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Temperature Dependence of Heat Integration Possibilities of an MEA Scrubber Plant at a Refinery

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Abstract

A study has been conducted in order to investigate how the specific heat requirements in the stripper reboiler of a MEA capture plant changes with changing temperature. It was found that the increase in heat demand is dramatic when lowering the temperature, approximately 40% when the temperature changes from 120 to 90° C. Heat integration with a refinery was also studied, and showed that even if the heat demand was larger for the lower temperature the heat integration possibilities were also larger for the base case.

CCS; Refinery; MEA; Heat integration

1. Introduction

The International Energy Agency (IEA) has developed a roadmap towards a carbon neutral energy system, in which a mix of technologies is used in order to drastically decrease global CO_2 emissions. In this scenario about 19% of the reductions are achieved via the use of Carbon Capture and Storage (CCS). Although a majority of CO_2 emissions originate from combustion of fossil fuel in power plants, the potential for carbon abatement via CCS is roughly the same for the power sector and other industrial applications[1]. The steel, cement and refinery industry are three important examples of where CCS could be deployed.

CO_2 capture at an industrial site has much in common with CO_2 capture on a power plant, but there are significant differences. For instance an industrial process often have large quantities of excess heat available at low or medium temperature. If this heat cannot be used in the industrial processes it could

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prove economically favorable to use this heat in order to provide the stripper column with necessary heat for solvent regeneration. Previous works have indicated that the specific heat requirement decreases with increasing temperature and pressure[2][3], but in the case of the large industrial processes it might still be positive to decrease the temperature since excess heat is most often available at increasing amounts with decreasing temperatures. If post combustion techniques would be implemented in the refinery industry, it is of utmost importance that the cost for solvent regeneration is minimized, since it can constitute up to 70% of the total capture cost [4].

In this paper, a model of a MEA scrubber plant constructed in the software Aspen Plus is presented. The model uses rate based calculations to determine the specific heat of regeneration for a given process setup. Rate based calculations are based on reaction kinetics and thus give more realistic results in comparison to equilibrium based calculations. In the model the reboiler temperature in the stripper column varies and three different temperature levels 90° C, 105° C and 120° C are investigated. Results from this model are then used for a case study of a possible future CO_2 capture facility at a complex refinery in Sweden, emitting approximately 1.7 Mtonne CO_2/year.

Nomenclature

ACLC	Actual Heat Load Curve	$\dot{F}$	Mole flow
CCS	Carbon Capture and Storage	$\dot{m}$	Mass flow
GCC	Grand Composite Curve	MEA	MonoEthanol Amine

2. Aim

The main aim of this paper is to investigate how the specific heat demand for solvent regeneration in a MEA scrubber plant varies with the temperature in the stripper reboiler. This is done by process modeling in Aspen Plus. Another aim is to see to what extent the stripper reboiler can be heat integrated with a refinery at the different temperature levels and how much external heat that has to be supplied in the different cases. This is done via pinch analysis.

3. Previous works

There have been numerous attempts to determine and lower the minimum specific energy requirement for solvent regeneration for MEA scrubber plants, which seem to converge around 3 300-3 800 kJ/kg CO_2 [2], [5], [6]. Alabdulkarem et al [7] used Aspen HYSYS to see how better use of waste heat within the CO_2 capture cycle and better integration with the heat recovery steam generator system in a natural gas plant affected the power output. They found that a steam cycle without steam extraction but with high temperature condenser provided more electricity than steam extraction cycles. Harkin et al[8] used pinch analysis to see how waste heat in the MEA cycle could be used in the power cycle. This work is interesting, since it concludes that old design rules for coal power plants may no longer be valid when implementing CCS, and new rules will be developed both for greenfield plants and for retrofit.

Studies on CCS for industrial applications are scarcer. Kuramochi et al [9] concluded that post combustion CCS is the only viable option for cement and refineries in the short term, whereas the steel sector has other options. Hektor and Berntsson [10] and Johansson et al [11] studied heat integration of post combustion capture at a pulp and paper mill and a refinery respectively. Both studies used pinch analysis to see how the heat demand could be satisfied at standard solvent regeneration temperature.

Johansson et al also showed that heat pumps are beneficial to use for supplying remaining heat to the process. Ho et al [4] investigated costs for CO_2 capture from industrial sources, concluding that the costs for capture is greater in refineries than in coal power plants. They did however not include waste heat utilization in their calculations, an action that to a large extent could lower the capture costs.

Regarding different temperature levels in the stripper reboiler which is the parameter studied in this paper, Abu-Zahra et al [12] made a study varying the temperature between 108 and 128° C. Notz et al [13] made an experimental study with temperature levels ranging from 102 to 125° C and Duan et al[14] made a comparison between stripper pressures of 1.2 to 2.1 bar. The conclusion from these studies is that the specific heat demand increases with decreasing temperature/pressure.

4. Methodology

The methodology used in this paper can be divided into two main parts. The first part is to develop the model of a MEA scrubber plant in the Aspen Plus software, the second is to use the model in conjunction with stream data from a refinery in order to do a heat integration case study.

The purpose of doing a case study is to put the study about temperature dependence in a bigger context. It is interesting to get a realistic size of the process and the heat flows, and to see how the refinery heat flows corresponds to it.

4.1. The Aspen Plus Model

The simulation model consists of a simple absorber/stripper process with heat exchange between lean and rich solvent. The scope is to find the parasitic heat load in the stripper at three different temperature levels; 120, 105 and 90° C. The main outline of the process is shown in Figure 1.

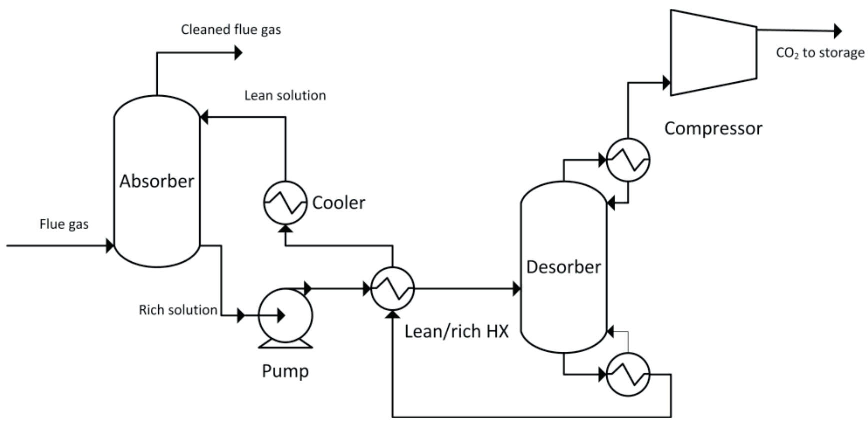

Figure 1 Schematic over the MEA process as modelled in this work.

The model uses rate-based distillation with kinetics collected from the KMEA package found in Aspen Plus. For pressure drop in the columns Stichmlair correlation is used and for mass transfer the work by Onda et al [15] is implemented. The model is based on 85 % removal of CO_2 in flue gases, corresponding roughly to 400 000 tonnes/year (322 000 m^3 flue gas/h). This flue gas flow does not correspond to the total flue gas flow of the refinery, but it is assumed that large scale benefits are present and that scaling up can be made in the future in order to do economic calculations. The lean/rich loadings chosen are showed by Abu-Zhara[2] to have the lowest energy demand, and for transparency in the comparison the same loading applies in all three simulations. Packing material has been taken from Sherif [16]. Main parameters of the process are given in Table 1. The data provided in this article should be enough to reproduce the model.

The flue gas goes through a dewatering step before entering the absorber. Table 2 shows the composition of the flue gas both before and after the dewatering step. NO_X and SO_X are present at low concentrations, but since it is not certain that further NO_X and SO_X cleaning are needed, they are neglected in this work [17].

Table 1: Main parameters of the MEA scrubber plant model.

Parameter	Value
Lean loading (mol CO_2/mol MEA)	0.32
Rich loading (mol CO_2/mol MEA)	0.493
Minimum temperature difference in lean/rich heat exchanger (° C)	10
Temperature of lean solution entering absorber (° C)	38
Temperature of flue gas entering absorber (° C)	49
Packing in absorber and stripper	38 mm ceramic Intalox saddle
Height of absorber (m)	33
Diameter of absorber (m)	6,6

Table 2 Flue gas composition before the absorber.

Compound	Vol% before dewatering [17]	Vol% after the dewatering step
H_2O	15	7,3
CO_2	14	15,3
N_2	70	76,3
O_2	1	1,1

After the stripping process, the CO_2 is compressed to 100 bar. The compression takes place in 5 stages, and the CO_2 is intercooled to 40° C between each step [18]. The compressor train is designed so that the pressure ratio would be the same in all compressors. The isentropic efficiency of the compressors is 0.8.

Design specifications are used in the model to set the make-up flows of water and MEA, but there are also important process and column specifications, which are listed below:

$$\dot{m}_{CO2,scrubbed\,gas}/\dot{m}_{CO2,flue\,gas} = 0.15 \tag{1}$$

$$\dot{m}_{top\,product,stripper} = 50.027\,\text{tonne/h} \tag{2}$$

$$\dot{F}_{CO2,\text{top product,stripper}}/\dot{F}_{\text{top product,stripper}} = 0.98 \quad (3)$$

The desired outcomes from the model are the heat loads in the reboiler, the size of the stripper column and the electricity demand for compression.

4.2. Pinch analysis

To do the heat integration part of this study, pinch analysis was used. This method was first developed in the 70s, and a thorough description can be found in Smith [19]. Pinch analysis can be used e.g. as a tool to see the minimum utility demand for a process if maximum internal heat recovery is implemented. It can also be used to see at what temperatures a process has a surplus of heat, and where the process has a deficit of heat.

In order to do a heat integration study, the heat flows of both processes that should be integrated must be extracted. Then several possibilities to do the study occur.

- To see the theoretical maximum of heat that can be extracted from the process, a Grand Composite Curve (GCC) can be constructed [19]. This graph starts from a given ΔT_{min} in the heat exchangers, and then calculates the minimum hot and cold utility assuming that maximum internal heat recovery is carried out.
- Another possibility is to construct an Actual Cooling Load Curve (ACLC) [20]. The ACLC is based on the cooling demand in all coolers using utility. Data for the streams on the hot side, i.e. the process streams that should be cooled, are compiled and creates a graph showing how much available heat there is in the process at a given temperature level. This gives a more accurate description of how much heat that is ready to use without retrofitting the heat exchanger network.

In this study, it was decided that an ACLC would give the most reasonable estimate of how much heat that could be utilized for CCS integration. Two different cases have been investigated, one for the whole refinery and one for the 5 (out of 16) most energy demanding subareas of the process. The heat demands calculated in the Aspen Plus simulation can then be compared to available excess heat in the ACLC. It is assumed that a ΔT of 10 K between the process and the reboiler is sufficient (5 K for steam production, and 5 K additionally between steam and the reboiler), e.g.in order to transfer heat from the process to the reboiler when it operates at 120° C, heat needs to be available at least at 130° C. The results show that there are significant amounts of excess heat available at the refinery, but also that the amounts are highly temperature dependent.

The refinery in this study has CO_2 emissions of approximately 1.8 Mtonne annually. Of these, the 1.74 Mtonne that originates from four main chimneys are deemed to be the potential for CCS at the refinery [17].

5. Results

5.1. Modeling results

The simulation models created in Aspen Plus shows a significant change in specific heat for the three temperature levels considered. Since the conditions for absorption were not changed, the absorption column was not affected in the simulations. Figure 2 shows the relation between heat demand and temperature in the reboiler for this study and also for Abu-Zahra et al[2][12]. The heat demand for 120° C corresponds well with this study for the same loading and wt% of MEA. Heat demands for lower temperatures differ, but are harder to compare due to differences in loading.

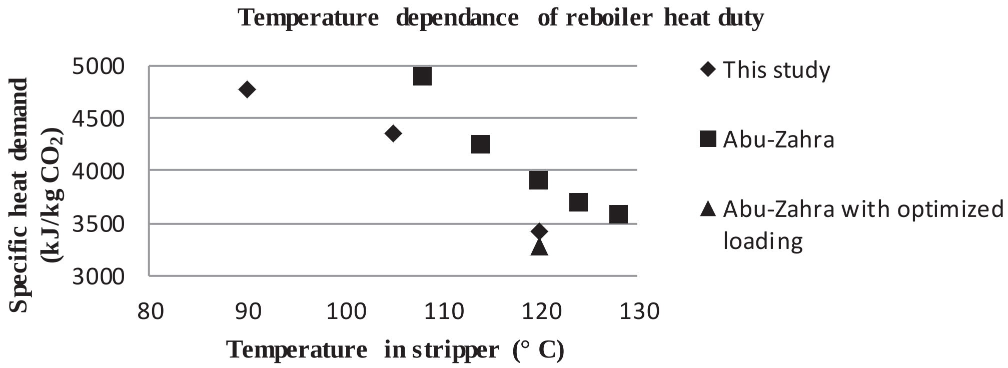

Figure 2 The specific heat demand in the reboiler of a desorption column used to regenerate MEA for three different temperature levels. Values from Abu-Zahra et al[2][12] are also presented.

It can be seen that the change in specific heat is much larger between 120 and 105° C than for the next step down to 90° C. The change in specific heat demand is approximately 40% from the lowest to the highest. Other parameters that are affected are pressure in the desorption column, electricity demand for compression, diameter of the column and the cooling demand in the condenser. The values for the different simulation runs are shown in Table 3.

Table 3 Pressure, cooling demand and stripper diameter in the different cases.

Parameter	90° C	105° C	120° C
Pressure in stripper (kPa)	65	119	209
Electricity demand in compressors (kJ/kg CO_2)	407	357	313
Cooling demand in condenser (kJ/kg CO_2)	1540	1 350	1 600
Diameter of stripper (m)	8,2	7,1	6,6

The resulting pressure when lowering the temperature in the stripper tower leads to a significant increase of compressor power. It also results in larger equipment.

5.2. Heat integration results

The complex refinery in this study is divided into 16 subareas that are to be considered as independent of each other in terms of process operation. The heat from these 16 areas can be collected via steam and transported to one or several stripper columns at the plant site. There are two main options that have been considered, either to extract steam from all 16 areas, or to focus on the 5 areas with the highest energy demands. The two ACLC graphs can be seen in Figure 3.

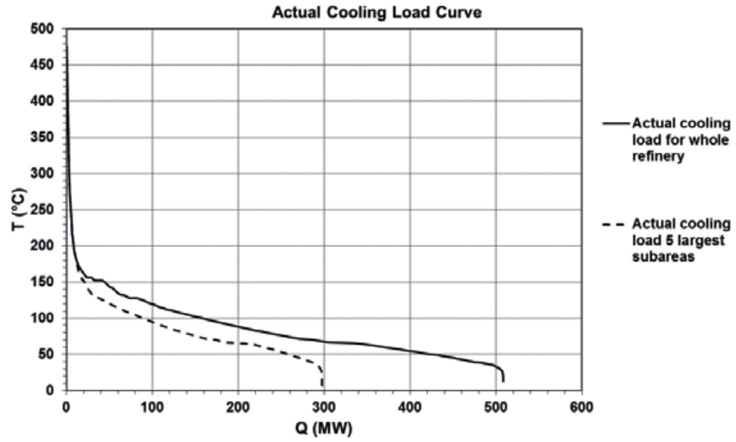

Figure 3 Actual cooling load curve in two levels, both for the whole refinery and for the 5 most energy demanding subareas.

From the figure it can be seen that 158, 110 and 70 MW are available at 100, 115 and 130° C respectively if considering the whole process. If only considering the 5 areas with highest energy demand, the figures are 89, 59 and 35 MW. Further results from the analysis are shown in Table 4. The need for heating, e.g. the amount of flue gas, is calculated on 8 200 full load hours/y.

Table 4 Results from the heat integration study

Parameter	90° C	105° C	120° C
Specific heat demand in reboiler (kJ/kg $_{CO2}$)	4 760	4 340	3 370
Heat demand for integration of 85% carbon capture (MW)	239	217	169
Heat available for CCS integration, full refinery (MW)	158	110	70
Heat deficit in the CCS process after integration with full refinery (MW)	81	107	99
Heat available for CCS integration, 5 major areas	89	59	35
Heat deficit in the CCS process after integration with 5 major areas (MW)	150	158	134

As can be seen in the table, there is a lack of heat available for all three temperature levels even if the whole refinery is used for integration. The deficit is then largest at a reboiler temperature of 105° C and smallest at 90° C. For the case where only the 5 major areas are chosen for integration, the deficit is still largest for a reboiler temperature of 105° C, but now the smallest deficit is at 120° C.

6. Discussion

Looking at the results from the simulation model part of this paper, it can be seen that the rise in specific heat is dramatic when lowering the temperature in the stripper reboiler. This is in accordance with results previously shown in other papers. In this first phase of the work all temperature levels use the same lean and rich loading, which may have affected the results. The low temperature options could benefit from not being stripped so far, an action that would increase the amount of MEA flowing in the system and make the equipment bigger, but may also lower the heat demand. This will be investigated further in coming work. It could also be possible to better utilize the heat from intercooling of the compressors to further lower the demand for external heating.

A way of utilizing more heat from the refinery, and at the same time supply more heat to the capture process, is to use a heat pump to cover the remaining heat demand. A heat pump is needed for all cases investigated in this study, if no external heat source is available. As can be seen from the figures, large amounts of heat are available at lower temperatures. Here, less compressor work would have to be used to produce 1 kWh of heat for the 90° C process than for the 120° C, which could to some extent make up for the higher electricity use in the compressor train after the capture process. The heat pump would also be smaller in size, since only 81 MW has to be supplied, compared to 99 MW for the case with 120° C. The use of heat pumps is interesting, and will be investigated in later studies.

According to the results of the study, the options where least external heating must be used is changed when switching between the options of integrating against the whole refinery or just the 5 major energy demanding areas. For the entire refinery, the amount of heat that is available at 90° C is covering most of the heat demand, but there are still large quantities of heat needed in order to fulfill the need. If only integrating against the 5 major areas, approximately 20% of the heat demand could be satisfied at 120° C. This shows that the temperature level for which the capture plant should be designed depends on what type of refinery it should be integrated with. All refineries do not contain the same subareas, and since the refineries are trying to maximize profit, they will run the subareas which produce the most profitable products at each given time. The designer should follow the trends of what subareas that are most profitable for the refinery, and try and integrate them with the capture plant before integrating other areas.

7. Conclusions

The heat demand for the stripper reboiler increases with decreasing temperatures. This, however, should normally be compensated to some extent since more heat is available at lower temperatures. In this case study, the higher heat demand is compensated fully, making the 90° C reboiler the case with lowest external heating demand. With our conditions, the refinery process can cover 66% of the heat demand for 90° C.

It is important to look at the specific conditions present in this refinery before deciding temperature level of the capture plant. Adding or subtracting certain subareas can change the integration possibilities, as could be seen when making the comparison between integration with full refinery and integration with 5 subareas.

The compression work required for the CO_2 to be ready for transport is not negligible. When decreasing the temperature in order to achieve a lower heat demand the electricity demand increases, if not taking into additional heating into account.

Acknowledgements

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