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Reducing Power Penalty Related to Post-Combustion CO₂ Capture in Coal Power Plants

Considering the important role of coal in energy security and in the same time the growing need to reduce CO_2 emissions, amine-based post-combustion CO_2 capture is considered as one of the most proper technologies to be implemented in coal fired power plants as well in natural gas fired plants, refinery gas, cement plants etc.. The main challenge for CO_2 post-combustion is reducing the energy demand of the process, especially for solvent regeneration. In this paper, the energy reduction potential when waste heat of flue gases is integrated in the CO_2 capture configuration scheme is discussed. The results are compared with a conventional coal power plant configuration when low-steam pressure is extracted from the water-steam cycle of the power plant.

Keywords: *CO_2 capture, post-combustion, monoethanolamine*

1. Introduction

Considering the important role of coal in energy security and in the same time the growing need to reduce CO_2 emissions, post-combustion capture, in particular chemical absorption, represents a feasible option for retrofitting existing coal-fired power plants. Monoethanolamine (MEA) is the proven solvent for this application.

Generally, the CO_2 capture based on aqueous monoethanolamine (MEA) solvent consists of two main processes: absorption and desorption (stripping/regeneration) (Figure.1) CO_2 packed absorption columns with MEA, operating at atmospheric pressure and 40-60°C are most commonly used. Columns are specifically suited for mass and heat transfer processes, since packed material provides great contact area between the two phases, flue gases entering at the bottom of the column and aqueous solution that it is sprayed at the top of the column [1]. CO_2 is transferred from the gas phase to the liquid phase through mass transfer with chemical reactions [2], [3]. CO_2-rich solvent with typical loading of

0.2-0.5 mol of CO_2/mol MEA [4] is then fed to the regenerator. The device is operated at 1.2-2 atm and 100-120°C [5] in order to break the bonds between the CO_2 and the solvent. The CO_2 is then compressed and transported to its storage place. Hot lean solution coming out from the desorber is cooled down by the cold rich solution in a cross heat exchanger and is further cooled to 40°C before entering the absorber. The solvent used is regenerated in a desorber column, for which energy is provided from the power plant in form of steam, thus affecting the efficiency of the power plant.

It is known that around 65% of the energy requirements in the amine based process is needed for MEA regeneration in the reboiler [16]. A simple energy balance across the desorber, as expressed by equations below, shows that the heat provided by condensing steam in the reboiler needs to cover the heat used to reverse the CO_2+MEA reaction ($Q_{des,CO2}$), the heat to generate steam in the reboiler ($Q_{steamgeneration}$), and to heat up the solvent from the temperature at the inlet to the reboiler temperature ($Q_{sensible\ heat}$). In this equation n_{CO2} and n_{H2O} is the number of moles of CO_2 and H_2O respectively, H_{absCO2} and H_{vapH2O} is the heat of absorption of CO_2 and heat of vaporization of water.; V is the vapor mole flow in the reboiler and L is the mole flow in the reboiler; cp is the liquid specific heat, T_{bottom}-T_{top} is the temperature difference between top and bottom of the desorber column [15].

$$Q_{reb} = \overbrace{- n_{CO_2} \cdot H_{absCO_2}}^{Q_{desCO_2}} + \overbrace{(V - n_{H_2O}) \cdot H_{vapH_2O}}^{Q_{steamgeneration}} + \overbrace{L \cdot cp \cdot (T_{bottom} - T_{top})}^{Q_{sensibleheat}} \quad (1)$$

These three contributions of the overall reboiler heat duty are dependent of each other, therefore an optimization of one would have influence on the others.

In literature different references on modeling, simulation and optimization of CO_2 capture with MEA can be found. Alie et al. [9] applied flow-sheet decomposition method for simulating key variables affecting MEA scrubbing process, assuming that the reboiler energy is provided by steam from the IP turbine. Singh et al. [4] used HYSYS and Aspen Plus simulator to estimate the CO_2 capture costs and to compare the performance of two technologies: MEA scrubbing and O_2/CO_2 recycle combustion process. Their simulation was performed using Aspen Plus. Aroonwilas and Veawab and Romeo et al. [11] studied the possibility to reduce CO_2 capture energy penalties and they stated that the optimal location to extract power for a solvent system is from the LP turbine at the appropriate pressure to provide steam at lowest quality that satisfies the solvent system reboiler requirements. Mimura et al. [12] uses 14% of the desorber condenser energy to heat the boiler feedwater. Desideri and Paolucci [13] and Romeo et al. [14] suggest utilizing some of the available heat from the CO_2 compressor intercoolers to heat the boiler feedwater. An IEA GHG report [15] utilizes a number of waste heat streams to increase the overall plant efficiency. Wibberley considers the integration of a solar energy field in order to directly provide heat for the desorber of the capture plant [16].

The present study the energy saving potential by flue gas heat recovery in the CO_2 capture process.

2. Reference case

The reference power plant is a 300 MW$_e$ circulating fluidized bed boiler (CFBC), the data for which is compiled in Table 1, and represents the basis for further discussion in this paper. The CFBC boiler was chosen because, beside the fact that the state of the art for the commercial scale is smaller compared to pulverized coal, and with one exception [6] the steam parameters are subcritical, combustion in CFBC presents some interesting advantages [7]. Some of the most important advantages of CFBC technology are: good combustion efficiency (90-99%), extensive fuel adaptability range, lower NOx emissions due to the low temperature in the furnace (between 800-950°C), the possibility to reduce the SO$_x$ emission by limestone injection in the furnace, etc.

The gaseous products from coal combustion that this study focuses on (CO$_2$, N$_2$, O$_2$, H$_2$O and SO$_2$) are calculated on the basis of stoichiometry relations for coal combustion. The results are presented in Table 1. For this study, boiler efficiency has been assumed 90% (LHV). Coal composition and the main characteristics of the power plant are presented as well in Table 1.

Table 1.   Main design conditions for 330 Mwel CFBC boiler

Coal composition [8]	
Moisture	8.97 wt%
Ash content	40.30 wt%
Carbon	37.20 wt%
Hydrogen	2.43 wt%
Oxygen	9 wt%
Nitrogen	1 wt%
Sulphur	1.1 wt%
High heating value (HHV)	14.000 MJ/kg
Power plant data design	
Gross/Net Power Output	311 MWe/300 MWel
Gross/Net efficiency	39.07%/37.68%
Main steam pressure	185 bar
Main steam temperature	530°C
Main live steam flow	238 t/h
Reheat steam temperature	530 °C
Feed water temperature	254 °C
Condenser pressure	0.054 bar
Pre-heating stages	7

The CFBC boiler produces 240 kg/s live steam at 185 bar and 530°C (subcritical conditions). The steam expands through a high pressure turbine up to 40 bar

and reheated up to 530°C and then conducted to the IP and LP turbines where it expands up to 0.054 bar, the pressure which corresponds to condenser temperature. The mass flow is then preheated in seven feedwater heaters with small parts of steam extracted from different parts of the three turbines and pumped back to the steam generator. The simulations have been carried out using Aspen Plus software [9] where each turbine was modeled as a series of single turbine stages interspersed with flow mixers and splitters. The close feedwater pre-heater are shell and tube heat exchangers that were modeled with HEATEX blocks. The deaerator is an opened feedwater pre-heater and was modeled using the MIXER block. The feed water pumps are modeled using PUMP blocks. The boiler, the reheater and the condenser are modeled using HEATER blocks. The STEAM-TA property method was used. This method implements ASME [10] stream tables to calculate the thermodynamic property of water and steam.

3. Base case with CO_2 post-combustion capture

The base case with CO_2 post-combustion capture was simulated with Aspen Plus considering the complete and closed CO_2 capture process flowsheet in order to keep the overall water balance to zero. Despite the difficulty to make the flowsheet to converge due to the recycle structure, just in this way the results are much realistic. For all simulations aqueous solution of ethanolamine (MEA) was considered, as compared with other solvents MEA is cheap, largely available, non toxic and highly effective solvent with high capacity for CO_2 capture and fast reaction kinetic as well the results might represent a basis for further work, when other solvents would be considered.

**Table 2.** Main input parameters for CO_2 capture process

Flue gas composition	
CO_2	12 vol%
O_2	6.6 vol%
H_2O	10 vol%
SO_2	0.05 vol%
N_2	71.35 vol%
NO_2	0 vol%
Flue gas mass flow	354.5 kg/s
Flue gas temperature at absorber	55°C
Absorber pressure	1.013 bar
Desorber pressure	1.8 bar

The main component of the process, the absorber and desorber were modeled using RADFRAC blocks and equilibrium based model. The data on chemical media provided by Aspen Plus was used. The Non-Random-Two-Liquid (NRTL) unit for electrolyte solutions was chosen for modeling equilibrium in the desorber and absorber.

Even though 30wt% MEA is considered the state of art technology for CO_2 capture processes by chemical absorption as increasing MEA concentration it is known to increase the level of degradation [11], recent studies [12] identified new degradation inhibitors that can reduce the degradation of 40%-wt MEA to a level close to zero. As well, 40 wt% MEA it is expected to allow higher process performances with reduced solvent flow rate. For this reason the simulations were performed for 30, 35 and 40wt% MEA. The simulations were performed as well for different capture rates (Ψ_{CO2} = 85% 90% and 95%). The flue gases composition used for the simulations and other parameters used in the simulations is presented in Table 2.

Steam from the power plant is used to provide heat for desorber reboiler. Generally there are several locations along the turbine where it is feasible to extract steam process use: (a) at the inlet of the IP, and LP sections, (b) at the turbine outlet, (c) at locations where steam is already extracted for feed water preheating, (d) at IP/LP crossover. The lowest grade heat should be used.

The solvent temperature in the reboiler was around 122°C. Considering a hotside approach temperature of 10°C the reboiler steam pressure required should be the saturation pressure for the temperature of 132°C. Assuming a pressure drop of 0.5 bar through piping from extraction point to reboiler inlet then the minimum extraction pressure and temperature required are 3.4 bar and 138°C. However, none of the original steam bleedings have saturated temperate 138 °C.
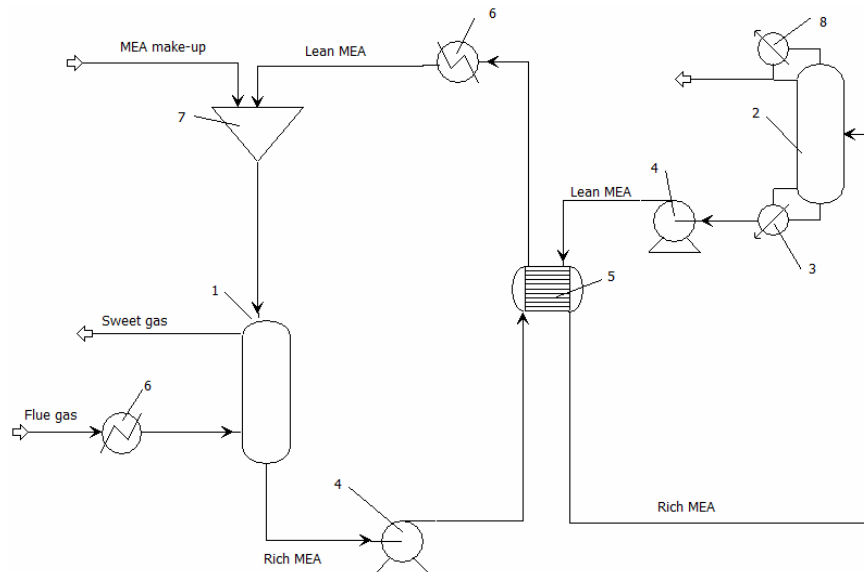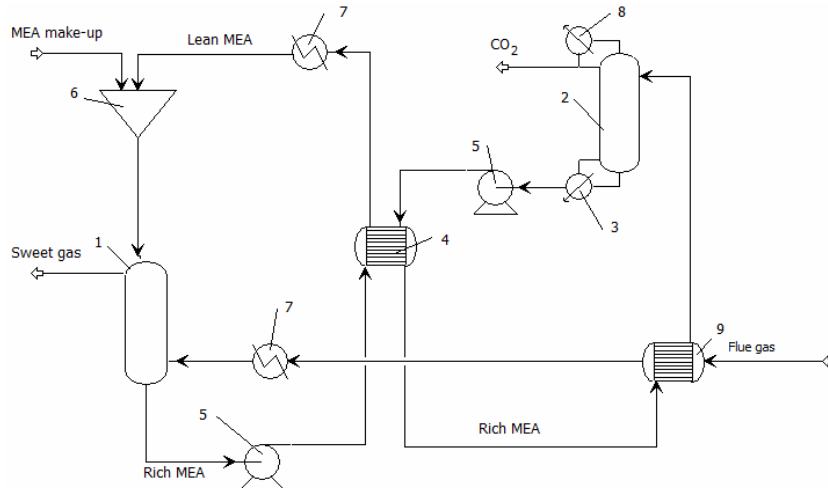

Absorber; 2. Desorber; 3. Reboiler; 4. Lean/Rich Heat Exchanger, 5. Mixing tank; 6. MEA Cooler; 7. Pump

Figure 1. Diagram of conventional MEA based CO_2 capture system

Therefore the closest extraction point to p=3.4 bar should be located and used. In our case, the extraction point was at IP/LP crossover at 4.8 bar.

3. Waste heat of flue gas integration in CO_2 capture process

The same parameters as mentioned above have been used for the simulations when waste heat of flue gases is integrated in the CO_2 capture system. Before entering the desorber the rich MEA that gets out from lean/rich heat exchanger (4) passes through a flue gases-MEA heat exchanger. The flue gases enter at 160°C on the hot side of the heat exchanger. The flue gas – MEA heat exchanger was modeled using HeatX unit with chemical reactions from the available Aspen Plus Model Library. If temperature of the flue gases would have been high enough to provide the heat required in the regeneration process, then the reboiler could have been modeled just as a HeatX with a flash with the role to separate the vapor phase from liquid phase. But, in this study, the flue gas temperature is considered to be 160ºC as usually flue gases are released to the atmosphere at temperatures typically between 150 and 200 ºC. In the heat exchanger (9), flue gases are cooled down to 125 ºC and then they are further cooled in order to meet the requirements of temperature in absorber (40 ºC).

1. Absorber; 2. Desorber; 3. Reboiler; 4. Lean/Rich Heat Exchanger, 5.; Pumps; 6. Mixing tank MEA; 7. Cooler; 8 Condenser; 9. Flue-gases/MEA Heat Exchanger

Figure 2. Integrated scheme for CO_2 capture process by absorption/stripping

To prevent corrosion that might occur due to temperatures at or below dew point, the heat transfer surfaces need to be constructed from corrosion-resistant materials, such as steel-resistant alloys or corrosion-resistant plastic [13] [14]. Steam required for solvent regeneration was extracted as well at the IP/LP crossover at 4.8 bar. A hot-side approach temperature of 10°C was assumed.

4. Results and discussions

When CO_2 captured is integrated to existing or new power plants the over-all efficiency of the power plant it is significantly reduced. The main power reduction for amine based CO_2 capture is due to the steam required to regenerate the chemical solvent in the desorber. Additional power is consumed due to compressing the flue gas and pumping the solvent. Finally, power is required to compress the recovered CO_2 prior to sequestration. The power loss and the energy recovery possibilities for and from CO_2 compression are not part of this work.

The results for CO_2 capture process obtained for the studied cases are summarized in Table 3. In the table the grey cells correspond to the case with waste heat of flue gases integrated in the CO2 capture process

Table 3.   Main results for CO_2 capture process

MEA (wt%)	30			35			40		
Ψ_{CO2} (%)	85	90	95	85	90	95	85	90	95
L/G (kg/kg)	1.26	1.37	1.48	1.08	1.16	1.24	0.95	1.02	1.08
	1.25	1.35	1.44	1.06	1.13	1.12	0.93	0.98	1.04
Rich loading	0.53	0.49	0.45	0.5	0.47	0.44	0.48	0.44	0.43
	0.52	0.5	0.47	0.52	0.49	0.46	0.5	0.47	0.45
Q_{reb} (MWth)	271	279	292	238	250	265	192	211	219
	232	240	252	194	207	223	148	168	178
Q (GJ/t$_{CO2}$)	3.8	3.92	4.1	3.34	3.5	3.72	2.7	2.96	3.07
	3.25	3.36	3.53	2.72	2.9	3.13	2.08	2.35	2.5
Energy penalty reduction (%)	**14.47**	**14.28**	**13.9**	**18.56**	**17,14**	**18.65**	**22.96**	**20.61**	**18.57**

In the base case with CO_2 post-combustion capture simulation results obtained for reboiler heat duty are similar with the values presented in literature by different authors (3.65 GJ/tonne CO_2 by Amadeo [15], 4 GJ/tonne CO_2 by Desideri [16]). Results show that thermal energy required for MEA regeneration decreases substantially with increasing the solvent concentration. It seems more effectively to use higher MEA concentrations. In the case of 90% CO_2 capture efficiency 3.9

GJ/tone are required for 30 wt% MEA while 2.96 GJ/tone are required for 40 wt%. The present study reveals an interesting possibility of power reduction that could be applied if advanced and non-toxic inhibitors or similar but more corrosion resistant solvents are used.

Additional thermal reduction for solvent regeneration can be achieved by using the waste heat of flue gases as presented in the integrated scheme. It was noticed that the temperature change across the desorber is smaller and the reboiler duty is reduced compared with the reference case by 10-20%. In figure below the heat required for different MEA concentration and different CO_2 capture efficiency for both cases is represented. It is indeed clear that significant reduction of the required energy to achieve the same CO_2 capture efficiency performance when flue gases are integrated into the scheme and high amine concentration are used.
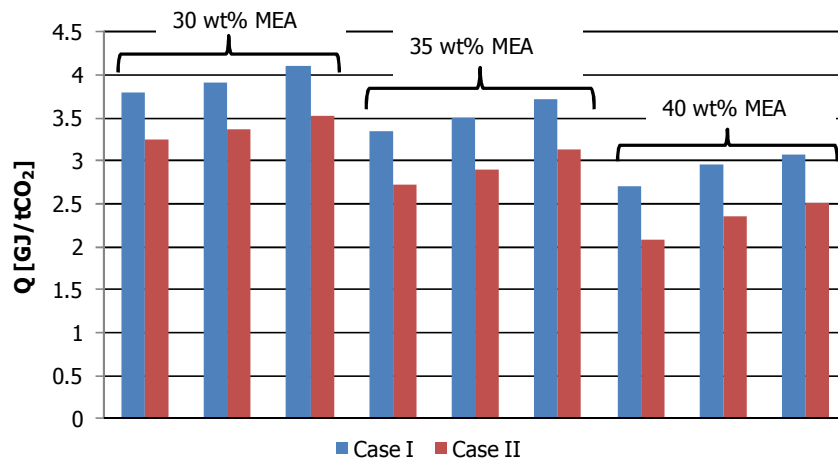
Figure 3. Desorber reboiler heat duty sensitivity for different MEA concentrations

However, for case II, the heat exchanger network suggested and the required modifications to the existing equipment have to be further analyzed in order to determine if the scheme can be economically implemented.

Compared to the reference case without capture, performance calculations show an efficiency drop as low as approx. 14%-pts for the 30 wt% MEA concentration and 90% CO_2 capture rate to 12% for the same case. A reduction of 8% -pts was achieved when high solvent concentration as 40 wt% MEA and waste flue gas integration was considered.

4. Conclusion

Capture and storage of CO_2 from fossil fuel fired power plants represents a potential method for greenhouse gas emissions reduction from the atmosphere. The present study analyzes CO_2 capture process optimization by investigating the effects of CO_2 removal percentage, MEA concentration and waste heat integration. The simulations have been performed using ASPEN Plus software.

An interesting possibility of power reduction could be achieved if 40%-wt MEA solvent is used in presence of advanced and non-toxic inhibitors or similar but less corrosion solvents. In the case of 90% CO_2 capture efficiency 3.9 GJ/tone are required for 30 wt% MEA while 2.96 GJ/tone are required for 40 wt%.

This study shows further potential to reduce the energy penalty associated with the addition of CO_2 capture by waste heat flue gases integration in the CO_2 capture process as presented in the article. The reboiler duty is reduced by 10-20% compared to reference case with CO_2 capture.

Acknowledgements

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