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Design of a CO_2 Removal Section Treating Very High Flue Gas Flowrates

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Carbon capture and storage (CCS) is a technology that can be used to significantly reduce the gradual global increase in Earth warming. Several methods are available, with absorption by amine solvents being the most feasible and technologically mature. One possible successful application of this process is to the post-combustion removal of carbon dioxide from flue gas from power plants before its emission to the atmosphere. The design and optimization of this plant in order to minimize the power consumptions and the overall costs is of primary importance, in particular when dealing with very high gas flowrates to be treated. This paper aims at determining the best scheme of CO_2 removal plant to be installed in a facility for power production in Italy which allows the lowest power and economic losses. Three different configurations with columns provided with trayed or packed internals have been considered and the analysis with a comparison of the schemes has been carried out. The assessment of the technical performance of the plant has been performed by employing a rigorous rate-based model in ASPEN Plus®, and the selection of the scheme which minimizes the power losses has been made by comparison of the obtained results.

1. Introduction

Coal is one of the World's primary energy resources, and it produces large amounts of carbon dioxide, which causes Earth's temperature to increase. In the last years, then, coal combustion for electric power generation and technologies to remove carbon dioxide from the associated flue gas emissions have been widely studied, with many literature papers and reviews focusing on it (Dutcher et al., 2015; Goto et al., 2013; Granite and O'Brien, 2005; Li et al., 2013; Mondal et al., 2012; Mumford et al., 2015). In addition, the promotion of clean technology and the ever increasing energy demand has made Natural Gas Combined Cycle (NGCC) power plants substituting coal-fired power units. This trend has been further enhanced by the extensive use of fossil fuels for power production, which still remain the main source in this field, and the need of replacement of ageing coal-fired power units.

The International Energy Agency (IEA) has estimated that the total gross consumption of natural gas has increased of 3.7% in 2018 in comparison with the previous year, with a total consumption increase of 4.6% from January to October (IEA, 2019). For power production, NGCC plants are preferred because of the lower carbon content in natural gas compared to coal and oil, so that emissions to the atmosphere of the exiting flue gas contain low amounts of carbon dioxide (Global CCS Institute, 2013). However, to make the production of energy cleaner, post-combustion CO_2 removal systems are required also in this type of plants and, analogously to coal-fired power plants, chemical absorption by conventional aqueous amine solutions can be employed for this purpose (Moioli and Pellegrini, 2018b). This technology has been used since decades (Kohl and Nielsen, 1997) for the purification of gaseous streams from acid gases as carbon dioxide and hydrogen sulfide in industry and is recognized to be an effective method for the removal of CO_2 from atmospheric flue gas streams. Though making the electricity production environmentally cleaner, the construction and the operation of the CO_2 removal and compression section downstream power plants always requires additional energy compared to the one needed in similar plants without Carbon Capture and Storage (CCS) units (Gibbins and Chalmers, 2008). Indeed, energy for regenerating the amine solvent by extracting low pressure

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steam from the turbine (therefore reducing the power production) and for compressing the absorbed carbon dioxide is needed (Abu-Zahra et al., 2007; Giuffrida et al., 2016), and reduces the net power output of the plant, with increase of costs for electricity production (Davison, 2007). To make CCS viable also in NGCC units, then, the impact on the performance of the overall power plant must be the lowest. The design and the optimization of the CO_2 removal section is then of primary importance in order to minimize the power losses and the associated costs, in particular when dealing with large gas flowrates to be treated, as the ones of large power plants in the Italian territory (Terna Group, 2014). This paper focuses on the design of the post-combustion CO_2 removal section downstream a NGCC power plant, with the aim of determining the scheme which allows the lowest power and economic losses to the overall system.

2. Methodology

The work has been carried out by comparing three different configurations of the CO_2 removal plant for the 630 MW power plant by Fout et al. (Fout et al., 2015), which differ mainly for the number and the type of columns. For each alternative, the units have been specifically sized and the characteristics of the circulating solvent, in particular flowrate and lean loading (defined as moles of carbon dioxide per moles of amine) have been chosen to minimize the energy consumption. The design of the plant has been performed also taking into account the rules of thumb by Turton et al. (Turton et al., 2012) and by Walas (Walas, 1988) and the issues of degradation and corrosivity of the MonoEthanolAmine (MEA) solvent (Rochelle, 2009), used in this study. The chemical absorption system is characterized by the occurrence of chemical reactions in the liquid phase where the carbon dioxide absorbed from the vapor phase as molecule reacts with water and MEA forming ions. The formation of ions enhances the absorption process, though it makes the system thermodynamically strongly non-ideal. In addition to the description of the thermodynamics, also mass transfer with kinetic-controlled reactions must be taken into account.

ASPEN Plus®, user customized by the GASP group of Politecnico di Milano for the best description of the system (Moioli and Pellegrini, 2015, 2016, 2018a, 2019; Moioli et al., 2017) has been employed for the simulation of the CO_2 removal plant. The same software has been employed for the simulation of the compression section of the CO_2-rich stream (*CO2*). Figure 1 shows one of the process flowsheets used for the simulation.

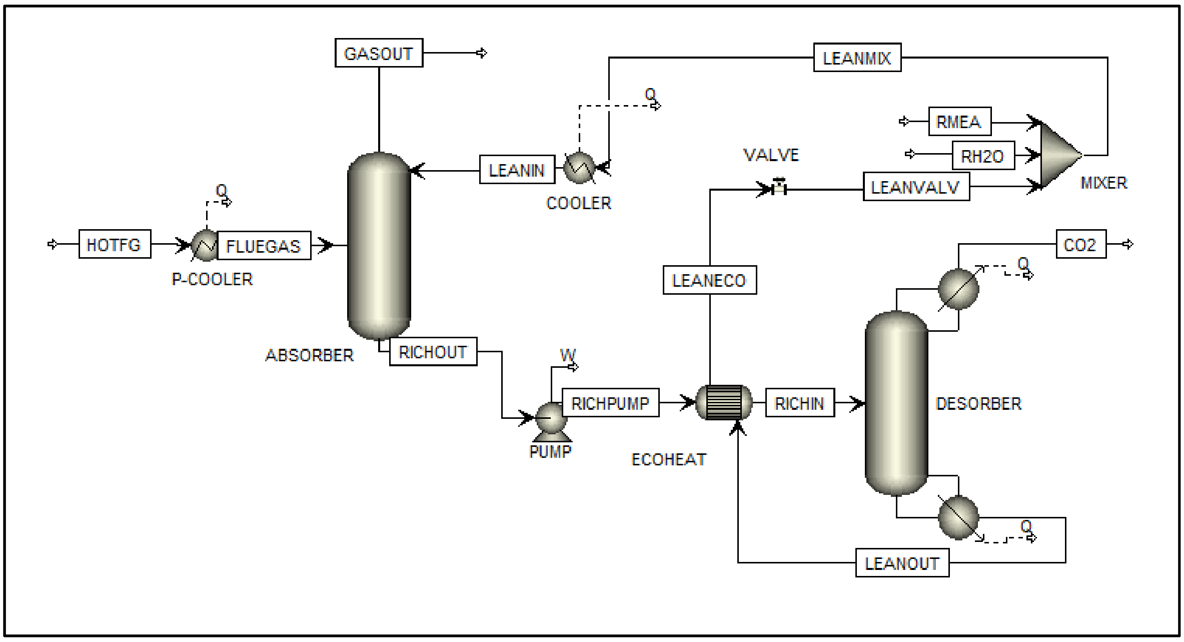

Figure 1: Process flow sheet in ASPEN Plus® for simulation.

The flue gas (*FLUEGAS*), that must be purified, flows upward through the absorber (*ABSORBER*), counter currently to a stream of aqueous amine solution (*LEANIN*). Before entering the absorber, the gaseous stream (*HOTFG*) is cooled down to its dew temperature with cooling water (*P-COOLER*). The rich solution (*RICHOUT*) from the bottom of the absorber pressure is pumped (*PUMP*) to the desired stripper pressure and then the solution (*RICHPUMP*) is warmed in a process-process heat exchanger (*ECOHEAT*) by the lean solution (*LEANOUT*) from the bottom of the regeneration column (*DESORBER*). The rich solution (*RICHIN*) is then fed to the stripping column at the top of the stripper. After partial cooling in the lean-to-rich solution heat exchanger, the lean solution from the regenerator (*LEANOUT*) is expanded to 1 atm in an isenthalpic valve (*VALVE*) and integrated with MEA and water make-up. After that, it is further cooled by heat exchange with cooling water (*COOLER*) and fed to the top of the absorber. The acid gas removed from the solution in the stripping column (*CO2*) is cooled to condensate a major portion of the water vapour and is then sent to the CO_2 compression station for transportation and geological sequestration.

3. Results and discussion

The considered flue gas stream, available at atmospheric pressure, has a flowrate of 36.26 kmol/s and a composition of 3.91% carbon dioxide, 8.41% water, 74.42% nitrogen, 12.38% oxygen and 0.89% argon. It is cooled to its dew point before its entrance to the absorption column where it is counter currently contacted with a 30% wt. MEA aqueous solution, for achieving 95% of carbon dioxide removal.
To this aim, both tray and packed columns have been considered and three different alternatives have been analyzed. Because of the large flowrate, feeding the flue gas to one single tower would make the unit need to be built with huge diameters, higher than 30 m, which are not generally employed at industrial level. The typical maximum diameter for tray columns is usually lower than 10 m, and for packed columns diameters up to about 15 m have started to be considered only recently (Fluor, 2017; Just, 2013; Shell, 2017). Moreover, because of wind load and foundations, the maximum suggested height for towers is 53 m, as generally considered by heuristics (Walas, 1988), and this value has been taken as a reference.
Considering tray columns with the maximum height (53 m) two possible configurations include the use of 40 or 20 parallel columns. The use of twenty columns would require higher solvent flowrates because of the lower contact time for transfer of carbon dioxide from the vapor to the liquid phase. In both the cases, the number of columns is very high and has a significant influence on both the investment and the operating costs of the system, in addition to the management of the plant, which is more complicated in the presence of a higher number of units. By providing a higher area for mass transfer, packing has been considered as internal for the units in the third scheme, resulting in only three parallel absorption columns with diameter of 12.5 m (in the range of those already industrially employed), to treat the overall flue gas stream.

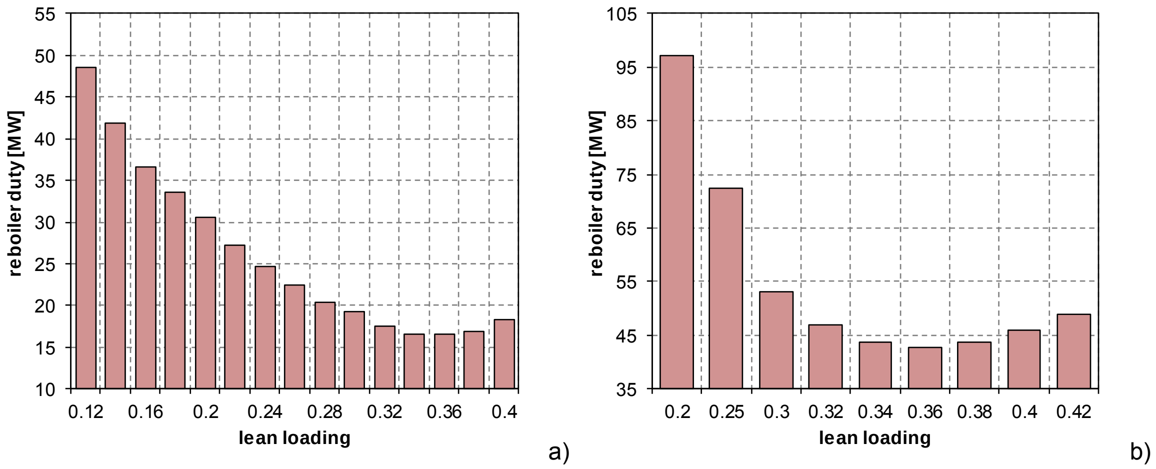

Figure 2: Variation of reboiler duty (expressed in thermal MW) referring to the CO_2 removal in one single absorption column with lean loading for a) scheme with 40 parallel absorption tray columns and b) scheme with 20 parallel absorption tray columns.

Figure 2 and Figure 3 show the variation of the reboiler duty for treating the solvent flowrate of each single absorption column due to the different values of lean loading. The reboiler duty is the main energy requirement of the plant and depends on the heat needed to reverse the chemical reactions, on the sensible heat to bring the liquid solution to the reboiler temperature and on the latent heat to vaporize the stream which acts as stripping agent. For 95% CO_2 removal, the relative contribution of the three terms depends on the lean loading and on the solvent flowrate, which is directly related to the lean loading. Therefore, by selecting the proper lean loading the minimization of the energy requirement can be obtained.

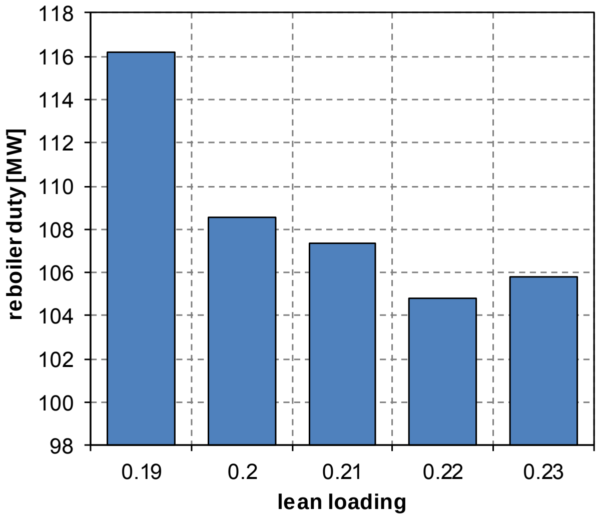

Figure 3: Variation of reboiler duty (expressed in thermal MW) with lean loading (mol CO_2/mol MEA) for the scheme with 3 parallel packed columns.

For tray columns the lowest reboiler duty is obtained with a lean loading of 0.36, while for packed columns with a lean loading of 0.22. For a fixed amount of carbon dioxide to be removed, the other main contribution of the CCS section, which is the power needed for compression, is the same for all the schemes. For this reason, the selection of the best configuration has been based only on the analysis of the reboiler duty, while the compression requirement is considered at the end of the paper to account for the total energy penalty of the power plant.

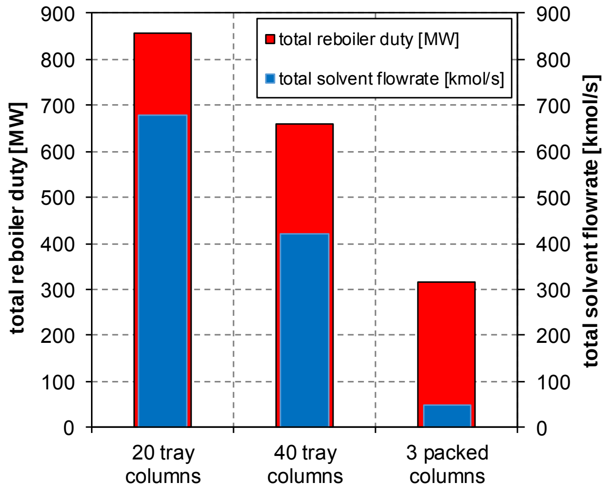

Figure 4: Total reboiler duty (expressed in thermal MW) and total solvent flowrate for the three schemes.

Figure 4 shows the comparison among the three schemes, in terms of total reboiler duty and total needed flowrate. For both the configurations with tray columns, the obtained reboiler duty is very high. The configuration with packed columns results the best one in terms of minimum energy requirement and total circulating solvent flowrate, therefore allowing for minimum power losses and so related expenses. In addition, this low number of units helps in saving investment costs and in dealing with the management of the plant.
As for the regeneration column, one single unit can treat the rich solvent for removal of the absorbed carbon dioxide, since its flowrate is lower than the one of the flue gas, because of the relatively low mole fraction of CO_2. The final scheme is represented in Figure 5.

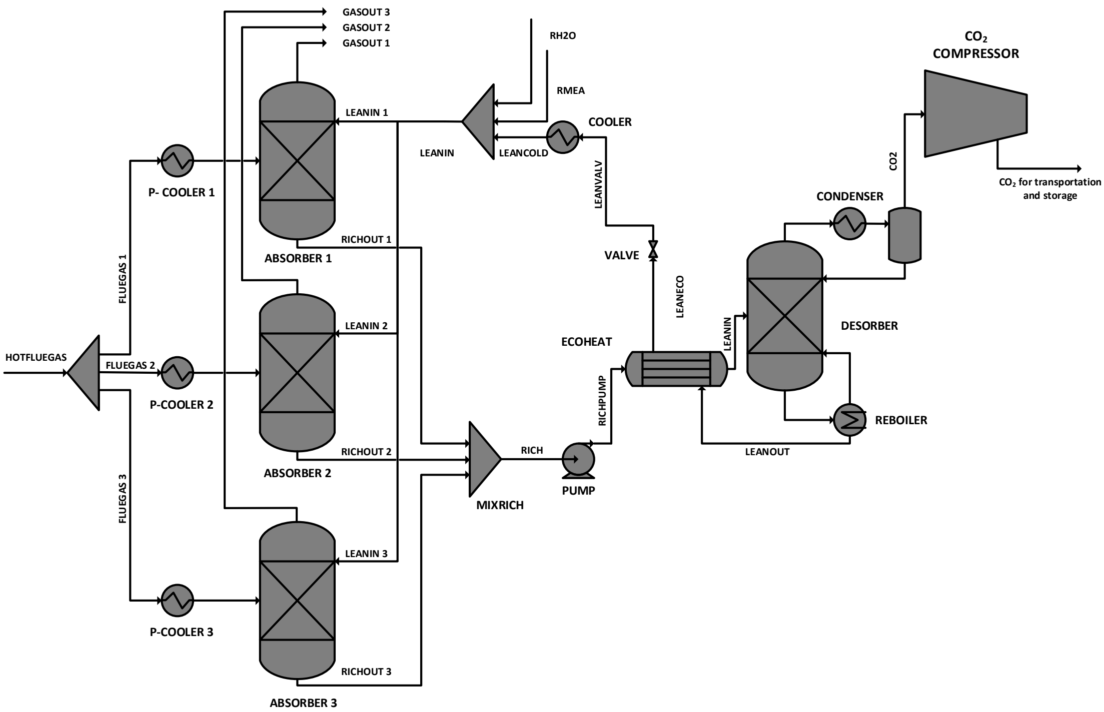

Figure 5: Process scheme of the selected configuration.

For the selected configuration, which is composed of three parallel absorption columns and one regenerating column, the net equivalent work has been considered for calculating the total power requirements for the overall CCS system, which include also the compression of the absorbed carbon dioxide.
The net equivalent work takes into account the power losses due to the CO_2 removal section in terms of electric MW and is calculated as:

$$W_{eq} = \eta Q_{reb}\left(\frac{T_{reb}+10-313.15}{T_{reb}+10}\right),\ \eta = 0.85 \quad (1)$$

with Q_{reb} the reboiler duty and T_{reb} the temperature of the reboiler. This parameter is generally considered for the estimation of the electric energy requirements due to use of steam for providing thermal duty to the process.
The plant consumption is estimated to be 76 MW_{el}, with a net power output of 554 MW, and corresponds to 12% of the total power production. This value is much lower than the one generally found for coal-fired power plants, for which up to 30% is required for the Carbon Capture and Storage system. This confirms the feasibility and the economic advantages of operating a CCS section downstream a power plant fed by natural gas, in addition to the higher environmental benefits.

4. Conclusions

This paper has been focused on the study of the post-combustion CO_2 removal plant of a Natural Gas Combined Cycle plant for power production in the range of those operating in Italy.
The purification process from acid gases by chemical absorption and solvent regeneration is an extremely energy intensive process, mainly due to the high energy requirement associated with the regenerator's reboiler. As a consequence, the main source of energy consumption of the CO_2 capture plant is represented by the reboiler heat duty, along with the power required to increase pressure.
In this work three different possible configurations have been considered, with trayed or packed towers, with the aim of determining the best process scheme. The technical performance of the plant has been carried out by employing a rigorous rate-based model in ASPEN Plus®, and the selection of the best scheme has been performed. The obtained results can be considered for understanding the directions for a feasible application of the post-combustion CO_2 removal process from NGCC power plants.

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