

Economic process design for separation of CO₂ from the off-gas in ironmaking and steelmaking plants



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ABSTRACT

We develop an economic process design for separation of CO₂ from the off-gas in ISMPs (iron and steel making plants). Based on the characteristics of the off-gas from which CO₂ must be separated, we design two process configurations: PSA (pressure-swing adsorption) and MEA (monoethanolamine)-based chemical absorption. We also develop a simulation model of each process, and perform an economic evaluation of the configurations. Our technical performance analyses show that the CO₂ recovery and purity are >90% in the both processes and that highly-concentrated combustible gas (CO and H₂) can be obtained as a byproduct. Our economic performance analyses show that the designed processes lead to cost-effective and competitive options (\$62/t CO₂ separated), compared to the CO₂ separation processes used in power plants. Using the combustible gas as a fuel for the boiler of power cycle greatly reduces the cost of CO₂ separation in ISMPs.

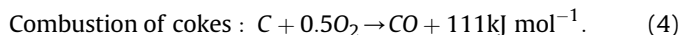
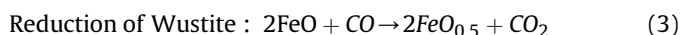
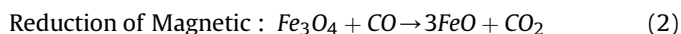
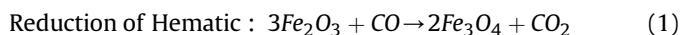
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1. Introduction

Many countries have agreed to reduce their emissions of CO₂, which is a major greenhouse gas that contributes to global warming [1], and signed the Kyoto Protocol in 1997 [2,3]. CO₂ is emitted mainly by burning fossil fuels to generate energy in power plants and for production of cement, iron and steel in industrial processes [4]. CO₂ separation technologies have been a promising solution for removing CO₂ from gas streams emitted by power plants and industrial processes [1,5,6]. Four major separation technologies are used to separate CO₂ from exhaust gases: absorption, adsorption, membranes and cryogenics [5,7]. A chemical absorption process using a solvent based on MEA (monoethanolamine) is well known as the most suitable technology for use in conventional power plants, because it is effective for dilute CO₂ streams (about 3.5–13.5 mol% in mostly N₂) emitted from the plants [7–11], but requires a very high heating energy to regenerate the MEA solvent

[12,13]. The PSA (pressure-swing adsorption) process can be also commercially viable for CO₂ separation [14,15], but has some drawbacks such as low capacity and low CO₂ selectivity of available adsorbents [16–18].

However, despite the large number of techno-economic evaluations of the CO₂ separation processes in power plants [6,7,12,13,19–34], few studies have been conducted in other industrial processes, especially ISMPs (iron- and steel-making plants). Iron (or steel) can be produced by indirect reduction of iron oxides (Equations (1)–(3)) by a reducing gas (CO) produced from burning coke (Eq. (4)); the reaction pathway emits a huge amount of CO₂ [35]:



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Especially, the steel industry in Korea emits 14% of the country's total CO₂ emissions, which is second only to power plants (30%) [35]. CO₂ separation processes have been demonstrated in power plants [7–11,16], but the off-gas emitted by ISMPs differs from the flue gas emitted by power plants, so designing a suitable process for CO₂ separation from off-gases requires understanding of their characteristics.

Our goal is to develop an optimal design for CO₂ separation processes in ISMPs. We present a broad overview of the technologies to develop the design of CO₂ separation processes in Section 2. We then design two process configurations and develop each process simulation model in Section 3. Last, we perform an economic evaluation of the configurations in Section 4. Thus, we can suggest the best design of CO₂ separation process in ISMPs in Section 5.

2. Technology overview

ISMPs typically emit three types of off-gas: BFG (blast furnace gas), oxygen furnace gas (LDG) and COG (coke oven gas). They all contain large amounts of CO and CO₂, moderate amounts of H₂ and N₂, and small amounts of CH₄. But they also have unique features. Compared to the other gases, BFG has a higher concentration of N₂ [36], LDG has a higher concentrations of CO [37] and COG has a higher concentration of H₂ [38]. Thus, this paper considers the gas composition and a certain value of gas flow rate as an input gas condition of the CO₂ separation process (Table 1). The gas flow rates are real data, which were obtained directly from a conventional ISMP in Korea.

Four technologies are available for separation of CO₂ from the off-gas: chemical absorption, pressure swing adsorption, cryogenic, and membrane (Table 2). Although these technologies have been demonstrated in power plants [7], the technologies are not suitable for application in existing ISMPs for two reasons. The first is that the off-gas emitted from ISMPs contain higher concentrations of CO₂ (30–40 mol%) and lower concentrations of N₂ (10–20 mol%) than gases emitted from power plants [36–38]. Higher purity of CO₂ (90–99 mol%) can be obtained using PSA in ISMPs than in power plants (48 mol%) because CO₂ purity in the recovered (separated) stream depends on the composition CO₂ in the off-gas that enters the PSA process [39]. PSA can then be a cost-effective and competitive option to commercial MEA-based CO₂ absorption process. The other difference is that the off-gas contains combustible species, which can be burned to produce heat and electricity; this process can decrease the operating cost of separating the gases.

The cryogenic and membrane processes are not suitable [7] for separating off-gases. The cryogenic process requires a very large amount of energy for refrigeration. The membrane process requires high operating pressures and needs multiple stages and recycling to separate CO₂ from the off-gas. Thus, CO₂ separation using PSA or MEA-based chemical absorption is considered in this paper.

Table 1
Input gas information.

Descriptions	Values	Units
Flowrate	7000–8000	kmol/h
Temperature	25–45	°C
Pressure	1–3	Bar
Composition		
H ₂	10–20	mol %
CH ₄	0–10	mol %
CO	30–40	mol %
CO ₂	30–40	mol %
N ₂	10–20	mol %

3. Process development

3.1. PSA modeling

The design of PSA process (Fig. 1; Table 2) is modified from Ref. [39] that includes a pre-treatment system and a dehydrator, because off-gases do not include water and impurities (i.e., NO_x and SO_x). In principle, an off-gas is pressurized by a compressor and then sent to PSA vessel to separate CO₂. Adsorbents (e.g., zeolites) are used to adsorb CO₂ from the off-gas at high pressure and the process then swings to low pressure to desorb the adsorbed material. After desorption, a product gas containing a high concentration of CO₂ is pressurized for transport to a CO₂ storage site. Thus, the operation of PSA process is assumed to be a Skarstrom cycle [39,40], which is composed of four steps: pressurization, adsorption, depressurization, and purging.

Detailed process flowsheet of PSA was developed using short-cut modeling [39,40] and simulated using gPROMS [41]. This modeling categorizes four steps of the Skarstrom cycle into two groups: “adsorption”, which consists of pressurization and adsorption; and “desorption”, which consists of depressurization and purging. This modeling provides an approximate result is fast and simple. The assumptions of the modeling are [39,40]:

1. All steps are assumed to be batch processes.
2. The batch process occurs in a vessel with a fixed volume.
3. The bulk gas and adsorbed gas are in equilibrium with each other.
4. After desorption, the bed does not contain residual gases.
5. Adsorption is adiabatic.
6. All gas components can be adsorbed, assuming a multicomponent system compared to the bicomponent system of [39,40].

Modeling Equations (5)–(10) (notation definitions: Appendix 1; input parameters: Supplementary Information) are the developed material balances based on the Langmuir isotherm using zeolite 13X [39,42–44]. Equations (5) and (6) are overall material balances of each component in the adsorption and desorption processing steps, respectively. Equations (7) and (8) are total flow rates of each component in exhaust and product streams separated from the processing steps, respectively, and are determined by the efficiency at which each component is removed in each processing step (Equations (9) and (10)).

$$f_{in,n}^{vessel} = m_n + q_n + s_n \quad (5)$$

$$m_n + q_n = n_n + r_n + t_n \quad (6)$$

$$f_{Exhaust,n}^{vessel} = s_n + t_n \quad (7)$$

$$f_{Product,n}^{vessel} = n_n + r_n \quad (8)$$

$$q_n = \frac{a_n b_n P_n^{hp} W_{ads}^{vessel}}{1 + \sum_n b_n P_n^{hp}} \quad (9)$$

$$r_n = \frac{a_n b_n P_n^{lp} W_{ads}^{vessel}}{1 + \sum_n b_n P_n^{lp}} \quad (10)$$

Equations (11) and (12) calculate electricity requirements of compressors and vacuum pumps in the process [45].

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