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Optimization of CO₂ concentration captured by membrane technology - Possibility of reduction in CO₂ capture energy and cost -

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Abstract

The influence of specific power requirements and the membrane area on the CO₂ recovery ratio and the CO₂ concentration is investigated for CO₂ membrane separation from a pressurized gas stream. Three different membrane configurations of a simple single stage, a single stage with permeate recycle, and an ideal two-cascade are considered. A feed gas containing 40% H₂ and 60% CO₂ and having a total pressure of 2.5 MPa is used. In the cases of a simple single stage and a single stage with permeate recycle, a higher CO₂ recovery ratio leads to a larger membrane area and higher energy consumption for the gas recycle. In addition, a higher CO₂ concentration needs a larger membrane area and considerable power. An ideal two-cascade reduces the compressor power requirement as compared to a single stage with permeate recycle; however, it increases the membrane area. A lower CO₂ concentration in the recovered CO₂ stream implies a smaller membrane area and lower power requirement in the CO₂ capture from the pressurized gas stream.

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1. Introduction

Membrane separation is a pivotal candidate in energy- and cost-saving technologies for CO₂ capture in

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CO₂ capture and storage (CCS). In the case of CO₂ capture from a pressurized gas stream, the cost of the capture is estimated to be 1,500 JPY (15 USD)/ t-CO₂ or less [1]. Many studies in the field of membrane research are focused on the development of noble membranes because of the immense potential of the membrane process. For example, dendrimer membranes that have a CO₂ molecular gate function exhibit excellent CO₂/H₂ selectivity and moderately high CO₂ permeance [1]. A cross-linked polypropylene membrane has excellent high CO₂ permeance, and the facilitated transport membranes have significantly high CO₂ selectivity [2-8]. To obtain considerably high performance from these characteristic membranes, the method of use of these membranes in an optimal separation process is critically important for the CO₂ capture in CCS. The membrane process analyses have been reported previously [9-11].

The CO₂ capture energy and cost depend considerably on the membrane module configuration and the operating condition of the membrane process. In this study, the influence of CO₂ concentration in a recovered CO₂ stream on the membrane area and the power consumption is investigated for three different module configurations.

2. Experimental

The CO₂ capture from a pressurized gas stream such as an integrated coal gas combined cycle (IGCC) with a water-gas shift reaction was considered. In the capture, the CO₂ permselective membrane was used for the CO₂ separation from a CO₂/H₂ gas mixture. The content of the CO₂/H₂ gas mixture was assumed to be 60% CO₂ and 40% H₂, and the total pressure was 2.5 MPa. The separation membrane performance was assumed to be CO₂ permeance of 7.5×10^{-10} m³/(m² s Pa) and CO₂/H₂ selectivity of 30.

Figure 1 shows the flow diagram of the membrane process of a simple single stage. This membrane process is believed to attain the least membrane area and energy consumption if the CO₂/H₂ selectivity of the membrane is sufficient for obtaining the required gas specification for CCS.

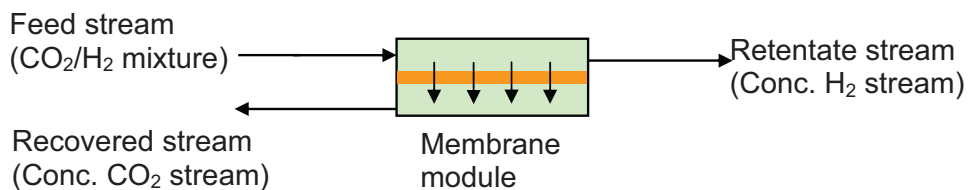


Figure 1. Flow diagram of a simple single stage.

However, CCS seems to require a high CO₂ concentration of 90% or more. In the case of several membrane selectivity values at present, a simple single stage configuration is not sufficient for obtaining the desired CO₂ concentration, and hence, a refined membrane process is preferred.

Figure 2 shows the flow diagram of a membrane process of a single stage with permeate recycle (SSPR). In this process, a part of the permeate stream is recycled to the feed stream in order to obtain a higher CO₂ concentration in the recovered gas stream. Further, a higher recycle ratio leads to a higher CO₂ concentration.

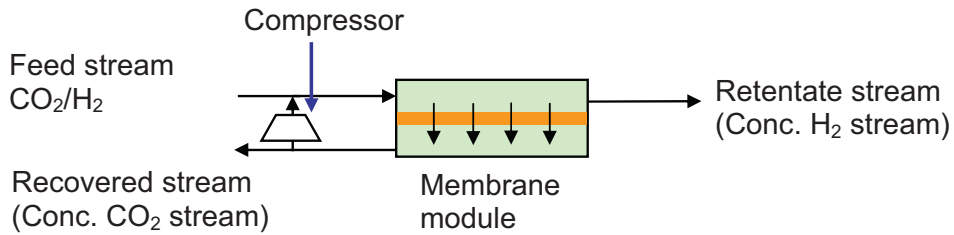


Figure 2. Flow diagram of a single stage with permeate recycle.

Figure 3 presents a schematic representation of the membrane process of an ideal two-cascade. In this process, a permeate stream is compressed and introduced into the second membrane module. The retentate gas stream of the second membrane module is recycled into the feed stream.

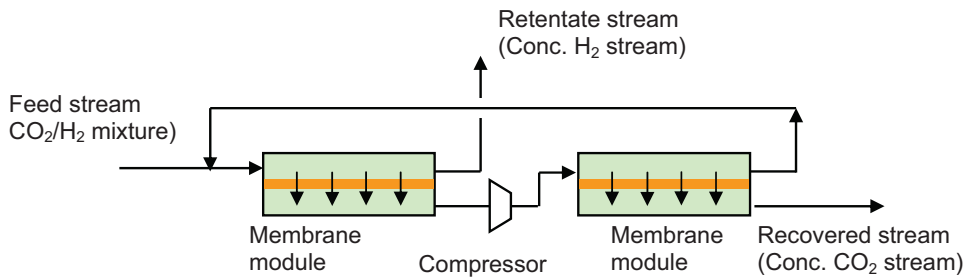


Figure 3. Flow diagram of ideal two-cascade.

To obtain the membrane area, a conventional calculation method for the counter-current module was used in the membrane process simulation [11]. The power requirement (PW_C) of the compressor was calculated using equation 1.

$$PW_C = \frac{RTq_p}{h} \frac{nk}{k-1} \left(\left(\frac{p_h}{p_l} \right)^{\frac{k-1}{nk}} - 1 \right) \quad (1)$$

Here, PW_C denotes the power requirement of the compressor (W); R , the gas constant (8.31 J/K/mol); q_p , the flow rate (mol/s); n , the number of compression stage (-); T , the temperature (K); k , the heat capacity ratio (-) = C_p/C_v (C_p : specific heat at constant pressure (J/K/mol); C_v : specific heat at constant volume (J/K/mol)); p_h , the feed pressure (Pa); p_l , the permeate pressure (Pa); h , the pump efficiency (-).

In this study, n , k , and h were 1, 1.33, and 0.8, respectively. The temperature (T) was 323 K.

3. Results and discussion

Table 1 shows the influence of the CO_2 percentage in the recovered CO_2 stream on the membrane area and the specific power requirement of the compressor in the simple single stage and the SSPR. The CO_2 recovery ratio was 90%. The membrane performance was calculated using the target value of a dendrimer membrane in RITE; in this case, the CO_2 permeance was $7.5 \times 10^{-10} \text{ m}^3/(\text{m}^2 \text{ s Pa})$ and the CO_2/H_2 selectivity was 30 [12]. The feed gas pressure, composition, and flow rate were 2.5 MPa, $\text{CO}_2/\text{H}_2 = 40/60(\%/%)$, and 1 mol/s, respectively. The permeate gas pressure was 0.1 MPa. This condition roughly met that for the CO_2 capture from IGCC with a water-gas shift reaction.

In the table, it can be seen that the simple single stage membrane configuration needed the smallest membrane area of 24.5 m^2 . Further, there was no requirement of energy consumption of the compressor. However, the CO_2 concentration of the recovered CO_2 stream was 87.0%. On the other hand, the single stage with permeate recycle attained a higher CO_2 concentration of 90% or more in the recovered CO_2 stream. The CO_2 concentration depended on the recycle ratio. That is, the higher recycle ratio led to the higher CO_2 concentration. However, the membrane area and the compressor energy consumption became large in the case of a large recycle ratio. When the CO_2 concentration was 90%, the smallest membrane area of 31.6 m^2 and the specific power requirement of $0.0708 \text{ kWh/kg-CO}_2$ were obtained. When the CO_2 concentration was 95% and 99%, the membrane area and the specific power requirement were 56.5 m^2 and $0.415 \text{ kWh/kg-CO}_2$, and 239 m^2 and 4.09 kWh/kg-CO_2 , respectively. The lowest CO_2 concentration exhibited the smallest membrane area and energy consumption among the three different CO_2 concentrations in SSPR.

The membrane area and the specific power requirement are the indicators of CAPEX and OPEX, respectively. That is, a large membrane area invokes high CAPEX, and a large specific power requirement leads to high OPEX. The higher CO_2 concentration engages both the larger membrane area and higher specific power requirement. That is, a higher CO_2 concentration leads to both large CAPEX and large OPEX in the membrane CO_2 separation from the pressurized gas stream.

Furthermore, at the CO_2 concentration of 99%, both the membrane area and the specific power requirement increased sharply.

Table 1. Relationship between CO_2 concentration, membrane area, and power requirement at 90% CO_2 recovery.

Membrane System	Recovered CO_2 Concentration	Membrane Area	Specific Power Requirement
	%	m^2	kWh/kg-CO_2
Simple single stage	87.0	24.5	0
Single stage with permeate recycle	90.0	31.6	0.0708
Single stage with permeate recycle	95.0	56.5	0.415
Single stage with permeate recycle	99.0	239	4.09

The membrane area corresponds to a feed flow rate of 1 mol/s.

Table 2 shows the influence of the CO₂ percentage in the recovered CO₂ stream on the membrane area and the specific power requirement in a simple single stage and a membrane process of SSPR at a CO₂ recovery ratio of 95%.

In the table, it can be seen that the simple single stage membrane configuration needed the smallest membrane area of 31.4 m². Further, the CO₂ concentration of the recovered CO₂ stream was 84.2%. On the other hand, the single stage with permeate recycle attained a higher CO₂ concentration of 90% or more in the recovered CO₂ stream. This trend was similar as that seen in Table 1 at the CO₂ recovery ratio of 90%. By comparing the two different CO₂ recovery ratios, we found that the large CO₂ recovery ratio of 95% needed both a large membrane area and considerable compressor energy consumption. For example, in the case of the recovered CO₂ concentration of 95%, the membrane area and the specific power requirement at the CO₂ recovery ratio for 90% and 95% were 56.5 m² and 0.415 kWh/kg-CO₂, and 74.2 m² and 0.543 kWh/kg-CO₂, respectively.

Table 2. Relationship between CO₂ concentration, membrane area, and power requirement at 95% CO₂ recovery.

Membrane System	Recovered CO ₂ Concentration	Membrane Area	Specific Power Requirement
	%	m ²	kWh/kg-CO ₂
Simple single stage	84.2	31.4	0
Single stage with permeate recycle	90.0	45.5	0.138
Single stage with permeate recycle	95.0	74.2	0.543
Single stage with permeate recycle	99.0	284	4.60

The membrane area corresponds to a feed flow rate of 1 mol/s.

Table 3 shows the influence of the CO₂ percentage in the recovered CO₂ stream on the membrane area and the specific power requirement in an ideal two-cascade. The ideal two-cascade is often used for obtaining a higher gas concentration in the membrane separation process.

In the table, we see that for the CO₂ recovery ratio of 90%, the membrane area and the specific power requirement were 101 m² and 0.117 kWh/kg-CO₂ at the CO₂ concentration of 95%, respectively. The membrane area was larger than that of the single stage with permeate recycle given in Table 1. On the other hand, the power requirement of the compressor was smaller than that of the single stage with permeate recycle. The ideal two-cascade reduced the power requirement of the compressor. The same trend was observed for the CO₂ recovery rate of 95%. Parameters such as the recycle ratio in this ideal two-cascade should be optimized for obtaining a small membrane area and energy consumption.

Table 3. Relationship between CO₂ concentration, membrane area, and power requirement of ideal two-cascade.

CO ₂ Recovery	Recovered CO ₂ Concentration	Membrane Area	Specific Power Requirement
%	%	m ²	kWh/kg-CO ₂
90	95.0	101	0.117
95	95.0	182	0.122

The membrane area corresponds to a feed flow rate of 1 mol/s.

As mentioned above, the membrane area closely related to the capital cost of the membrane plant and the power consumption of the compressor mainly determined the operation cost. In this study, a simple single stage attained the smallest membrane area; that is, this membrane configuration seemed to contribute the smallest capital cost. However, insufficient membrane selectivity sometimes led to a small recovered CO₂ concentration of less than 90%. Two membrane configurations of a single stage with permeate recycle and an ideal two-cascade were useful for achieving the CO₂ concentration of 90% or more.

The reduction of the CO₂ capture cost is a considerably important issue for CCS. This study may indicate an important strategy for reducing the CCS cost. From this study, in the case of the CO₂ capture from the pressurized gas stream such as IGCC with a water-gas shift reaction, the CO₂ concentration in the recovered CO₂ stream strongly affected the membrane area and the energy consumption of the compressor. That is, a low CO₂ concentration implied a small membrane area and power requirement, which led to a small CO₂ capture cost.

The CO₂ concentration of the captured CO₂ stream should be determined with various considerations. The first priority is safety. The impurity in the recovered CO₂ stream is a critically important concern for the CCS issues. If the safety condition is satisfied, the CCS cost will be one of the next important concerns. With respect to the CO₂ capture with a membrane, a low CO₂ concentration leads to small capital cost and low energy consumption for the CO₂ capture. In the case of the simple single stage at the CO₂ recovery ratio of 90%, the membrane area is 24.5 m² at the CO₂ concentration of 87.0%. On the other hand, the membrane area for the CO₂ concentration of 90.0% increases to 31.6 m² by a factor of 1.29. Furthermore, the membrane area for the CO₂ concentration of 95.0% and 99.0% increases to 56.5 m² and 239 m² by a factor of 2.31 and 9.76, respectively. Because the capital cost of the CO₂ membrane capture facility is roughly proportional to membrane area, the CO₂ facility cost for the CO₂ concentrations of 90.0%, 95%, and 99% is more than that for the CO₂ concentration of 87.0% by a factor of 1.29, 2.31, and 9.76, respectively. With respect to the power requirement, the compressor consumes 0.0708 kWh of electricity per kg of CO₂ at the CO₂ concentration of 90.0% in the case of the single stage with permeates recycle. When the cost of electricity is 10 JPN/kWh, the electricity consumption cost of the process is 708 JPY per ton of CO₂. At the CO₂ concentration of 95%, the electricity cost increases to 4,150 JPY per ton of CO₂ for the electricity consumption of 0.415 kWh/kg-CO₂. As a result, if the low CO₂ concentration is adapted for CCS, the CO₂ capture cost will decrease considerably.

4. Conclusions

The influence of the membrane area and the power requirement on the CO₂ recovery ratio and the CO₂

concentration in a recovered CO₂ stream were estimated for the CO₂ separation from a pressurized gas stream. Three different membrane configurations of a simple single stage, a single stage with permeate recycle, and an ideal two-cascade were investigated.

The simple single stage achieved the smallest membrane area among the three different module configurations. However, the CO₂ concentration of the recovered CO₂ stream was also the smallest in this case. On the other hand, the single stage with permeate recycle increased the CO₂ concentration of the recovered CO₂ stream. In the case of this membrane configuration, a higher CO₂ concentration implied a large membrane area and considerable compressor power consumption. The ideal two-cascade reduced the compressor power consumption and increased the membrane area.

The CO₂ concentration of the captured CO₂ stream strongly influenced both the membrane area and the energy consumption, that is, a higher CO₂ concentration increased both these parameters. The membrane area and the power consumption were the indicators of the CO₂ capture cost in the membrane separation process. A small membrane area and/or low power consumption reduced the CO₂ capture cost. As the membrane area in the case of the simple single stage was the smallest among the three different module configurations, this module configuration led to the least CO₂ capture cost even though the CO₂ concentration in the captured CO₂ gas stream was not insufficient for an existing CCS system. A smaller CO₂ concentration in the captured CO₂ stream is worth considering for the reduction of the CO₂ capture cost.

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