Simulation and Economic Optimization of Vapor Recompression Configuration for Partial CO_2 capture

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Abstract

A standard method for CO_2 capture is by absorption in an amine based solvent followed by desorption. Such plants are traditionally designed for removal of 85-90 % CO_2 from the exhaust gas as a reasonable trade-off between high removal efficiency and low investment. The major challenge is the high energy demand for CO_2 desorption. In many industrial cases, a limited amount of cheap waste heat is available and this makes partial CO_2 capture an interesting option. It is not obvious whether a high removal efficiency from a part of the exhaust or a low removal efficiency from the total exhaust is the optimum solution. In this work, simulations of traditional and vapor recompression processes are performed, and it is found that vapour recompression treating the total exhaust is energy optimum. A traditional process with a low absorption column treating the total exhaust gives the lowest cost per ton CO_2 captured.

Keywords: CO_2 absorption, Aspen HYSYS, partial capture, vapor recompression

1 Introduction

The aim of this work is to perform simulations of various process configurations including vapour recompression to find the energy optimum and the most cost effective solution. Especially the focus is to perform a cost-benefit analysis of various configurations to evaluate whether it is cost optimum to treat all the exhaust gas or only a part of it.

1.1 Literature

There have been many research activities to identify the techno-economic feasibility of different CO_2 capture concepts. Several studies have investigated utilization of waste heat with a standard MEA (monoethanol amine) absorption and desorption process (IEAGHG, 2009), but there are few studies which have focused on different process configurations powered by waste heat. Several studies (Fernandez, 2012; Øi et al. 2014; Aromada and Øi, 2015) have concluded that vapour recompression is an attractive configuration.

(Dong et al., 2012) performed a study of the possibility to utilize waste heat from a cement plant to capture CO_2 effluent from the plant. Up to 78 % capture could be achieved using only waste heat by integrating heat recovery with CO_2 capture.

A project called CO_2stCap (a part of the Climit programme), is now run in Norway and Sweden to evaluate different possibilities for partial CO_2 capture from industrial sources.

At University College of Southeast Norway there have been performed simulations of possible CO_2 capture from Norcem's cement plant in Brevik (Svolsbru, 2013). (Park, 2016) simulated partial CO_2 capture and concluded that in case of partial CO_2 capture of approximately 40 % of the CO_2 in the flue gas from a cement plant, treating all the flue gas would probably be more cost optimum compared to treat only a part of the flue gas. (Sundbø, 2017) included an evaluation of vapor recompression for partial CO_2 capture. This work is based on the Master Thesis work of Erik Sundbø.

1.2 Process description

A sketch of a general post-combustion CO_2 capture process is presented in Figure 1. The whole or a part of a flue gas is sent to an absorber where CO_2 is absorbed in a solvent. The solvent is regenerated by releasing the CO_2 in a desorber and the regenerated solvent is sent back to the absorber.

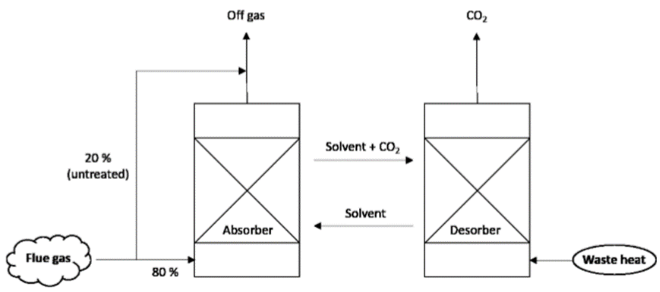

Figure 1. Principle of partial CO_2 capture (Park, 2016)

Figure 2 shows a standard process for CO_2 absorption into an amine based solvent. It comprises an absorption column, a stripping column including a reboiler and condenser, circulating pumps and heat exchangers.

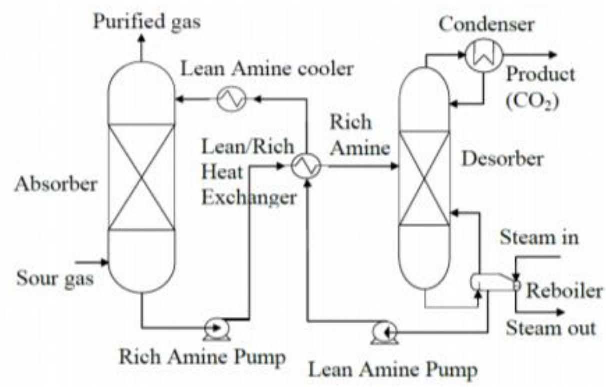

Figure 2. Principle of standard process (Aromada and Øi, 2015)

A process configuration which has been shown to be very energy efficient is vapor recompression where the regenerated amine from the desorption column is depressurized to a pressure below the desorption pressure, and then the liquid is recycled back to the top of the absorber while the gas is compressed and recycled back to the bottom of the desorption column. The principle is shown in Figure 3.

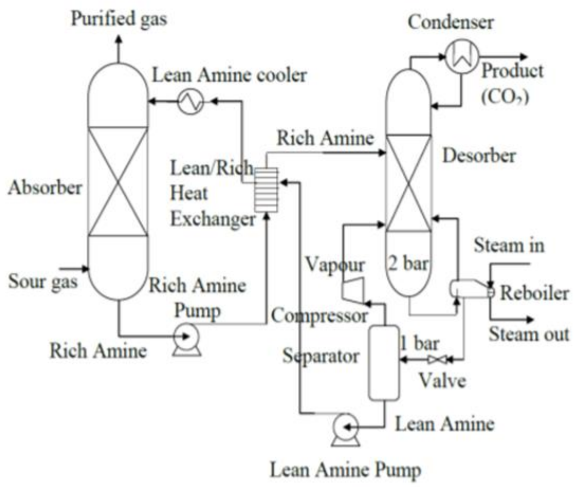

Figure 3. Principle of vapor recompression process (Aromada and Øi, 2015)

2 Process simulation program and specifications

2.1 Process simulation program

Aspen HYSYS is a commercial general purpose process simulation program from AspenTech. It contains several equilibrium models, process unit operation models and flow-sheeting calculation alternatives.

Different alternatives were simulated using Aspen HYSYS version 8.6 using the Kent-Eisenberg vapour/liquid equilibrium model.

The absorption and desorption columns can be simulated with equilibrium stages including a stage efficiency. Murphree efficiencies for CO_2 can be specified in the absorption column and the desorption column. The Murphree efficiency for a stage is defined by the change in mole fraction CO_2 from a stage to another divided by the change on the assumption of equilibrium. Pumps and compressors were simulated with an adiabatic efficiency of 0.75.

2.2 Specifications and simulation of standard process for CO_2 capture

A standard process as in Figure 2 has been simulated in Aspen HYSYS. The specifications for a base case calculation are presented in Table 1. The conditions are from a cement plant, and the (waste) heat is assumed to be constant 25 MW. Most of the specifications are the same as in (Øi, 2007) and (Svolsbru, 2013).

Table 1. Standard process simulation input specifications for 85% CO_2 removal

Parameter	**Value**
Inlet gas pressure	80 °C
Inlet gas pressure	1.1 bar
Inlet gas molar flow rate	8974 kmol/h
CO_2 in inlet gas	17.8 %
Water in inlet gas	20.63 %
Nitrogen in inlet gas	89.56%
Lean MEA temperature	40 °C
Lean MEA pressure	1.01 bar
Lean MEA molar flow rate*	545000 kg/h
MEA content in Lean MEA	29.0 mass-%
CO_2 in Lean MEA	5.5 mass-%
Number of stages in absorber	10
Murphree efficiency in absorber stages	0.15
Number of stages in desorber	8
Murphree efficiency in desorber stages	1.0
Reflux ratio in desorber	0.3
Reboiler temperature	120 °C
Temperature in amine before desorber	101.2 °C
Desorber pressure	2.0 bar
Pump efficiency	0.75

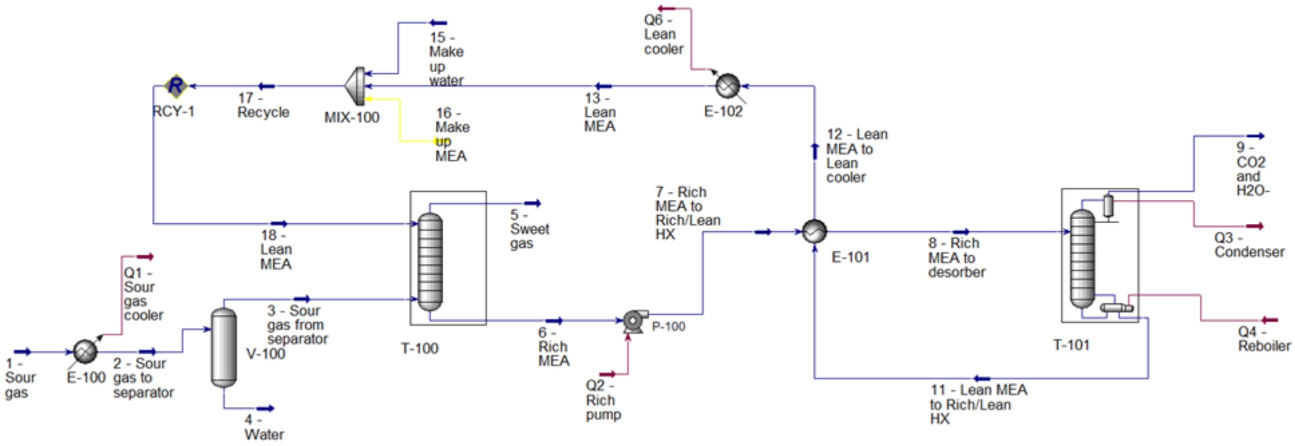

Figure 4. Aspen HYSYS flow-sheet of standard process

Figure 4 shows the representation of the standard process in the simulation program Aspen HYSYS. The calculation sequence is similar to earlier works (Øi, 2007; Aromada and Øi, 2015). First the absorption column T-100 is calculated from the inlet gas and the lean amine (which is first guessed). The rich amine from the bottom of the absorption column passes through the pump P-100 and the main rich/lean heat exchanger E-101 and gains heat from the lean amine from the desorption column. The heated rich amine is entering the desorption column T-101 which calculates the hot lean amine leaving the desorption column. The lean amine from the lean/rich heat exchanger passes through the lean cooler E-102 and is checked in a recycle block RCY-1. It is checked whether the recycled lean amine is sufficiently close to the earlier guessed lean amine stream, which may be changed by iteration. To simulate a process with vapor recompression, a few specifications in addition to the specifications in Table 1 are necessary. The pressure after depressurization is 1.2 bar and the compressor efficiency is 0.75.

Figure 5 shows the representation of the vapor recompression process in the simulation program Aspen HYSYS. The calculation is slightly more complex than in the standard case. In the calculation sequence, the recompressed gas has to be guessed prior to the calculation of the desorber. After recompression, the recompressed gas has to be iterated by utilizing a recycle block until convergence.

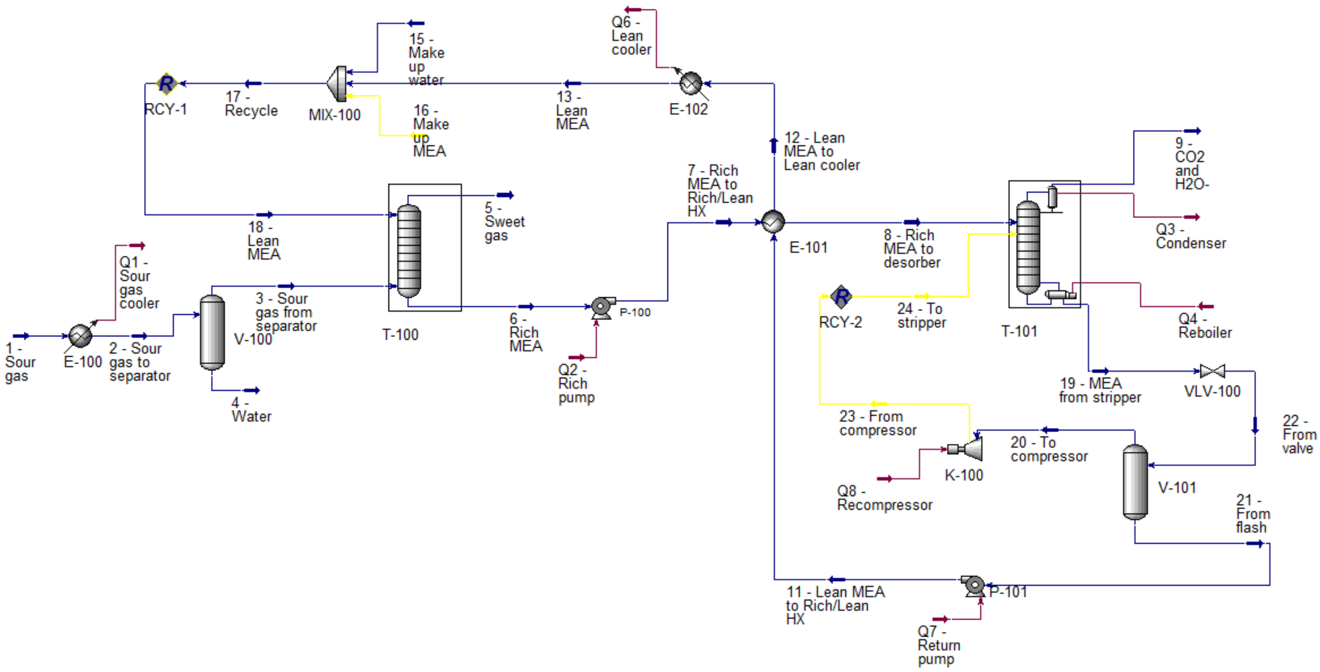

Figure 5. Aspen HYSYS flow-sheet of vapor recompression process

3 Specification of dimensioning and cost estimation calculations

3.1 Scope analysis

The process and cost analysis is limited to the equipment in the flow-sheets in Figure 4 and 5. No pre-treatment like inlet gas purification or cooling is considered. And no treatment after stripping like compression, transport or storage of CO_2 is considered.

The cost estimate is limited to installed cost of listed equipment. It does not include e.g. land procurement, preparation, service buildings or owners cost.

3.2 Assumptions

The dimensions of the process equipment are estimated based on typical dimension factors. The absorption column diameter is based on a gas velocity of 2.0 m/s and the desorption column is based on a gas velocity of 1 m/s. The packing height of the absorption and desorption column is 1 meter per stage with a specified stage efficiency. The total height of the absorption column is the packing height plus 23 meter and the total height of the desorption column is the packing height plus 17 meter.

The heat transfer area of the heat exchangers are calculated based on heat transfer numbers. The main amine/amine heat exchanger has 1500 W/(m^2K), the reboiler has 2500 W/(m^2K) and the condenser has 2000 W/(m^2K). The compressor effect is calculated with an adiabatic efficiency of 0.75.

The electricity cost is set to 0.05 Euro/kWh. The cooling cost is neglected, and the waste heat is specified to be free (zero cost) except for a sensitivity calculation. The maintenance cost was set to 4 % of the total investment per year. The yearly operating time was 8000 hours, the calculation time was set to 25 years and the interest was set to 7.5 %. The construction time was not included.

3.3 Methods used

The equipment cost is calculated in 2013-$ by the program Aspen In-Plant v8.4. The cost is escalated to 2016 using the CEPCI index and converted to EURO with an exchange rate of 0.904. Stainless steel (SS316) with a material factor of 1.75 was assumed for all equipment units. To calculate the installed cost, all equipment cost (in carbon steel) was multiplied with a detailed installation factor based on data from Eldrup as in earlier works (Øi, 2012; Park, 2016). The installation factors was decreasing with equipment cost. Details can be found in the Master Thesis (Sundbø, 2017).

4 Results and discussion

4.1 Results from removal rate and energy consumption

The CO_2 removal efficiency and energy consumption was calculated for all the alternatives. The process was simulated with a part of the total exhaust gas (part-flow) from 40 up to 100 % (which is full-flow) of the gas through the absorber column. Both the standard case as in Figure 4 and the vapor recompression case as in Figure 5 were simulated. The results are presented in Figure 6 and Figure 7 for the standard case.

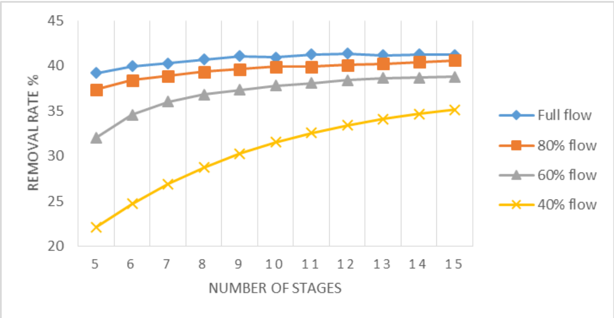

Figure 6. Removal rate as a function of percent full flow and number of stages for the standard case

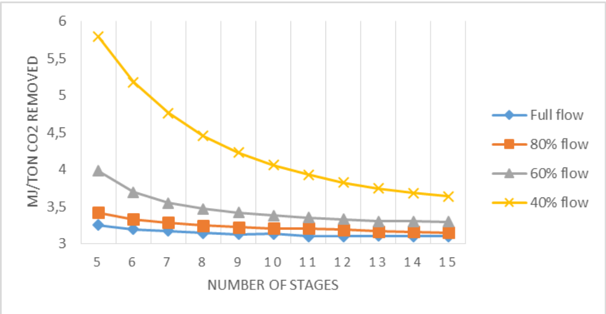

Figure 7. Energy consumption as a function of percent full flow and number of stages for the standard case

Figure 6 clearly shows that the full flow alternative gives a higher removal rate at all column heights and Figure 7 shows that the energy use (per kg CO_2 captured) is lower with full flow. The figures also show that the removal rate increases and the energy use decreases with the number of stages up to about 10 stages. Above 10 stages, there is only small changes.

The results are presented in Figure 8 and Figure 9 for the vapour recompression case.

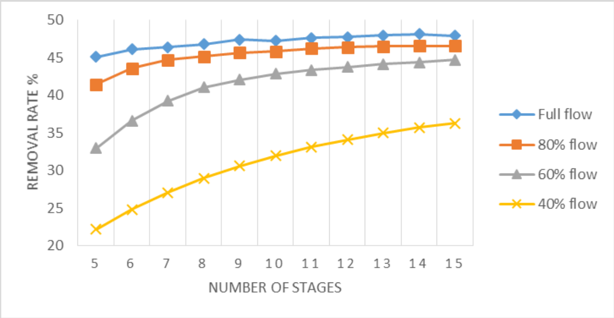

Figure 8. Removal rate as a function of percent full flow and number of stages for the vapor recompression case

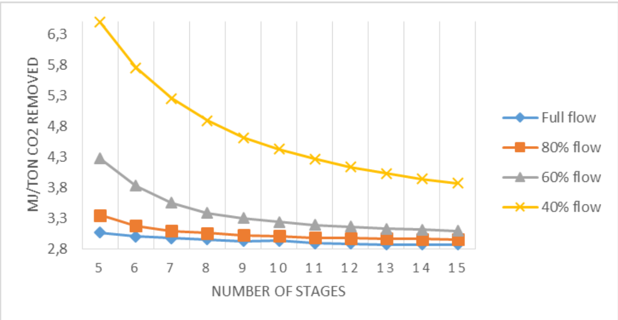

Figure 9. Energy consumption as a function of percent full flow and number of stages for the vapor recompression case

The results show that the full-flow alternative achieved the highest removal efficiency and lowest energy consumption for both the traditional and for the vapour recompression configuration. Without vapour recompression, the removal efficiency varied between 39 and 41 % where the highest removal efficiency was achieved with 15 absorption stages. With vapour recompression, 45 to 48 % was achieved with 5 and 15 absorption stages, respectively. The vapor recompression solution with the highest removal efficiency and the lowest energy consumption at 15 stages, was regarded as the energy optimum process.

4.2 Cost optimization results

The cost estimate was performed after process simulation in Aspen HYSYS and dimensioning of the process equipment. Figure 10 shows the cost estimate distributed on each equipment type for the full-flow standard case and the vapor recompression case.

The cost for 80 % flow was also estimated, and had a higher capital cost. This indicate that a full-flow process is more cost optimum.

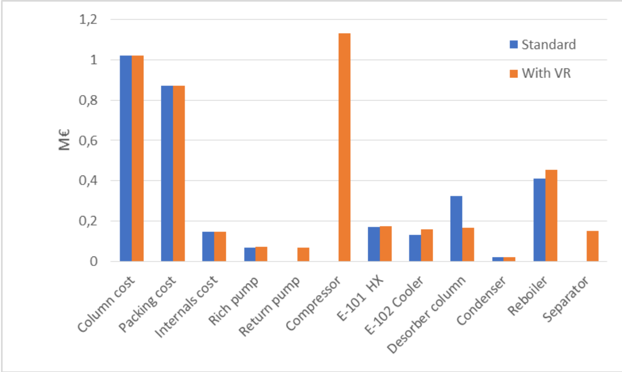

Figure 10. Cost comparison of standard and vapor recompression full-flow process as a function of number of stages

The cost including operating cost was used to calculate the total cost per ton CO_2 captured. Calculated cost for a standard and vapour recompression as a function of number of stages is shown in Figure 11.

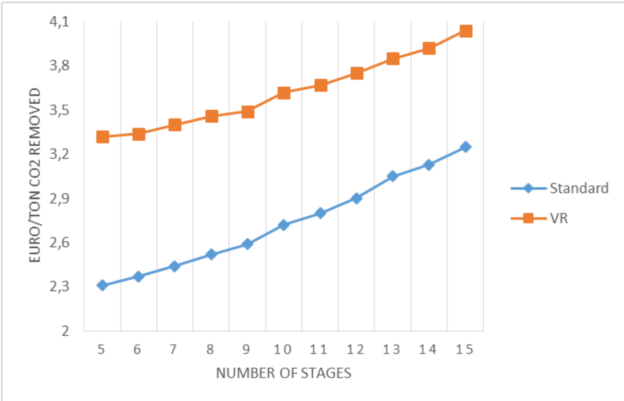

Figure 11. Cost comparison of standard and vapor recompression full-flow process as a function of number of stages

The figure shows that a standard process with a low number of stages gives the lowest cost per ton CO_2 capture. 2.3 Euro/ton CO_2 captured is a very low cost. However, a vapour recompression process will capture considerably more CO_2 as shown in Figure 6 and 8. 3.3 EURO/ton CO_2 captured is also an attractively low cost for CO_2 capture. Another way to compare the two alternatives using the optimum 5 stages, is to calculate the additional cost to capture the additional amount of CO_2. In this case this cost is 10.3 EURO/ton.

In Figure 12, the total project cost for the two alternatives as a function of captured amount CO_2 is shown. The figure shows the cost for the standard process removing 5.5 Mton CO_2 compared to the higher cost for the vapour recompression process removing 6.4 Mton CO_2. The figure illustrates that the capture cost per ton CO_2 captured (which is the slope) increases when the amount of CO_2 captured increases.

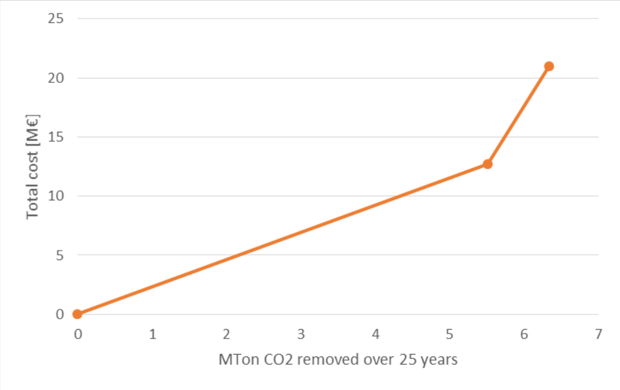

Figure 12. Total project cost for the standard and vapour recompression full-flow alternatives as a function of amount CO_2 captured

4.3 Comparisons with earlier work

(Dong et al., 2012) calculated that it was possible to capture 78 % CO_2 in a cement case under other conditions. The amount captured was dependent on the degree of integration. (Park, 2016) concluded as in this work that the lowest total cost per ton CO_2 captured was calculated for the standard full-flow process with 5 absorption stages. This conclusion was however based on the assumption that transport and treating of the gas before or after CO_2 capture was not considered.

4.4 Sensitivity analysis

The capture cost was calculated for varied specifications. The packing equipment cost was doubled in one case, and the recompression compressor cost was doubled in another case. These changes increased the capture cost, but it did not change the conclusions of the optimum solution.

The price of heat was increased from 0 and up to 0.02 EURO/kWh. At a price of 0.02 EURO/kWh, the total cost for both the standard process and the vapor recompression process was 10.6 Euro/ton CO_2 captured. At a higher heat cost, the vapor recompression process would give the lowest cost per ton CO_2 captured.

5 Conclusion

Different process alternatives for partial CO_2 capture were simulated and cost estimated using the process simulation tool Aspen HYSYS.

The number of absorption stages was varied between 5 to 15. The process was simulated with a part of the total exhaust gas (part-flow) from 40 up to 100 % (which is full-flow) of the gas through the absorber column.

The total CO_2 removal efficiency and energy consumption was calculated for all the alternatives. The results showed clearly that the full-flow alternative achieved the highest removal efficiency for both the traditional and for the vapor recompression configuration. The solution with the highest removal efficiency with a heat consumption of 25 MW, was regarded as the energy optimum process.

For some of the process alternatives, the process was cost estimated to find the cost optimum alternative. The lowest total cost per ton CO_2 captured was calculated for the standard full-flow process with a low number of absorption stages. However, the full-flow process with a vapor recompression configuration and a low number of absorption stages had a considerably higher CO_2 removal rate and only a slightly higher total cost per ton CO_2 captured.

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