed proton-/electron-conducting membranes for $H_2/CO_2$ separation.
- Development and characterization of dense ceramic mixed oxygen ionic-electronic conducting membranes for $O_2/N_2$ separation.
- Modelling of transport issues and surface exchange behaviour (especially for dense ceramic membranes).
- Design and development of a demonstration unit (proof of concept) for $O_2/N_2$ separation.

### *2.2. Polymeric and hybrid membranes*

Material synthesis, membrane manufacture and characterization, and module development on a pilot scale for separation in temperature ranges of up to 200 °C is a second research topic. Polymeric membranes are the furthest developed option.

Polymeric and organic/inorganic hybrid membranes are being developed for $CO_2/N_2$ separation (post-combustion process) as well as for $CO_2/H_2$ separation (pre-combustion process). In contrast to the ceramic membranes described above, these membranes are more permeable for $CO_2$ than for $H_2$. In addition to pure polymeric membranes, new hybrid organic/inorganic membranes with inorganic molecular sieves are being prepared. Membranes should