CHEMICAL ENGINEERING RESEARCH AND DESIGN 104 (2015) 247–255

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Techno-economic analysis of mechanical vapor recompression for process integration of post-combustion CO_2 capture with downstream compression

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ARTICLE INFO

Article history:
Received 5 June 2015
Received in revised form 13 August 2015
Accepted 17 August 2015
Available online 28 August 2015

Keywords:
Process integration
Post-combustion CO_2 capture
Vapor recompression
Economic analysis
Exergy analysis

ABSTRACT

Post-combustion capture of CO_2 using amine solvent is by far the most practical and mature technology, however, energy requirement for solvent regeneration still remains as the biggest obstacle to overcome. In this article, post-combustion CO_2 capture process model was validated using experimental data of an existing test bed. Based on the validated model, mechanical vapor recompression (MVR) process is proposed which reduces thermal energy for solvent regeneration by recovering heat from compression process required for CO_2 transportation. MVR process not only reduces the amount of steam extracted from the power plant, but can also serve as an interface between CO_2 capture and compression for process integration. According to the simulation results, energy saving of 8.4% was observed in comparison with the base case, which is a conventional CO_2 capture process followed by 2-stage compression. In addition to energy analysis, exergy analysis based on the 2nd law of thermodynamics and economic evaluation were performed to determine optimal operating condition of the MVR process.

1. Introduction

Among the OECD countries, South Korea has shown the highest carbon dioxide emission increase rate since 1990. In 2009, Korean government announced the CO_2 reduction target which corresponds to 30% of the total emission level in 2020 based on state of the art standards. Since then, tremendous efforts were made to reduce the CO_2 emission, and carbon capture and storage (CCS) technology emerges as the most promising solution. Among several CO_2 capture technologies, post-combustion technology has drawn much attention due to its applicability to large-scale CO_2 emission sources such as power plants or steel industries, and its suitability for retrofitting. Wet type capture of CO_2 requires the use of chemical absorbents, and amine-based solvents have been widely studied because it not only allows a large amount of CO_2 to be processed, but is also robust for a wide range of CO_2 concentrations. Although this approach in general is technically reliable since it had been successfully implemented in several chemical processes, the performance of solvent and the process itself still needs to be improved (Yu et al., 2012). In the past, reducing the energy demand of CO_2 capture was achieved either by developing innovative absorbents with low energy consumption or suggesting process alternative configurations

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http://dx.doi.org/10.1016/j.cherd.2015.08.016
0263-8762/

Nomenclature

CCS	carbon capture and storage (sequestration)
MVR	mechanical vapor recompression
OECD	Organization for Economic Co-operation and Development
EOS	equation of state
SRK	Soave–Redlich–Kwong
VLE	vapor–liquid equilibrium
CO_2	carbon dioxide
MEA	monoethanolamine
MTA	minimum temperature approach
E_i	exergy loss due to mass transfer
$\dot{E}_Q$	exergy loss due to heat transfer
$\dot{E}_W$	exergy loss due to work
$\dot{m}_i$	mass flowrate of a stream
h_i	enthalpy of a stream
S_i	entropy of a stream
Q_{Reb}	heating duty of the reboiler
Q_{Cond}	cooling duty of the condenser
T_0	reference temperature
CW	cooling water
EAC	equivalent annual cost
NPV	net present value
CAPEX	capital expenditure
OPEX	operating expenditure

which involve process or equipment retrofit. However, process integration with other aspects of CCS technology has been intensively researched which led to a broad range of process alternatives in overall CCS value chain. Many studies based on process simulation have been published for post-combustion of CO_2 using amine solvent. Abu-Zahra et al. (2007) introduced a simulation-based parameter optimization study using Aspen Plus' equilibrium model (RADFRAC), and Plaza used a rate-based distillation model to simulate the capture process and reduce the regeneration of the solvent by changing both the operating parameters and stripper configurations (Plaza et al., 2010). Le Moullec and Kanniche (2011), Cousins et al. (2011), and Ahn et al. (2013) reviewed multiple process flowsheet configurations to observe the energy saving effects, and one of the cases they examined was heat recovery of stripper's overhead stream. They proposed a stripper configuration where CO_2-rich overhead stream is compressed and heat generated from compression is utilized to reduce the energy demand of the reboiler. Similar work in stripper configuration study was also done by Oyenekan and Rochelle (2007) and Van Wagener and Rochelle (2011). Instead of using simulation-based analysis, Zhang et al. (2014) mathematically modeled a similar stripper configuration. Although previous studies provided energy reduction effect from their simulation data, appropriate validation of their model was not present.

In this study, a CO_2 capture test bed in Boryeong, South Korea is modeled using Aspen Plus' rate-based model using MEA solvent. Real experimental data obtained from the test bed were used to validate the capture process model. Technical difficulties and limitations encountered during operation were also taken into account as Aspen Plus model has been developed. Downstream CO_2 compression process was also modeled in Aspen Plus using the design data of the test bed, but this model could not be validated against the experimental data. An alternative process scheme, mechanical vapor recompression (MVR) is suggested where overhead stream's heat is recovered in a similar way as previous studies, but is rather focused toward integration of CO_2 capture with compression processes. In addition to reducing the energy consumption, exergy analysis based on the 2nd law of thermodynamics and economic analysis were performed to suggest an optimal operating condition for this process configuration.

2. CO_2 capture process modeling and validation

With courtesy of KEPCO E&C Company, operation data from the 0.1 MW CO_2 capture test bed unit at Boryeong power plant were obtained, treating approximately 350 Nm^3/h of flue gas containing around 14 volume % of CO_2. Construction of this facility was completed in 2010 and it can recover two tons of CO_2 emitted from pulverized coal-fired Boryeong power plant #7 and #8, each with 500 MW of electricity generation capacity. Overview picture of the facility and process schematics are shown in Fig. 1. This post-combustion amine capture process configuration is conventional and similar to other CO_2 capture projects worldwide. Compression facility was also added to the CO_2 capture test bed in 2013, and it was designed to compress approximately 25% of CO_2 captured from the test bed. The process mainly includes a compressor package, dryer package for dehydration, and chiller package for CO_2 liquefaction. Liquefied CO_2 at 2000 kPa (20 bar) is temporarily stored in a vessel and then passes through an ambient evaporator before being sent back to the stack.

Using the data collected from the test bed campaign in 2011, CO_2 capture process using monoethanolamine (MEA) solvent was modeled and validated using Aspen Plus (V7.3) with RateSep^{TM} package, which can simulate the behavior of non-ideal reactive distillation systems appropriately. Compression process was also modeled in Aspen Plus by using the process and equipment data provided by KEPCO E&C.

2.1. *Thermodynamic model*

From previous simulation approaches of CO_2 capture process, a vapor–liquid-equilibrium (VLE) model based on the activity coefficients model, electrolyte non-random two-liquids (ElecNRTL), was the most apparent selection for describing CO_2–H_2O–MEA systems (Abu-Zahra et al., 2007; Plaza et al., 2010). This property method takes into account for the Hillard thermodynamic representation, reaction kinetics of CO_2 with MEA solution, and various heat and mass transfer phenomena associated with this system of mixture. On the other hand, Soave–Redlich–Kwong (SRK) equation of state (EOS) was employed for the downstream compression section of the Aspen flowsheet. Previous studies have shown that SRK equation of state can predict the phase behavior of CO_2 and CO_2 mixture systems at high pressure (Li and Yan, 2009; Coutinho et al., 1994).

2.2. *CO_2 capture process modeling and model validation*

CO_2 absorption reaction is an exothermic reaction which also accompanies multicomponent mass and heat transfer in an absorption column (Kucka et al., 2003). In the stripper column, CO_2 is thermally detached from CO_2-rich MEA solvent using the steam extracted from power plant. A fin-and-plate type lean and rich amine heat exchanger between two columns