Applied Energy 108 (2013) 383–391

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Designing learning curves for carbon capture based on chemical absorption according to the minimum work of separation

Pedro R.R. Rochedo *, Alexandre Szklo

Energy Planning Program, Graduate School of Engineering, Federal University of Rio de Janeiro, Centro de Tecnologia, Bloco C, Sala 211, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, RJ 21941-972, Brazil

HIGHLIGHTS

- This work defines the minimum work of separation (MWS) for a capture process.
- Findings of the analysis indicated a MWS of 0.158 GJ/t for post-combustion.
- A review of commercially available processes based on chemical absorption was made.
- A review of learning models was conducted, with the addition on a novel model.
- A learning curve for post-combustion carbon capture was successfully designed.

ARTICLE INFO

Article history:
Received 7 November 2012
Received in revised form 6 February 2013
Accepted 1 March 2013
Available online 12 April 2013

Keywords:
Carbon capture
Chemical absorption
Learning curve
Exergy analysis

ABSTRACT

Carbon capture is one of the most important alternatives for mitigating greenhouse gas emissions in energy facilities. The post-combustion route based on chemical absorption with amine solvents is the most feasible alternative for the short term. However, this route implies in huge energy penalties, mainly related to the solvent regeneration. By defining the minimum work of separation (MWS), this study estimated the minimum energy required to capture the CO_2 emitted by coal-fired thermal power plants. Then, by evaluating solvents and processes and comparing it to the MWS, it proposes the learning model with the best fit for the post-combustion chemical absorption of CO_2. Learning models are based on earnings from experience, which can include the intensity of research and development. In this study, three models are tested: Wright, DeJong and D&L. Findings of the thermochemical analysis indicated a MWS of 0.158 GJ/t for post-combustion. Conventional solvents currently present an energy penalty eight times the MWS. By using the MWS as a constraint, this study found that the D&L provided the best fit to the available data of chemical solvents and absorption plants. The learning rate determined through this model is very similar to the ones found in the literature.

1. Introduction

The scientific literature has recently emphasized the analysis of carbon capture in energy facilities [1–4], which is considered to be one of the most important alternatives for mitigating greenhouse gas emissions [2,5]. Its application is being widely assessed in the scientific literature, mostly in industrialized countries [6–10], although emerging countries such as China [11–15], India [16], and Brazil [3,16–19] are also evaluating this option. Actually, in 2012, a pilot plant was designed to demonstrate carbon capture in an already planned coal-fired plant in Brazil [17].

There are currently three routes for carbon capture: post-combustion, pre-combustion and oxy-combustion. The most studied case is the retrofitting of existing thermal power plants in order to integrate the carbon capture facility [4,12,13,20]. This alternative is usually based on the chemical absorption of the CO_2 diluted in the flue gas of the thermal power plant – the so-called post-combustion capture route [21,22].

This paper focuses mainly on the post-combustion route, since it is the most well-established one, being already used in the chemical sector. It is also the main option for the retrofitting of power plants. Even though it appears to be an outdated and fully developed process, in fact there is still considerable room for improving it, as will be shown further.

All capture processes essentially involve at least one separation facility, which raises the need of new equipment and the increase of the final energy consumption. This energy cost can be considerably high for capture purpose and is evaluated as an energy penalty in the power plant. Typically, in post-combustion capture plants, the regeneration of the solvent and release of carbon dioxide is

* Corresponding author. Tel.: +55 2125628775.
E-mail addresses: rochedopedro@gmail.com, pedrorochedo@ppe.ufrj.br (P.R.R. Rochedo).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.03.007

responsible for the most part of the energy penalty, up to 60% [23,24].

Hence, in order to compare the various capture processes available today for retrofitting thermal power plants, it is worth estimating the minimum energy required to capture the CO_2 emitted, in a conceptual unit. This study estimates this "minimum work of separation" (MWS), as the lowest amount of energy required for the separation of one or more components of one or more mass flows. The MWS will be used both as an indicator and a threshold for the energy penalty.

The objective of this study is to correlate the energy requirements regarding the regeneration of the absorption-based carbon capture process with the learning trend of this same technology. Initially, it presents the methodology used for calculating the thermodynamic limit of carbon capture. Then, it reviews different learning models available in the scientific literature and develops a novel learning model. Afterwards, the study determines the MWS for the chemical absorption of carbon dioxide. Several solvents and processes are, then, compared to the MWS, and the study details the nature of the energy penalty. Finally, the study indicates the learning model with the best fit for the post-combustion chemical absorption of CO_2.

2. Methodology

This section presents the methodologies used to relate the thermodynamic limit of absorption based carbon capture process and the models that simulate technological learning. Firstly, the methodology for calculating the thermodynamic limitation of the energy penalty (in other words, the MWS itself) is presented. The MWS is then used as an indicator of the current status of the available and promising absorption technology, based on the performance deviation of the real solvents from the theoretic MWS. Afterwards, the use of learning models is discussed. These models are a powerful planning tool, widely used in the energy sector [1,25–30], for it allows the evaluation of scenarios regarding the cost reduction of different technologies. As will be thoroughly shown, in cases such as the chemical absorption there may be conceptual advantages in using models that allow a minimum threshold. Finally, this paper presents a learning curve for the carbon capture plant based on the historical evolution of the chemical absorption process and the MWS.

2.1. Thermodynamic limits of capture processes based on chemical absorption

Basically all capture processes (post-combustion, pre-combustion and oxy-combustion) involve at least one separation step that is strongly linked with the energy penalty. In recent years, the development of absorption-based capture processes focused mainly on the reduction of the energy penalty, either with the development of new solvents or designing processes with entirely new concepts [24,31]. The separation step of the absorption process is the most energy intensive one, particularly the solvent regeneration in the reboiler. For this purpose, this is the main focus of research and development in absorption and is regularly used as an indicator for comparing absorption processes [24,31].

In order to compare the various available capture processes, it is worth knowing the minimum energy required of a conceptual capture unit. As a general simplification, all capture process can be divided into two major steps: separation and compression of CO_2.

Even though some systems (such as pre-combustion capture systems) can produce a CO_2 stream at high pressures [3], since the main option currently accepted for the sequestration of large quantities of carbon dioxide is the geological storage of CO_2, a stage of compression is always required [17,20].

The minimum work of separation (MWS) was calculated through the exergy difference of the process streams involved, as such:

$$W_{\min} = \Delta B = \sum_{in} B - \sum_{out} B \quad (1)$$

Two different methodologies were used for calculating the exergy of the streams. The first method considered an ideal solution of the components and the exergy was calculated by the following equation:

$$\overline{B} = -R \cdot T_o \cdot \sum_{i=1}^{nc} x_i \ln x_i \quad (2)$$

where R is the universal constant, T_o is the reference temperature (298 K) and x_i is the molar fraction of the component "i".

The second method uses an equation of state (EOS) to calculate precisely the streams' properties at the process conditions [32], specially the entropy and enthalpy. The EOS used in this paper was the Peng–Robinson. Both properties can be used to calculate each stream's exergy by the following relation:

$$W_{\min} = \Delta B = \Delta H - T_o \cdot \Delta S \quad (3)$$

There are some studies that have taken a similar approach for calculating the exergy of a process stream. For instance [33,34] uses an approach based on the first method, while [32] based their findings on the method similar to the second. In the current study, both methods were used and the results were compared. The basic difference between the two models is related to how these methods account for the non-ideal behavior of the components. The first method, considers an ideal solution of components, while the second one, by applying an equation of state, is able to represent the non-idealities with higher degree of accuracy.

To calculate the MWS, one can define a general conceptual capture system with chemical absorption reactions as the one shown in Fig. 1. Firstly, it is assumed a standard capture rate of 90% [13,17,20]. As this is used throughout this study, we can safely compare different solvents/processes with the MWS. Assuming a flue gas stream with a certain amount of CO_2, the capture process, whichever it is, should generate a rich-CO_2 stream (to simplify, let us consider this stream as pure CO_2) and another stream, containing the remaining CO_2, that was not captured, and the remaining contaminants.

Generally, the last step of the capture process is the compression of the captured CO_2. This can also be an energy intensive step, especially for low pressure systems, such as post-combustion carbon capture systems. As for the MWS, the Minimum Work of Compression (MWC) is also calculated according to two methods. The first considers the work of an isothermal compression of an ideal gas. The second method uses an EOS, just as the second method for

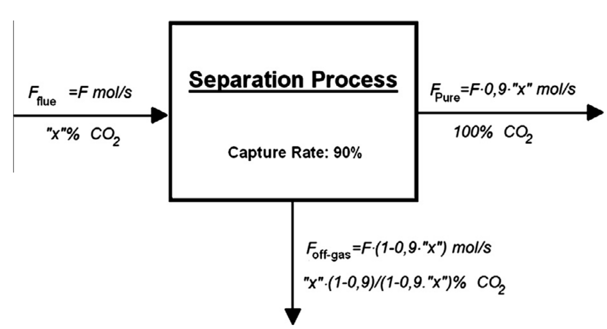

Fig. 1. Conceptual separation process.