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Integration of Oxygen Transport Membranes in an IGCC power plant with CO_2 capture

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Oxygen transport membranes (OTMs) offer a promising technology for use in oxy-fuel and pre-combustion CO_2 capture processes, for gas- and coal power plants. OTMs are dense ceramic membranes which exhibit mixed conductivity of oxygen ions and electrons. This work presents systems considerations when integrating an OTM based ASU in an Integrated Gasification Combined Cycle (IGCC) plant with CO_2 capture. An IGCC process using an OTM without sweep gas and 100 % air side integration with GT is presented. The OTM integrated IGCC shows an efficiency gain of 0.7 % points over the reference IGCC plant with cryogenic ASU.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that the potential of Carbon Capture and Storage (CCS) could be between 10% and 55% of the total carbon mitigation effort until the year 2100. Major research is in the field of CO_2 capture from power plants, particularly coal based power generation. In this context, Integrated Gasification Combined Cycle (IGCC) is one of the important concepts for coal based power plants with CO_2 capture.

A major drawback of CO_2 capture is the significant energy penalty, leading to reduced economic viability. The main sources of energy penalty in IGCC plants are the air separation unit (ASU), the shift reactors, the CO_2 capture unit and the gas turbine that uses a H_2 rich gas as fuel. Research efforts to improve efficiency of the IGCC are focused on the components. State of the art cryogenic ASU's typically consume between 175-200 kWh/t O_2 produced and is expected to be 145-160 kWh/t of O_2 by 2015 (Tranier et al., 2009; Beysel, 2009). This would lead to approximately 0.3 % points improvement in the efficiency of IGCC plants with CO_2 capture.

Oxygen transport membranes (OTMs) offer a promising technology for use in oxy-fuel and precombustion CO_2 capture processes, for gas- and coal power plants (Bredesen et al. 2004). OTMs are dense ceramic membranes which exhibit mixed conductivity of oxygen ions and electrons. These membranes can separate oxygen from air with 100 % selectivity - a promising alternative to oxygen production by cryogenic distillation. Overviews of OTMs are presented in Fontaine et al. (2008); Sunarso et al. (2008).

OTMs and their integration have been studied extensively for oxy-fuel CO_2 capture processes (Eichorn Colombo et al., 2010; Kneer et al. 2010; Stadler et al., 2010;

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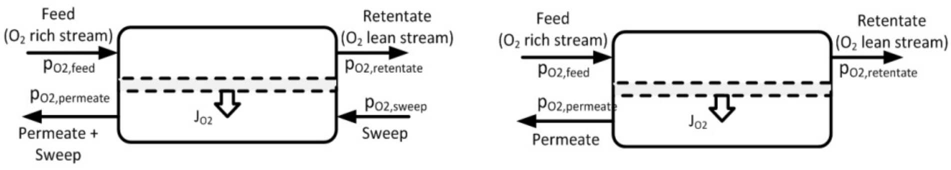
Anantharaman et. al., 2009) and the use of OTMs as an air separation unit for IGCC has also been evaluated earlier (Sander et al. 2008; Lindfelt and Westermark, 2006; Leo et. al., 2009; Dyer et al. 2000). In this work, systems considerations when integrating OTM as an air separation unit in an IGCC plant with CO_2 capture will be presented.



(a) (b)

Figure 1: Process schematic of membrane operating method (a) with sweep gas and (b) without sweep gas

2. Reference cases and membrane operating condition

The modeling assumptions for evaluation and cycle calculations are based on the European Benchmarking Task Force (EBTF) "Common Framework Definition document" (Franco et al., 2009). The reference IGCC case with CO_2 capture using cryogenic ASU is taken to be the case presented in the EBTF "Test cases and preliminary benchmarking results from the three projects" (Franco et al., 2009). This reference case is modified in this work to integrate an OTM-based ASU. Ceramic OTMs operate at temperature ranges between 800-1000 °C. For this work, we consider the operating temperature of the membrane (feed stream temperature) to be 900 °C.

3. Membrane operating method

The driving force for mass transfer is the partial pressure differential between the oxygen rich feed side and the permeate side of the membrane and the feed stream side of the membrane is kept at a higher pressure than the permeate side. The oxygen flux is given by a modified Wagner equation:

$$J_{O_2} = -\frac{RT}{16F^2L}\int_{\ln p_{O_2,feed\ side}}^{\ln p_{O_2,perm\ side}} \frac{\sigma_{el}\sigma_{ion}}{\sigma_{el}+\sigma_{ion}} \partial \ln p_{O_2}$$

(1)

The permeate O_2 partial pressure ($p_{O2,permeate} = x_{O2,permeate}/P_{permeate}$) should thus kept as low as possible and two options of achieving this are either reducing the permeate oxygen concentration ($x_{O2,permeate}$) or the permeate stream pressure ($P_{permeate}$). A schematic representation of the two membrane operating methods is shown in Figure 1.

3.1 Operating method with sweep gas

In the operating method with a sweep gas (Figure 1a), an oxygen free stream is sent to the low pressure permeate side to reduce the concentration (and thus partial pressure) of oxygen on the permeate side and thus increase the driving force. The advantage of this operating method is that the pressures of the feed and permeate sides can be set to be nearly equal, thereby reducing pressure differential across the membrane and improve its mechanical stability. Thus the oxygen produced is at a higher pressure and compression work to gasifier conditions is reduced. The temperature of the sweep gas should be close to the operating temperature of the membrane and in most cases the excess heat in the sweep gas can be used to preheat the feed stream to the membrane operating temperature. As the sweep gas stream dilutes the O_2 stream, sweep gas components are limited to either steam or CO_2. Figure 2 shows the approximate energy penalty using steam from the bottoming cycle as sweep gas assuming the air from the GT in the reference case to be the feed stream and setting $p_{O2,feed} - p_{O2,permeate}$ to 0.5 bar to ensure sufficient driving force across the membrane. Utilizing a sweep gas for OTMs in this application is associated with significant energy, and thus efficiency, penalty.

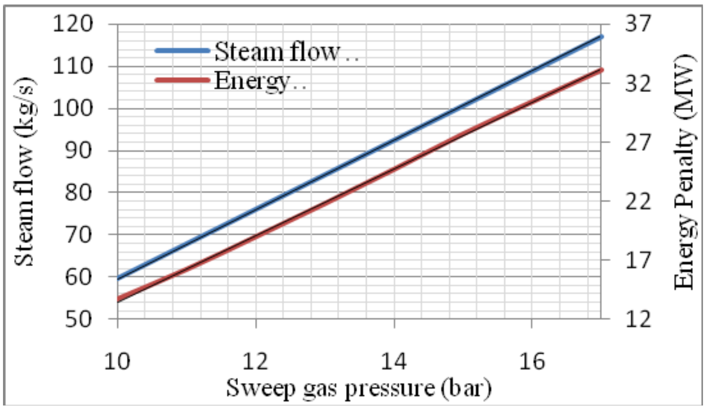


Figure 2: Sweep gas steam flows and associated energy penalty for extraction from bottoming cycle

3.2 Operating method without sweep gas

In the operating method without a sweep gas (Figure 1b), the pressure of the permeate side is set to be at vacuum or atmospheric conditions in order that $p_{O2,\ permeate}$ is lower than $p_{O2,\ feed}$ (Air Products, 2006). Thus in this operating method, there is no energy penalty related to steam extraction from the bottoming cycle for sweep gas. However, O_2 is produced at a low pressure and this gives rise to an energy penalty related to O_2 compression to gasifier conditions. Another disadvantage is the large pressure differential between the permeate and the feed side. This requires requisite consideration in fabricating such a membrane to prevent mechanical failure.

Preliminary analysis of the two operating methods showed that the one without a sweep gas gave better overall cycle efficiency and is chosen. The permeate side pressure is set to slightly above atmospheric and moderator steam to gasifier is supplied at these conditions to ensure that the permeate is not 100 % O_2.

4. OTM air integration with GT

The overall plant performance is expected to improve when increasing the extent of integration between the gas turbine and a cryogenic ASU, however this also reduces plant flexibility and operability while introducing start-up and shut-down problems. To balance these effects, an air side integration of 50 % (half of air supply to ASU) was assumed in the reference IGCC plant with and without CO_2 capture.

4.1 50 % air integration

An initial OTM ASU integrated with IGCC process with 50 % air integration was considered. Half of the air feed to the OTM was extracted by GT air compressor outlet and the other half was supplied by a standalone air compressor. This air feed was preheated to 900 °C (either by burning the H_2 rich fuel in the air or by heat exchange with GT combustor outlet stream) and sent to the OTM. The retentate is expanded and sent to a heat recovery unit before being discharged to the environment. An evaluation of the overall cycle performance resulted in this process having a lower efficiency than the reference IGCC plant with CO_2 capture. The reasons for the lower efficiency are:

1. Assuming the same turbine inlet temperature, raising the OTM feed temperature to 900 °C results in losses from the extra fuel conversion to H_2 and eventual combustion in this process.
2. The overall plant efficiency depends on the degree of O_2 separation, defined as $m_{O2,permeate}/m_{O2,feed}$. Efficiency of this process become equal to that of the reference case only when the degree of O_2 separation 0.80. The degree of separation for the process under consideration is 0.45.
3. Nitrogen required for gas turbine fuel dilution and coal transport is supplied by a cryogenic ASU. Steam can be used as diluent instead of nitrogen, and CO_2 could replace nitrogen required for coal feed. However, initial evaluation showed that these alternatives are associated with significant energy penalties. It must be noted that the cryogenic ASU required for N2 production is independent of the extent of air integration.

4.2 100 % air integration

An analysis of the reasons for the energy penalty and keeping the reference IGCC plant with CO_2 capture in mind it is clear that 100 % air integration is required for an increased efficiency. Figure 3 shows the IGCC process with OTM based ASU and 100 % air integration. The standard GT combustor replaced by a two stage combustor with the OTM placed between the two stages. Only part of the air, based on O_2 production requirement, from the compressor exhaust enters the OTM. Table 1 presents the overall plant performance of the process. The overall plant efficiency is 37.3 % as compared to 36.7 % for the reference IGCC plant with CO_2 capture. The reasons for better efficiency as compared to the 50% air integration case are

1. No extra fuel would be required to “preheat” the OTM feed to 900 °C.
2. The degree of air separation is does not affect the efficiency in this case.

A cryogenic ASU is required for this process also, albeit of a smaller capacity. A drawback of this process is that due to the tight integration of the OTM based ASU and the GT, flexibility and operability of the process is reduced.

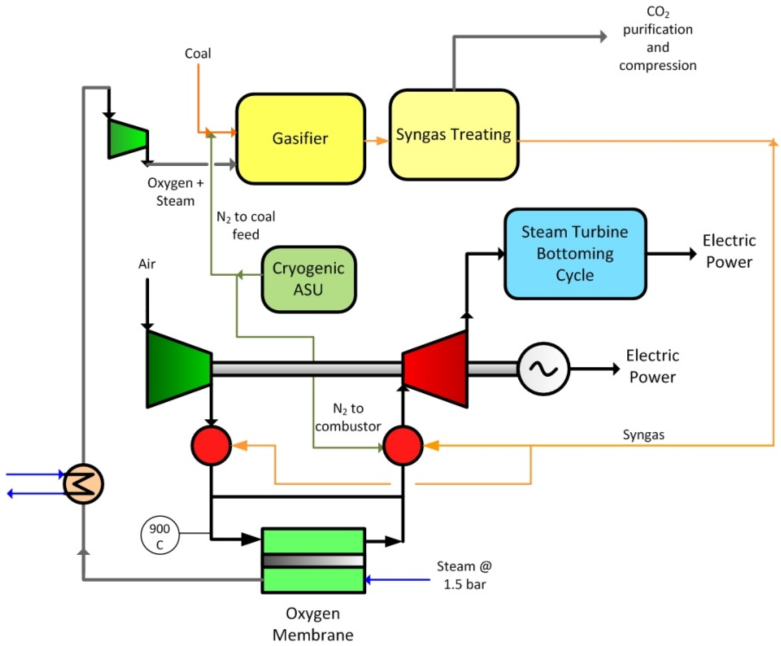


Figure 3: Process block diagram for OTM integrated IGCC plant with CO_2 capture

Table 1: Overall plant performance of OTM integrated IGCC plant with CO_2 capture

Coal flow rate	138.9Tph
Thermal energy of fuel (LHV)	969.7MWth
Thermal energy for coal drying	8.23MWth
Gas turbine output	280.5MWe
Steam turbine output	176.6MWe
Gross electric power output	457.1MWe
Total ancillary power consumption	92.1MWe
Net electric power output	365.0MWe
Net electric efficiency	37.3%
CO_2 capture rate	90.9%

5. Conclusions

System considerations for integration of an oxygen transport membrane based air separation unit are presented. Arguments for selection of membrane operating mode and air integration are discussed in detail. An OTM without sweep gas and 100 % air side integration with GT is selected. The OTM integrated IGCC shows an efficiency gain of 0.7 % points over the reference IGCC plant with cryogenic ASU. However, the trade-off is the tighter integration and reduced flexibility of the plant. Also, the number of plant components is increased as in addition to the OTM based ASU for O_2 production a cryogenic ASU is required for N_2 production.

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