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Optimization-based approach for design and integration of carbon dioxide separation processes using membrane technology

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Abstract

The purpose of this paper is to examine carbon dioxide (CO_2) separation process using membrane technologies. In achieving this goal, we develop an optimization model to design and integrate the CO_2 separation using multi-stage membrane technologies by maximizing the total profit calculated with the total capital and operating costs, and the expected revenue from the CH_4 selling. Using the proposed model, we are able to determine the optimal design and operation strategies of the individual membrane and compressor to meet the design specification (i.e., purity and recovery rate) in the scenarios of different CO_2 market prices.

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Keywords: CO_2 separation; coal bed methane; membrane process; optimization; process synthesis

1. Introduction

The depletion of conventional resources, in particular fossil fuels such as coal and petroleum, leads to the development of unconventional energies to meet a significant increase of energy demand [1]. Coal bed methane (CBM) gas is a kind of new promising alternative energy resources due to its huge potential; its total reserve is estimated to be 36% of the total natural gas reserve [2]. CBM gas is usually produced by pressure depletion in the coal reservoir. However, this conventional pressure depletion method is proper only to produce a limited amount of gas in place, which ranges 20-60% [3]. Thus, many studies have revealed that injecting carbon dioxide CO_2 into a

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coal seam can significantly improve the CBM production since the CO_2 has a stronger affinity with coals than other components in coal bed. The enhanced coalbed methane (ECBM) production through CO_2 injection into unminable coal seams is to be an efficient method to improve the productivity of CBM.

CBM gas from the CO_2 injected ECBM consists primarily of methane (CH_4) and CO_2, and remained components such as water and nitrogen (N_2) [4]. However, the amount of CO_2 contents in CBM gas varies from 30% to 90% depending on conditions of the coal seam and operations [5]. Thus, before transporting the CBM gas as a final energy form to customers (e.g., market or terminal), a low-quality CBM gas must be purified to meet the specification of the pipeline transportation, for example, the purity of CH_4 component in the final stream should be improved at least up to 98% by eliminating the other main component, CO_2 [6].

Compared with conventional methods to separate CO_2, such as cryogenic distillation and amine-based wet scrubbing, membrane-based separation is a competitive technology since it offers many advantages of i) relative effective energy consumption per the unit of CO_2 separation, ii) simple operation and maintenance, and iii) relatively easy scale-up compared to other separation processes [7,8]. In general, a single stage membrane process is not economical to separate CO_2 in a high purity with competent recovery rate [9]. Accordingly, a multi stage membrane process, which connects two more membrane processes in series, is widely necessary to improve both the separation performance and economics [10,11]. However, the multi stage membrane separation process needs also to be optimized to ensure high energy efficiency and separation efficiency. In most cases, the optimization is performed not by any heuristic methods but by mathematical models due to high complexity in the interaction between membrane modules and with recycles [12,13].

Therefore, this study aims to design and analyze CO_2 separation system using the multiple membrane process for the CO_2 injected ECBM application. In achieving this goal, we develop an optimization model using a nonlinear programming (NLP) technique. The optimization approach is applied to CO_2/CH_4 separation in the CO_2-ECBM production process, which maximizes the total expected profit. With the proposed model, we are able to determine the optimal design and operation conditions such as required membrane area and utility consumption to meet the design specification. Finally, we perform extended analyses to investigate the impacts of CO_2 content in the feed on the economics and design of the membrane-based separation process.

2. Membrane-based CO_2 separation system

2.1. Membrane process

Typically a membrane module consists of porous layers that allows a particular molecule to permeate faster than the other molecules. Molecules with lower size (or, higher diffusivity and solubility) in the membrane module can permeate faster. Thus, CO_2 with lower size can permeate faster than CH_4 having higher size. The residual stream from a membrane is called the retentate (CH_4 rich), while CO_2 rich stream is called the permeate. In this study, only one membrane process configuration is considered since it is proven that this configuration has the most economic process layout under wide ranges of feed conditions [14,15]. In this study, it is assumed no pressure drop, isothermal operation, ideal gas behaviour, and steady state operation. The proposed membrane process configuration is shown in Fig. 1.

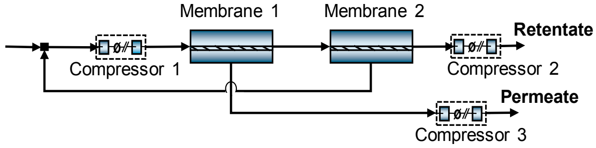

Fig. 1. Two-stage membrane process configuration with a recycle stream.

2.2. CO_2-ECBM process

Fig.2 shows a schematic diagram of the overall CO_2-ECBM production process. During CO_2 injection, CH_4 in the coal seam is desorbed by the injected CO_2 due to a higher affinity of CO_2 with coals compared to CH_4. After the