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CAPITAL COSTS AND ENERGY CONSIDERATIONS OF DIFFERENT ALTERNATIVE STRIPPER CONFIGURATIONS FOR POST COMBUSTION CO_2 CAPTURE

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Abstract
Capturing and storing the greenhouse gas carbon dioxide (CO_2) produced by power plants and factories before it is emitted to the atmosphere could play a major role in minimizing climate change. Among of the different technologies, aqueous amine absorption/stripping is a promising one. In this study 5 different configurations for aqueous absorption/stripping have been compared with regard to capital investment and energy consumption. The process simulations are made with the use of Unisim and ProTreat, while for the cost calculation relations from Turton et.al.[4] were used.

We can't identify that one single configuration is the best for all cases, because it depends on many parameters like energy and material costs, plant complexity, etc. The split-stream configuration with cooling of semi-lean amine stream has the minimum energy consumption, but the vapor recompression configuration is the optimum one because with a small increase in investment we can save significant amount of energy. The effect of heat integration between the compression section and the stripper also is considered for vapor recompression configuration. Reboiler energy may be saved with heat integration, however because of high temperature into the compressors the compression efficiency decreases. Also the capital cost and the complexity of the plant will increase. Heat integration between compression section and reboiler cause to increase water in produced CO_2 and increase the corrosion problem.

Keywords: stripper configurations, capital cost, energy consumption, MEA

1. Introduction

Capturing and storing the greenhouse gas carbon dioxide (CO_2) produced by power plants and factories before it enters the atmosphere could play a major role in minimizing climate change. Global warming is a result of increasing anthropogenic CO_2 emissions, and the consequences will be dramatic climate changes if no action is taken. One of the main global challenges in the years to come is therefore to reduce the CO_2 emissions. Increasing energy efficiency and a transition to renewable energy as the major energy source can reduce CO_2 emissions, but such measures can only lead to significant emission reductions in the long-term. Carbon capture and storage (CCS) is a promising technological option for reducing CO_2 emissions on a shorter time scale. CO_2 capturing plants are energy intensive processes. The energy consumption in the CO_2 capturing plant is estimated to be 15-30% of the net power production of a coal-fired power plant. A lot of work has been done to reduce energy consumption of CO_2 units. Alternative process configurations have also been proposed to reduce capital and operating costs of the CO_2 capture process[3]. Since large scale CO_2 capture plants are very expensive to build for research purposes, process simulation and modeling have an important role to play for system optimization and in evaluation of the various process alternatives. In the present study, different configurations have been simulated and the investment cost and energy consumption (the main change in operating cost is energy for different configurations) were estimated based on simulation to compare these configurations. All configurations are simulated for 90% CO_2 capture from flue gas of a 150 MW bituminous coal power plant. Simulations were performed in UniSim with the Amine Fluid package. Because most of the studies for CO_2 capture have been done with monoethanolamine (MEA), and it is considered as a base case, aqueous 30 wt% (MEA) was used as a solvent also in this study.

2. Process description

In this study five different process configurations were simulated and compared. These configurations are a simple stripper as base case, and in addition, split-stream, multi pressure stripper, vapor recompression, and compressor integration. All these configurations have been simulated for CO_2 capture from bituminous coal power plant flue gas. The specifications of the flue gas are given in Table 1. Following, the configurations are described.

Table 1. Flue gas specification

Temperature (^oC)	48
Flow rate (kmol/hr)	24,123
Pressure (bar)	1.1
Composition (mol fraction)	
CO_2	0.1176
Nitrogen	0.7237
Oxygen	0.0502
H_2O	0.1085

2.1 Conventional process configuration

A flow diagram depicting a conventional process structure, including absorber, stripper, rich-lean heat exchanger, cooler, pumps and compressors to compress CO_2 up to 110 bar has been simulated as a base case, shown in Figure 1.

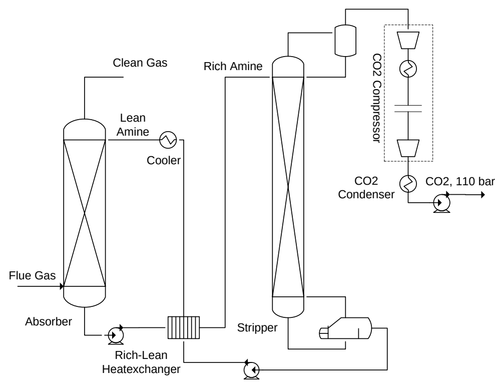

Figure 1. Conventional process configuration

The number of stages (height of packing) in absorber and stripper and lean loading were optimized to obtain minimum energy consumption. For other configurations the number of absorber and stripper stages were the same as in the base case, whereas lean loading and rich loading were optimized for each case. The optimum values for the base case are shown in Table 2.

Table 2. Optimum parameters for the base case

Absorber packing hight (m)	Stripper packing hight (m)	Lean loading	Rich loading
7	15	0.1986	0.4904

For the CO_2 compression, a multi-stage compressor with a pressure ratio of two[6] in each stage has been considered to compress the CO_2 up to 75 bar. The gas is cooled down to 30 ^oC between the stages. After compression, a condenser liquefies the CO_2 and a pump increases pressure to 110 bar.

2.2 Split-stream configuration

In this flow diagram the rich flow is split into two streams and goes to two sections of the stripper after preheating with two separate lean loading streams as shown in Figure 2. In this configuration, many parameters such as the number of stages in the various sections of absorber and stripper, the rich amine split ratio, and the lean loading need to be optimized to reach the minimum energy consumption. In this flow diagram a cooler can be used to cool the lean amine from the top section of the stripper before entering to the bottom section of the absorber. Simulation was done with no cooler and also with a cooler that cools down the liquid to 40 ^oC. The optimum values for the split-stream configuration are shown in Table 3.

Table 3. Optimum parameters for the split-stream configuration

Absorber stage		Stripper stage		Rich amine ratio		Lean	Lean	Rich
Top	bottom	Top	bottom	Top	bottom	loading1	loading2	loading
10	4	10	20	0.44	0.56	0.4553	0.1943	0.4974

2.3 Multi-pressure stripper configuration

In this configuration, the stripper works at more than one pressure level. The vapor from the bottom bed is compressed before entering to the upper section. The parameters such as the pressure levels, number of stages in each pressure section were taken from reference [1] and [2]. The optimum lean loading was found to be 0.2152 for this configuration.

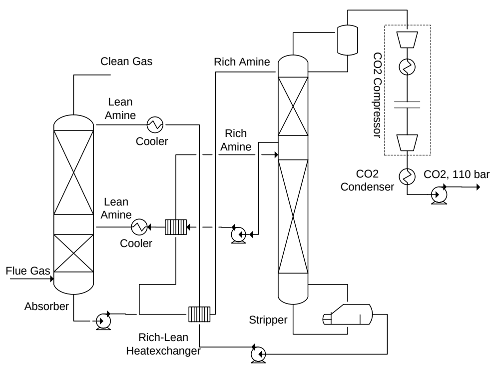

Figure 2. Split-stream configuration

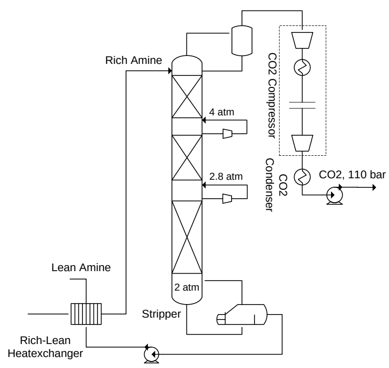

Figure 3. Multi-pressure stripper configuration

2.4 Vapor re-compression configuration

In this process configuration a pressure drop is created after the stripper reboiler and the resulting vapor is recompressed and sent to the stripper as shown in Figure 4. Because a compressor with a pressure ratio about 2 is used and the stripper bottom pressure is about 2 atm, the pressure drop is about 1 atm. The optimal lean loadings are 0.1922 and 0.1860 before and after the flash respectively.

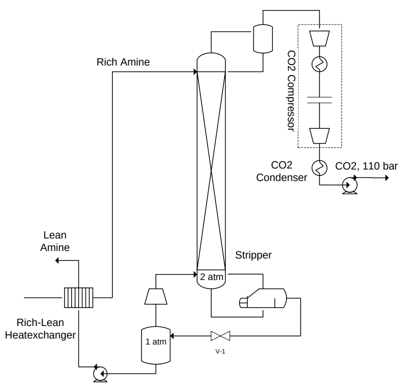

Figure 4. Vapor recompression

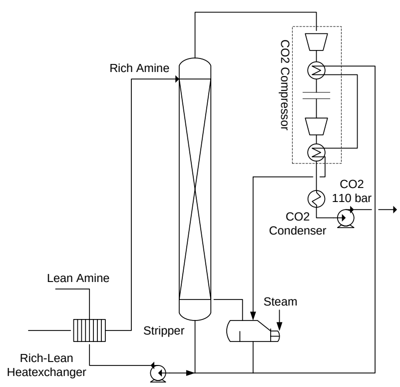

Figure 5. Compressor integration

2.5 Compressor integration

In this configuration the stripper doesn't have a condenser and the vapor goes to the compressor directly as shown in Figure 5. The liquid from the stripper is preheated by the hot gas out of each compressor stage to improve energy consumption. The gas between the stages is cooled down to 130 ^oC.

3. Results

The simple stripper has the lowest investment cost and is the easiest plant to operate and control. In all other cases the investment cost and complexity increase, but in most of the cases the energy consumption decreases. The summery results are shown in Table 4.

Table 4. Summary of the simulation results

	Case	Lean loading	Rich loading	Investment cost (M$)	Reboiler duty (kJ/kg CO_2)	Total work (kJ/kg CO_2)
dT = 5 ^oC	Base Case	0.2071	0.4896	116.10	3,515.5	917.7
	Split-stream without cooler	0.4262 0.1983	0.4831	127.77	3,089.9	846.4
	Split-stream with cooler	0.4330 0.1987	0.4968	127.82	2,944.2	822.6
	Multi pressure	0.2154	0.4890	126.02	2,388.2	851.0
	Vapor recompression	0.2064 0.1987	0.4906	118.28	2,576.1	832.5
	Compressor integration	0.2068	0.4897	140.67	1,355.1	945.4
dT = 10 ^oC	Base Case	0.1986	0.4904	109.34	3,576.2	928.1
	Split-stream without cooler	0.4437 0.1944	0.4794	116.51	3,346.9	890.7
	Split-stream with cooler	0.4553 0.1943	0.4974	117.31	3,113.2	849.7
	Multi pressure	0.2152	0.4890	118.05	2,578.5	881.9
	Vapor recompression	0.1922 0.1860	0.4914	110.64	2,703.4	851.5
	Compressor integration	0.1986	0.4904	130.92	1,684.4	964.4

In this table dT is the hot end temperature approach of the rich-lean heat exchanger. Two types of energy are needed in the process, electrical or mechanical energy for pumps and compressors and heat energy for reboiler of stripper. These two types have not the same economic value, but for comparing the total energy for different cases we need to unify them. In this work we convert the heat to equivalent thermodynamic work (power). It means that if the reboiler steam were used for electricity production, how much electricity would be produced. We assume that the temperature of steam in the reboiler (T_H) is 10°C higher than the reboiler temperature and that steam condenses at 40°C in the turbine (T_C). The total equivalent work for the plant (the objective function) is then

$$W_{eq} = Q_r\left(1-\frac{T_C}{T_H}\right)\times\eta + W_{Pumps} + W_{Compressors} \qquad W_{eq}\left(\frac{kJ}{kg\,CO_2}\right) \tag{1}$$

Where $T_H = T_C + 10\ [\mathrm{K}]$ and $T_C = 313\ \mathrm{K}$. The efficiency η of the imagined Carnot cycle (heat pump) that generates heat from power is assumed to be 75%. So the total equivalent work is calculated by using equation (1) and the results are shown in the last column in Table 4 as the total energy requirement of the capture plant.

The different configurations compared to the base case increase both investment cost and complexity in the plant. The energy savings and increase in investment compared to the base case are shown in Table 5. A simple stripper with dT=5 ^oC and dT=10 ^oC are considered as the base cases in this table.

Table 5. Energy saving Investment increase for different configuration compare to base case

Different configurations	dT = 5		dT = 10	
	Energy	Investment	Energy	Investment
Base Case	-	-	-	-
Split-stream without cooler	7.77	10.05	4.03	6.56
Split-stream with cooler	10.36	10.09	8.45	7.29
Multi pressure	7.27	8.54	4.98	7.97
Vapor recompression	9.28	1.88	8.25	1.19
Compressor integration	-3.02	21.16	-3.91	19.74

One of the things that can seen from Table 4 is that for the different configurations, the difference in energy saving when going to dT=5 compared to dT=10 is not equal. The reason is that the reboiler and condenser duties are not the same for the different cases. Table 6 shows these differences for all configurations. The split-stream configuration without cooling is the most sensitive to dT and the simple stripper is the least sensitive.

Table 6. Effect of temperature approach to the energy consumption and investment

	Base Case	Split-stream without cooler	Split-stream with cooler	Multi pressure	Vapor recompression	Compressor integration
Energy consumption difference by dT (kJ/kg CO2)	10.4	44.3	27.1	30.9	19	19
Investment change by dT (M$)	6.76	11.26	10.51	7.97	7.64	9.75

3.1 Simple stripper

Simulation shows that in the simple stripper case we can have 1.12% energy saving by decreasing the temperature approach in rich-lean heat exchanger from 10 to 5 ^oC, but the investment cost increases about 6.18%. Most of this increase is related to the rich-lean heat exchanger, because a bigger area is needed when the temperature approach decreases.

3.2 Split-stream configuration

This configuration was simulated with and without cooling of the semi-lean stream to the middle of the absorber. Adding a cooler to the semi-lean stream has both positive and negative effects on investment (cooler cost increase investment, but there is a cost reduction because the size of condenser and reboiler decrease), so the investment does not change very much. However, it has a positive effect on energy saving. By adding a cooler, the investment increases just 0.04% for dT=5, but the energy saving is about 2.59%. Investment increase and energy saving are 0.73% and 4.42% respectively. Because there are two rich-lean exchangers, the investment will probably increase more than with the other configurations when dT changes from 10 to 5 ^oC (Table 6). A negative point for this configuration is that the complexity is higher than for the other configurations. Absorber and stripper with two different sections, two rich-lean heat exchangers, and the need to split streams are some factors that increase the complexity and make the controllability of the plant more complex.

3.3 Multi-pressure

In this configuration the stripper operates at 3 pressure levels, 2, 2.8 and 4 atm. This configuration has the 4^{th} rank in energy requirement (Table 4) and the 2^{nd} rank for sensitivity to dT (table 6). For increasing the pressure of the stripper two compressor stages are needed and this is the main cause of the investment increase compared to base case, because these two stages must compress more gas (vapor volume decrease from bottom to the top) compare to the CO_2 stream from the top of the stripper.

3.4 Vapor recompression

This configuration, with a small margin, has the 2nd rank in energy requirement, but the increase in investment is very small compare to the other configurations (Tables 4 and 5). From the results it is predicted that this configuration is the optimum one because with a small increase in investment (1.88% for dT=5 and 1.19% for dT=10) we can save significant energy (9.28% for dT=5 and 8.25% for dT=10). In addition, the plant complexity does not increase very much compare to the base case.

3.5 Compressor integration

This configuration causes an increase of investment and energy consumption, so it is not a good option for CO_2 capture. The reason for this increase is that the stripper does not have a condenser and a lot of water vapor goes to the CO_2 compressor. So for the compression, a large compressor with a high energy shaft is needed. Because gas between stages is cooled down by liquid from the bottom of the stripper, the reduction in temperature is small and the water does not separate from the CO_2 and the produced CO_2 has water content much higher than what is normal. The high water content in the CO_2 must be reduced or otherwise increase corrosion problem in compressors, piping and other equipment.

Conclusion

In this study five different configurations have been investigated for post combustion CO_2 capture of a flue gas with about 12 percent CO_2 on wet basis, produced by a 150 MW bituminous coal power plant. These configurations are simple stripper as a base case, split-stream, multi pressure stripper, re-vapor recompression, and compressor integration. Among these configurations, the split-stream configuration with cooling of semi-lean amine stream has the minimum energy consumption. However, this configuration increases the investment cost and plant complexity significantly. The best configuration seems to be the vapor recompression configuration. The energy consumption is a little higher than the split-stream configuration (Table 4), but the complexity and investment cost are much lower. Split-stream without cooling and multi-pressure configurations are the next ranked in energy consumption. Compressor integration seems to be the worst case where both energy consumption and investment costs are higher than for the base case.

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