



The 6<sup>th</sup> International Conference on Applied Energy – ICAE2014

## Techno-economic performance of a hybrid membrane – liquefaction process for post-combustion CO<sub>2</sub> capture

Rahul Anantharaman<sup>a\*</sup>, David Berstad<sup>a</sup>, Simon Roussanaly<sup>a</sup>

<sup>a</sup>*SINTEF Energy Research, Trondheim, Norway*

### Abstract

Gas separation membranes, considered among one of the promising emerging capture technologies for post-combustion capture, requires a two-stage process with significant compression work for CO<sub>2</sub> capture from a coal fired power plant flue gas. A hybrid membrane–liquefaction process for post-combustion CO<sub>2</sub> capture from the power plant flue gas is developed to mitigate the deficiencies of the two-stage membrane process. The energy efficiency of the process depends on the permeate CO<sub>2</sub> composition from the membrane unit. The performance envelope of the hybrid process is evaluated and shows that the optimum CO<sub>2</sub> concentration in the permeate is 65%–67% depending on the targeted CCR. A techno-economic analysis for 85% CCR was performed and the cost of CO<sub>2</sub> avoided is calculated to 48 €<sub>2008</sub>/t<sub>CO<sub>2</sub>,avoided</sub>, that is, 9% more cost-efficient than the baseline MEA absorption process.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Organizing Committee of ICAE2014

*Keywords:* Post-combustion capture; Gas separation membrane; Hybrid process; CO<sub>2</sub> liquefaction

### 1. Introduction

Gas separation membranes are considered among one of the promising emerging technologies for post-combustion CO<sub>2</sub> capture and this process has been studied extensively [1–3]. Membrane technology has a few advantages over amine-based solvent systems in that the process has no steam requirement and therefore is far less complicated to retrofit into existing power plants, and it has no environmental impacts caused by solvent losses and degradation. The disadvantage of this technology is limitations in membrane selectivity and permeability, and multiple-stage processes and significant compression work are required to attain high CO<sub>2</sub> capture ratios (CCR) and product purity, while ensuring sufficient driving force. While there is no clear consensus in the literature in comparing performance of amine-based solvent systems and membrane systems, earlier work has shown that membrane processes are more energy intensive than amine-based post-combustion capture [4].

\* Corresponding author. Tel.: +47 73593631; fax: +47 73593950.  
*E-mail address:* [rahul.anantharaman@sintef.no](mailto:rahul.anantharaman@sintef.no).

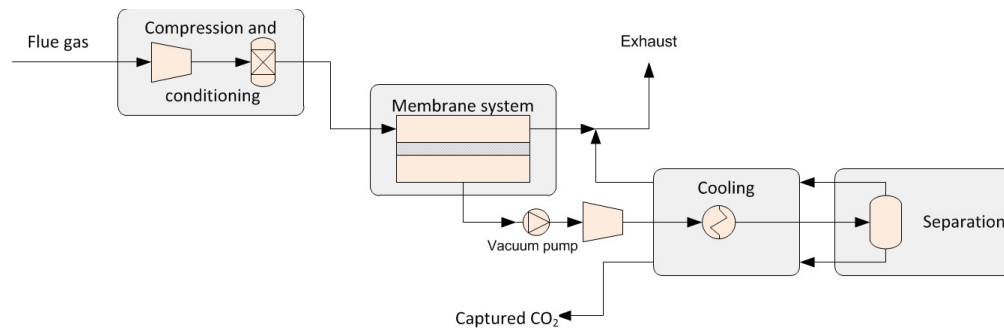


Fig. 1: Process block diagram of the membrane–low temperature hybrid process for post-combustion capture

Due to the low triple point of pure CO<sub>2</sub> (216.58 K, 5.185 bar), separating CO<sub>2</sub> from a gas mixture by liquefaction, especially for gases with high CO<sub>2</sub> partial pressure, is quite attractive and close to commercialization in oxy-combustion carbon capture processes [5]. The permeate from the first stage of a polymeric membrane separation process can reach relatively high CO<sub>2</sub> concentration (around 70%) which is similar to that of oxy-combustion exhaust. The CO<sub>2</sub> separation process by liquefaction can be integrated with a single-stage membrane process to reduce the energy penalty of the capture process.

This paper presents results from investigation of a hybrid membrane process combined with low-temperature CO<sub>2</sub> separation for post-combustion capture from coal-fired power plants. The potential of the hybrid process combining the technologies for reducing the capture energy penalty is investigated, and the hybrid-process operating window is evaluated.

## 2. Hybrid membrane – liquefaction process

The working principle and sequence of the hybrid membrane-low temperature process is shown in Fig 1. Through this capture process, the CO<sub>2</sub> concentration in the flue gas from a coal-fired power plant is first increased using a single-stage membrane process. Subsequently, this CO<sub>2</sub>-enriched gas is compressed, first from vacuum pressure to ambient with a vacuum pump. This step is then followed by further multi-stage compression to the targeted CO<sub>2</sub> liquefaction and separation pressure required by the low-temperature separation process.

The single-stage membrane process is designed to capture 90% of the CO<sub>2</sub> from the exhaust gas. The purity of the "CO<sub>2</sub>-rich" permeate stream depends on the membrane properties, driving force and membrane area. The relevant membrane properties, selectivity and permeance, are fixed to 80 (CO<sub>2</sub>/N<sub>2</sub>) and 5 Nm<sup>3</sup>/(m<sup>2</sup>·bar·hr) respectively. The driving force is the CO<sub>2</sub> partial pressure difference across the membrane. This is manipulated by pressurizing the membrane feed and/or operating the permeate side under vacuum. The energy penalty of a membrane process increases with increasing purity of the permeate stream.

The CO<sub>2</sub>-rich permeate stream is fed to the low-temperature CO<sub>2</sub> processing unit (CPU). The stream is compressed to targeted separation pressure before it is cooled to separation temperature in a sequence of heat exchangers. A two-stage vapor compression cascade cycle with propane and ethane as refrigerants is assumed to provide the refrigeration duties in the CPU. After cooling to final separation temperature the CO<sub>2</sub>-rich liquid phase is separated from the nitrogen-rich vapor phase, then flashed and purified in a secondary drum, and is subsequently conditioned to the specified transport state.

### 2.1. Operational envelope of the hybrid process

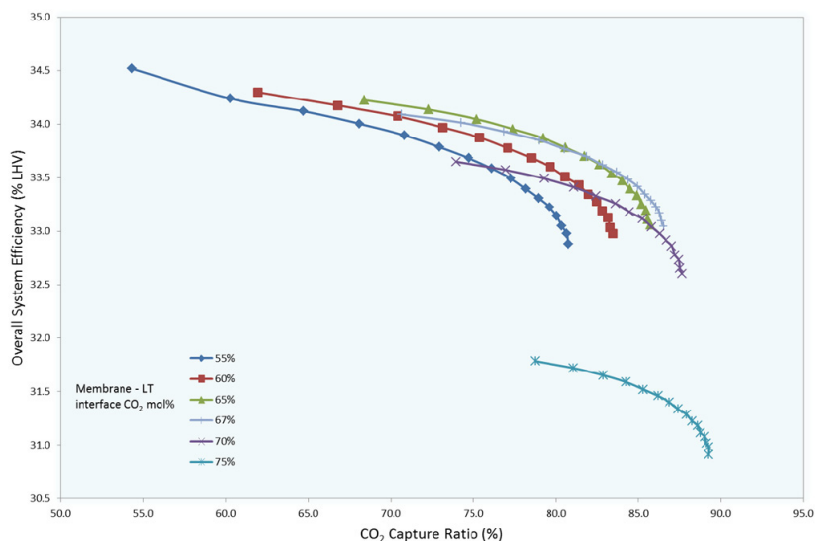


Figure 2: Operational envelope of the hybrid membrane-liquefaction process for different permeate CO<sub>2</sub> concentrations.

The CO<sub>2</sub> purity of the permeate from the membrane process determines the overall capture process energy penalty and attainable CCR. The higher the CO<sub>2</sub> concentration of the permeate, the higher the attainable CCR and lower the capture penalty in the low-temperature process. An operational envelope for the process can be developed by varying the CO<sub>2</sub> composition in the permeate and for each of the permeate cases, evaluating the liquefaction process for varying CCRs.

The European Benchmarking Task Force (EBTF) report on reference cases for CO<sub>2</sub> capture [6] is used as the basis for the exhaust gas composition from an ASC coal-fired power plant. In order to determine the energy-optimal permeate stream from the membrane part of the capture process, the CPU was run for a broad range of input concentrations, from 50% to 75% CO<sub>2</sub>. Moreover, to pinpoint optimal CCR for the CPU and for the capture process as a whole, a relatively wide interval of separation pressures were run for each permeate inlet concentration. The equilibrium CO<sub>2</sub> vapour fraction decreases with increasing separation pressure, and the CCR will therefore increase with pressure for a fixed separation temperature. It should also be noted that the liquid fraction of CO<sub>2</sub> decreases with increasing separation pressure, but as the process utilizes a low-pressure (7–8 bar) flash CO<sub>2</sub> purification unit downstream of the main separator, this effect is mitigated.

The results show that the specific energy penalty for the low-temperature process decreases as the CO<sub>2</sub> concentration in the permeate increases. There is in other words an optimum CCR, from an energy penalty perspective, for each CO<sub>2</sub> concentration in the permeate, and there is a sharp increase in the specific energy penalty as the CCR approaches its highest attainable value. From an overall system perspective, the operational envelope of the energy penalty of the hybrid process is shown in Fig 2. The efficiency penalty increases with decreasing CO<sub>2</sub> permeate composition from 75% to 65% and then starts decreasing as the permeate composition is lowered to 50%.

## 2.2. Techno-economic performance

The cost of the ASC power plant with hybrid membrane-liquefaction process with 85% CCR is evaluated and compared to the cost of an ASC power plant with and without MEA CO<sub>2</sub> capture. This study assumes costs of a "NOAK" (N<sup>th</sup> Of A Kind) plant to be built at some point in the future, when the technology is mature. The costs are based on the EBTF report [6] for the ASC power plants and the MEA

capture facility while the hybrid membrane–low temperature capture process is evaluated following Aspen Process Economic Analyzer for equipment costs and following the EBTF cost methodology in order to obtain consistent and comparable costs estimates.

The cost evaluation shows that the cost of electricity with hybrid membrane–low temperature CO<sub>2</sub> capture is 33% more expensive than the plant without capture. It is further 6% cheaper than the reference plant with MEA capture. Regarding the cost of capturing CO<sub>2</sub> [7], the results shows that the hybrid membrane–low temperature concept, with a cost of 48 €<sub>2008</sub>/t<sub>CO<sub>2</sub>,avoided</sub>, is 9% more cost-efficient than the MEA process.

### 3. Conclusions

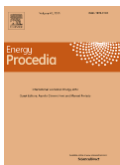
A hybrid membrane–low temperature process for post-combustion CO<sub>2</sub> capture from a coal-fired power plant is developed. The energy efficiency of the process depends on the permeate CO<sub>2</sub> composition from the membrane unit. The performance envelope of the hybrid process is evaluated and shows that the optimum CO<sub>2</sub> concentration in the permeate is 65%–67% depending on the CCR. A techno-economic analysis for 85% CCR was performed and the cost of CO<sub>2</sub> avoided calculated to be 48 €<sub>2008</sub>/t<sub>CO<sub>2</sub>,avoided</sub>. This figure is 9% more cost-efficient than the MEA-based CO<sub>2</sub> capture process.

### Acknowledgements

This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research program Centres for Environment-friendly Energy Research (FME). The authors acknowledge the following partners for their contributions: ConocoPhillips, Gassco, Shell, Statoil, TOTAL, GDF SUEZ and the Research Council of Norway (193816/S60).

### References

- [1] Merkel TC, Lin H, Wei X, Baker R.. Power plant post-combustion carbon dioxide capture: An opportunity of membranes. *Journal of Membrane Science* 2010;**359**:126-39.
- [2] Favre, E. Membrane processes and postcombustion carbon dioxide capture: Challenges and prospects. *Chemical Engineering Journal* 2011;**171**:782-93.
- [3] He X, Hägg M-B. Membranes for environmentally friendly energy processes. *Membranes* 2012;**2**:706-26.
- [4] Zhang X, He X, Gundersen T. Post-combustion carbon capture with a gas separation membrane: Parametric study, capture cost and exergy analysis. *Energy & Fuels* 2013;**27**:4137-49.
- [5] Berstad D, Anantharaman R, Nekså P. Low-temperature CO<sub>2</sub> capture technologies – Applications and potential. *International Journal of Refrigeration* 2013;**36**:1403-16.
- [6] Anantharaman R, Bolland O, Booth N, Dorst EV, Ekstrom C, Franco F, Macchi E, Manzolini G, Nikolic D, Pfeffer A, Prins M, Rezvani S, Robinson L. D1.4.3 European best practice guidelines for assessment of CO<sub>2</sub> capture technologies. DECARBit Project, 2011.
- [7] Rubin E, Booras G, Davison J, Ekstrom C, Matuszewski M, McCoy ST, Short C. Toward a common method of the cost estimation for CO<sub>2</sub> capture and storage at fossil fuel power plants. Global CCS institute, 2013.



### Biography

David Berstad is a research scientist at SINTEF Energy Research since 2008. His main field of research within CCS is capture by low-temperature condensation and separation of CO<sub>2</sub>. In addition to CCS, he has participated in various projects on natural gas processing and hydrogen liquefaction.