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Process analysis for the carbon dioxide chemical absorption–regeneration system

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HIGHLIGHTS

- The steady state design for a CO_2-MEA absorption-stripping system is analyzed.
- The column internal profiles are considered along with the outputs.
- An L/G ratio range is defined to avoid isothermal zones in the absorber.
- An alternative configuration without reflux is used for the stripper.
- A minimum energy consumption is found maximizing the stripper feed temperature.

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ABSTRACT

The process analysis for the post-combustion CO_2 capture using amine-based solvents is nowadays a fundamental step in its industrial scale design. In this work, the absorption-solvent regeneration system is deeply analyzed for different values of the loading in the solvent entering the absorber. The importance of the temperature and composition column profiles is highlighted for both the columns. In particular, the tight connection between the profiles and the L/G ratio is found to influence the choice of solvent flow rate for what concerns the absorber. On the other hand, an alternative configuration for the stripper is proposed together with a new criterion for the evaluation of the packing height. Finally, it is found that, in order to minimize the energy consumption in the stripper, the rich solvent must be sent at the highest possible temperature, taking into account the limitations imposed by the minimum temperature approach in the cross heat-exchanger and the solvent degradation.

1. Introduction

In the field of Carbon Capture & Storage (CCS) technologies, the post-combustion capture using amine-based solvents is nowadays recognized as the most mature and promising process, as it is retrofittable in already existing plants [1–4]. The main drawback for its implementation, at an industrial scale, is represented by the high energy consumption [4–10]. The process consists in the coupling of two main sections: the absorption, where the CO_2 is captured, and the stripping, where the solvent is regenerated.

Among the different research branches in this topic, the process modeling represents a fundamental part. A model that is able to reliably describe the behavior of the system, is a mandatory tool to study a large variety of process scenarios, in particular when it is necessary to design a new plant or when it is required to test and implement a new control structure.

Most of the works concerning the modeling have been focused on model validation using experimental and pilot plant facilities [11–17]. For what concerns the industrial plants, very few experimental data sets are available, mostly reporting values in the extremes of the columns only [18], leading to the impossibility to test models on that scale.

However, industrial plants have been taken into account in different works. For instance, Singh et al. [19] made an economical comparison between a post-combustion capture with MEA system and an O_2/CO_2 recycle combustion. Alie et al. [6] and Abu-Zahra et al. [7] studied the effect of different operating parameters on the process through sensitivity analyses. Cau et al. [8] compared two different power generation systems integrated with a CO_2 post-combustion capture plant. Lawal et al. [20] and Nittaya et al. [21] performed the design of a CO_2 post-combustion capture plant by means of a dynamic model.

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Nomenclature

G	flue gas flow rate [kmol s^{-1}]
H	packing height [m]
L	solvent flow rate [kmol s^{-1}]
T	temperature [K]
x	liquid molar fraction [mol frac]

Subscripts

b	boiling point
in	feed
low	lower limit
up	upper limit

Superscripts

app	apparent molar fraction
eff	effective
min	minimum

The results obtained in the different works are not in agreement in most cases, due to the different amount of flue gases treated and the different operating conditions considered. For instance, the optimal lean solvent loading ranges between 0.25 [6] and 0.32 [7]. The same was observed for the specific reboiler duty, which ranges from 1.7 GJ/t_{CO2} [19] to 4.1 GJ/t_{CO2} [21]. Furthermore, except for Abu-Zahra et al. [7], where a sensitivity analysis varying all the most important operating parameters was made, the majority of the works are focused on the effect of few operating parameters only. For example, Lawal et al. [20] and Nittaya et al. [21] investigate the effect of the absorber packing height on the energy consumption, while Cau et al. [8] reported the variation of the CO_2 removal with the L/G ratio and the reboiler duty. Moreover, all of these analyses are made using different mathematical models, from the equilibrium stage [6–8] to the rate-based model [20,21], and the choice of a rigorous model over a simpler one can lead to significant differences in the results.

In general, the approach for the design of the absorption-stripping processes is based on a number of sensitivity analyses, where the columns dimensions and the operating parameters are varied over a certain range of values in order to obtain the desired final performances. In these analyses the column profiles are usually neglected. This fact could lead to columns that do not work correctly, although the results at the extremes, i.e., product purity, duty, removal percentage, etc., are those required. Both the output values and the profiles should be considered as equally important in the process study. In this way, it is possible to avoid design results that could be misleading due to the fact that only the final performances are checked.

A design approach based on the contemporary focus on the internal column behavior and the final performances was adopted in this work, where an industrial CO_2 post-combustion capture system using MEA was examined on Aspen Plus. The rigorous rate-based model, that takes into account both the ionic equilibria and the kinetic reactions involving the CO_2 in the liquid phase, together with the material and energy transfer limitations due to the reactions, was used. In particular, the design of both the absorber and the stripper was studied for different loadings in the solvent entering the absorber. Starting from the lean solvent loading, the effect of various important process parameters was analyzed. For what concerns the absorber, the effect of the L/G ratio was taken into account, determining the limits where it was possible to have a column that was consistent both from the output streams and the internal behavior standpoints. When the stripper was considered, an alternative column configuration without reflux from the condenser was used to avoid an unnecessary energy consumption. Moreover, a criterion for the determination of the minimum packing height for the stripper was proposed through the liquid temperature profiles analysis. Finally, the influence of the stripper feed temperature was examined, identifying it as the most important parameter for what concerns the reduction of the energy consumption in the whole process.

The main aim of this work was to prove that the definition of the optimal operating parameters has a direct influence on the design of the absorber and the stripper. Optimal conditions derived by evaluating only the process global performance, like streams purity or component recovery, could lead to non-feasible design. This aspect was proved by the simultaneous analysis of the operating parameters and their impact on the column temperature and composition profiles for the absorber and the stripper.

This work provides a useful procedure for the process analysis and its direct impact on the process design.

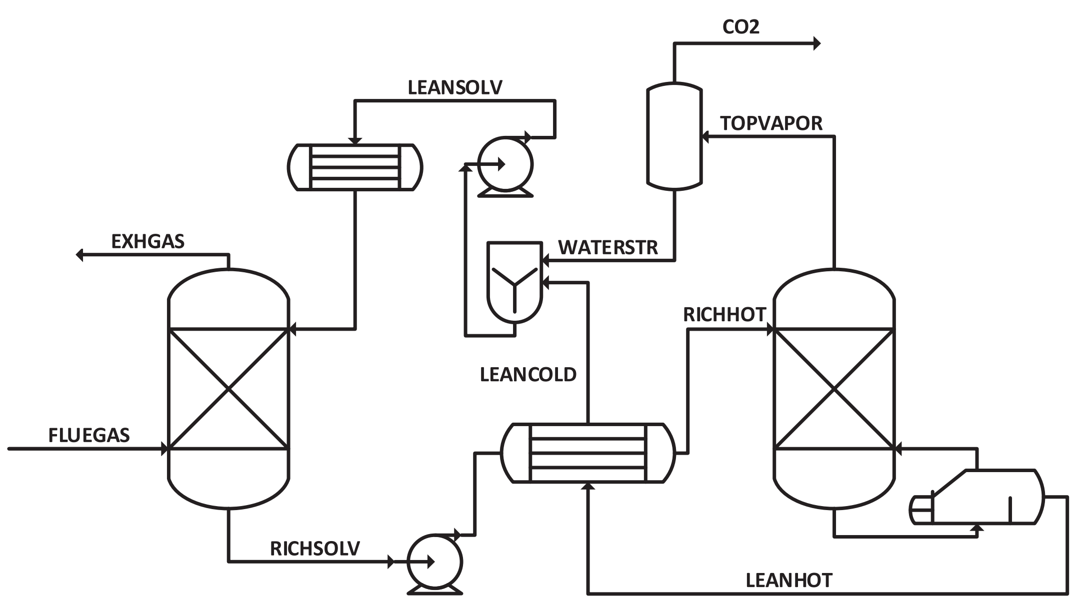

Fig. 1. Flowsheet of the plant.