Multi-objective optimization of a CO_2-EOR process from the sustainability criteria

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Abstract

Aim of this article is to estimate and discuss the economic and environmental impacts for the obtainment of CO_2 in such conditions to be injected as enhanced oil recovery (EOR) fluid. Particularly, this study focuses on the compression sector design needed to process the CO_2 coming from an already existing absorption plant. Currently, 18.68 kmol/h of a high-purity CO_2 stream may be used for injecting and increasing the production of a pilot crude oil well near the location of the industrial plant. However, it is still necessary to perform an economic evaluation to quantify the investment and the operating costs that the compression involves.

An optimization problem for minimizing the energy consumption of the new sector while increasing the pressure of the stream is solved. It has been found that the conditions to obtain the lower energy requirement are a 4-stage compressing layout with a pressure ratio equal to 4 and intercooling units of 41.73 °C. After discussing these results, an economic assessment to estimate investment, operating and utility costs is presented. Although the installation cost for the additional sector is more than 3000 kUSD, the investment might be compensated with the increasing production of the well under study. In addition to this, the development of EOR projects could create a market in a region where the technology is still not considered.

In the final part of the article, CO_2, CH_4, H_2O wastes and combustion gases emissions are calculated. As expected, almost the total amount of the vented CO_2 can be captured for this double-purpose technology, increasing the total incomes while geologically confining large-volumes of this pollutant and greenhouse gas.

Keywords: Sustainability, Economic assessment, Environmental impact, CO_2 EOR, CO_2 absorption process.

1. Introduction

Several industrial processes produce highly concentrated streams of carbon dioxide (CO_2) as a by-product (Herzog, 2011). For instance, the absorption of CO_2 from natural gas by using alkanolamines produces a high purity CO_2 stream, with a molar concentration over 87 % in most of the cases (Peters et al., 2011; Ahmad et al., 2012; Banat et al., 2014; Al-Lagtah et al., 2015; Gutierrez et al., 2016; Gutierrez et al., 2017).

As it can be inferred, this large amount of CO_2 produced continuously may be used for improving the crude oil production, during the stage of enhanced oil recovery (EOR). In this regard, the CO_2 for EOR has already demonstrated to be a technical and economic success in different locations for a number of years (Khan et al., 2013). Having a paramount potential for carbon dioxide capture and storage (CCS), the CO_2 EOR significantly increases the production of mature wells while decreasing the greenhouse gas emissions on a large-scale (Brush et al., 2000; Peters et al., 2011).

Different studies have assessed the economics involved in the installation of a CO_2 absorption for EOR purposes (Peters et al., 2011; Mazzetti et al., 2014; Kazemi et al., 2014; Suleiman et al., 2016). Peters et al. (2011) developed an economical model to calculate the capital investment and the gas processing cost of an amine-based process. To assess the economics, they performed a simulation model in Aspen HYSYS, where they assumed a molar concentration above 90 % CO_2 in the acid gas.

Mazzeti et al. (2014) estimated the costs of CO_2 removal from natural gas with subsequent geological storage by using a suitable simulation model. Particularly, they estimated the total capital cost to obtain CO_2 for EOR in North Europe, with an MDEA-based absorption process. From the economic viewpoint, they stated that large-scale EOR projects could cover the necessary expenditures to improve remote fields' production.

Kazemi et al. (2014) simulated an alkanolamine process with Aspen HYSYS and performed an economic assessment with Aspen Economic Analyser. Based on a typical gas produced in Iran, they compared the performance of the process with three other technologies in regard to their capital and annual costs, for different sour gas molar flows.

Suleiman et al. (2016) evaluated two absorption processes using a feed flow of 1245 kmol/h to produce a clean natural gas with purity of 99 %. Those authors used simulation models to define stream properties, heat duties, power requirements and equipment sizes. For the economic assessment, they introduced suitable raw material costs, working capital, capital of investment, and total annual incomes.

With reference to previous works, the alkanolamine process to clean the natural gas while obtaining a side-product CO_2 stream has been extensively studied worldwide. However, the economic assessment performed by the predecessors consider the units of absorption and regeneration only, and exclude the conditioning of the CO_2 to be used in different applications. This paper presents and discusses the optimal design, the economic evaluation, and the environmental impact to condition CO_2 for EOR. Although the costs of CO_2 obtainment and storage appear to be high, we discuss the sustainability and the effect of the investment in the region under study.

2. Location and process description

The southern Neuquén basin (NQNB) of Argentina is the location selected because its crude oil chemical properties favor the implementation of CO_2-EOR (Gallo and Erdmann, 2017). Large-scale volumes of CO_2 are emitted throughout this area from gas & oil processing industries, mining companies and power generation plants. Particularly, CO_2 coming from natural gas absorption plants is of special interest in this work for their permanent availability.

This typical CO_2 absorption process features two main operations. In the former, the acid gases of the natural gas are chemically absorbed by an alkanolamine liquid stream. In the latter, that rich amine leaving from the bottom of the absorption tower is sent to a stripping column, where the CO_2 is recovered at higher purity.

3. Methodology

Initially, the steady-state of the process to remove CO_2 from a natural gas stream is simulated in Aspen HYSYS (Aspen Tech., 2012). In the simulation model, a combination of the Non-Random Two-Liquid method for electrolytes (eNRTL) and the Peng- Robinson Equation of State for vapor phase is applied for the prediction of the thermodynamic properties (Song and Chen, 2009). Material streams, flowrates, compositions and conditions are taken from an existing MDEA-based absorption plant in Argentina (Figure 1).

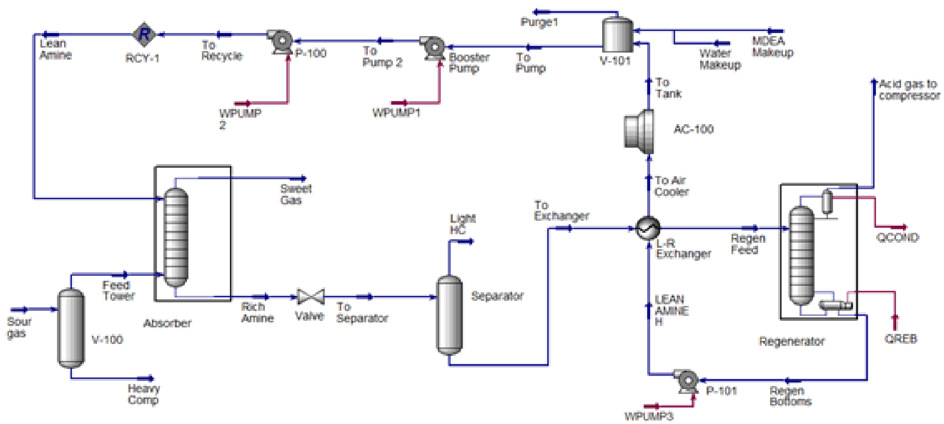

Figure 1. MDEA-based absorption plant for removing CO_2 from natural gas.

18.68 kmol/h of acid gas at 47.27 °C are obtained from the top of the stripping column, composed by CO_2 (87.93 mol%), water (9.32 mol%), methane (1.33 mol%), and heavy hydrocarbons. However, the pressure of the stream is considerably low (14.50 psia) and thus a subsequent compressing system should be design to properly dispose this high purity CO_2 stream.

According to empirical considerations, a 4-stage compression system might be implemented to increase the pressure of the acid gas leaving the plant. In the sector to be designed, the available variables are the temperature of the intercooling stages and the pressure ratio of each compressor. Centrifugal compressors with 75 % adiabatic efficiency are assumed and logical operators (SET and ADJUST) are used to unify the compression ratios and the cooling temperatures (Figure 2).

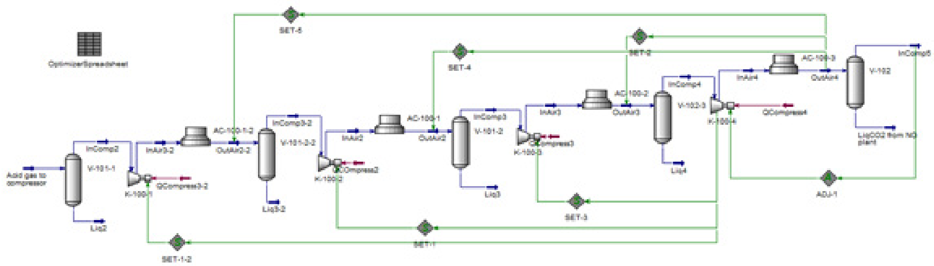

Figure 2. Compression and intercooling of 4-stages for CO_2 conditioning.

After modelling the compression sector, we propose a minimization problem to define the optimal conditions. Eq. (1) summarizes the mathematical expression representing the minimum problem to solve.

$$\begin{gathered}\min_{u_1,u_2}(Q_{Total})\\ s.t.:\\ 2 \leq u_1 \leq 10;\\ 25 \leq u_2 \leq 55;\\ y_{CO_2}^{Prod} > 0.87\\ P_{CO_2}^{Prod} > 6{,}000 kPa\end{gathered} \qquad (1)$$

Where $Q_{Total} = Q_{Compressing} + Q_{Cooling}$ (MJ/h) is the duty needed for the compression and the cooling stages. u_1 represents the pressure ratio for each centrifugal compressor, u_2 the temperature after the cooling units (°C), $y_{CO_2}^{Prod}$ and $P_{CO_2}^{Prod}$ the purity and the pressure of the CO_2 product stream.

Similar to Kazemi et al. (2014), we employ Aspen Economic Analyser to estimate capital costs, operating costs and utility costs of each process. Using Aspen Energy Analysis and material balances, we also estimate the greenhouse gases emissions (GHG) particularly CO_2, H_2O, and CH_4 for the studied alternative.

4. Results and discussion

In Table 1, the values of optimal Q_{Total}, u_1, and u_2 are shown. As it can be seen, the compression ratio remains equal to 4 for design purposes, and the temperature of the intercooling stages slightly under the initial acid gas temperature.

Table 1. Optimal values of Q_{Total}, u_1, u_2, $y_{CO_2}^{Prod}$, and $P_{CO_2}^{Prod}$ for the 4-stage process design.

Q_{Total} (MJ/h)	u_1	u_2 (°C)	$y_{CO_2}^{Prod}$	$P_{CO_2}^{Prod}$ (kPa)
639.85	3.849	41.73	0.9777	6,865

A total equipment cost of 3,828 kUSD is estimated for this design, distributed in accordance with the Figures 3 (a) and (b). Concerning the distribution of the investment cost, the compressors represent 86 % of the total investment.

Figure 4(a) shows the total operating and utility costs. The values observed might be attributed to the significant consumption of electricity.

Figure 4(b) presents the distribution of the energy consumption. Contrary to the expected, the highest consumption corresponds to the air-cooling system due to temperature drops of around 40ºC.

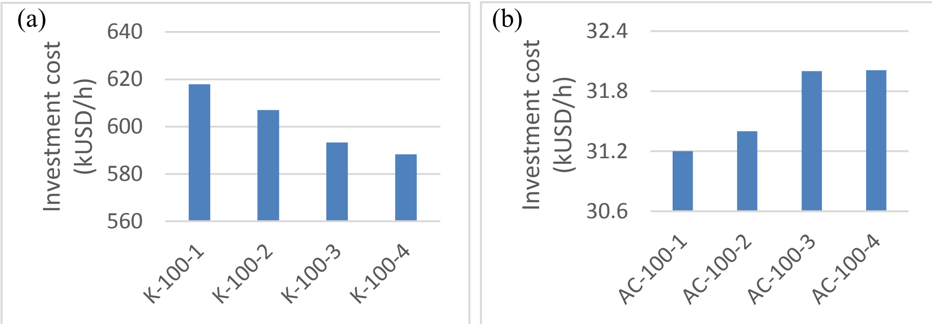

Figure 3. Investment cost (kUSD) per each (a) compressor, and (b) cooling unit of the 3 and 4-Stages system.

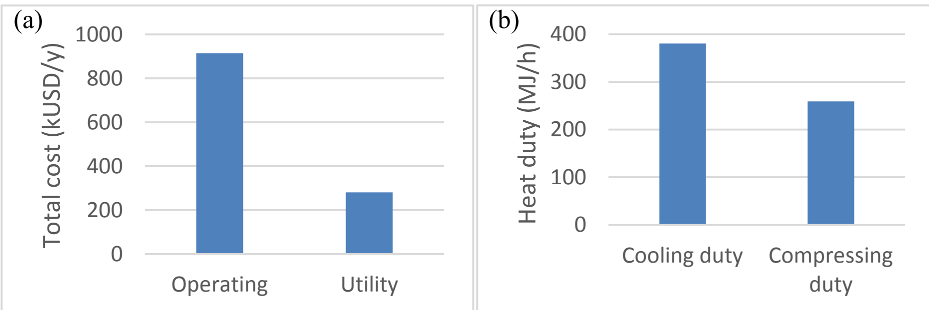

Figure 4.(a) Operating and utility costs (kUSD/y); (b) Distribution of the heat duty (MJ/h).

Even though the total cost for including the compression section falls in the order of million USD, the income for the industry should also increase. Gallo and Erdmann (2017) estimate a production of more than 2 bbl of crude oil per CO_2 ton, injected in a sample well of the NQNB.

Figure 5 shows the leaks to the environment. Molar flows (kmol/h) of CO_2, H_2O, CH_4, and other GHG are plotted. Respect to the combustion GHG emissions, they were estimated assuming hot oil burning in the stripping column. As it can be observed, the CO_2 wastes remain almost negligible with the addition of the compression section.

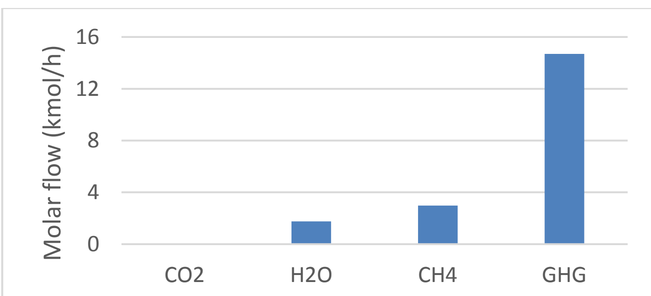

Fig. 5. Comparison of gases leaks (kmol/h).

5. Conclusions

An optimal design to condition CO_2 for EOR purposes is presented. According to the study, a total amount of 18.26 kmol/h of high purity CO_2 at 6865 kPa can be obtained from an already existing gas plant for improving crude oil production. Although the investment for the additional sector to start is over 3,000 kUSD, the investors should also take into account that not only the CO_2 emissions are almost reduced to zero but also that the EOR may start a market in the NQNB where this technology is not still exploited.

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