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Evaluation of Integration of Flue Gas Scrubbing Configurations with MEA for CO_2 Separation in a Coal-Fired Power Plant

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Abstract

An analysis of the integration of an advanced coal-fired power plant with a CO_2 capture unit including the compression of the captured CO_2 was conducted. The simulation was undertaken with the software programmes Aspen Plus and EBSILON®Professional. The scrubbing plant used a 30 % Monoethanolamine (MEA) solution as a solvent and the capture rate was set to 90 %.

Keywords: CO_2 capture, integration, coal-fired power plant, MEA, compression, simulation.

Introduction

CO_2 capture technologies with chemical absorption are not new and are at some point commercially available. The idea of using this sort of technology for capturing a large amount (90 %) of the CO_2 emitted from coal-fired power plants is however, a new approach that has a series of obstacles to overcome before chemical absorption can commercially be applied in the electrical energy generation sector. One of the main problems relies in the amount of energy required for the regeneration of the solvent, which leads to high efficiency penalties from existing and new coal-fired power plants. Since coal-fired power plants make out for a considerable amount of the generated electricity (approximately 51 % in Germany [1]) it makes sense to try to adapt and improve this technology, in order to be able to capture CO_2 from flue gases and therefore contribute to the reduction of this anthropogenic gas in the atmosphere.

The performed study presents an overview of the technology used for the coal-fired power plant used as a reference. The CO_2 capture unit is also considered, as well as the compression process. This study looks for possible links between power plant and scrubbing system, in order to detect possible ways to reduce the energy requirement for the chemical absorption process that would have to be provided by the power plant.

Process description

The integration design was based on an advanced coal-fired power plant, a conventional absorber-stripper configuration for a scrubbing process using MEA as a solvent and the compression of the captured CO_2 in 5 stages, which will be described in more detail in the following pages.

Reference power plant North Rhine-Westphalia (RPP-NRW)

Table 1: Design data of RPP NRW [2]

Gross Output	600 MW_{el}
Net Output	555,6 MW_{el}
Net Efficiency	45,9 %
Main Steam	285 bar 600°C
Condenser Pressure	45 mbar
Pre-heating Stages	8

In the upcoming years several coal-fired power plants will be built in Germany. Their technology will be that of RPP-NRW with an efficiency of 45,9% (LHV). It is indeed possible to reach a higher efficiency with coal-fired power plants, due to site specific conditions. However, given that most power plants have to operate with cooling towers and hence can not achieve such efficiencies, it was decided to use RPP-NRW as the reference for this study. The main parameters of RPP-NRW can be taken from Table 1.

The simulation of RPP-NRW was undertaken with the software EBSILON®Professional from Evonik Industries. This is a software specialized in serving the energy- and mass balancing of power plant processes. It is frequently used in Germany for planning, construction, optimization and plant control and is therefore a suitable simulation tool for representing RPP-NRW.

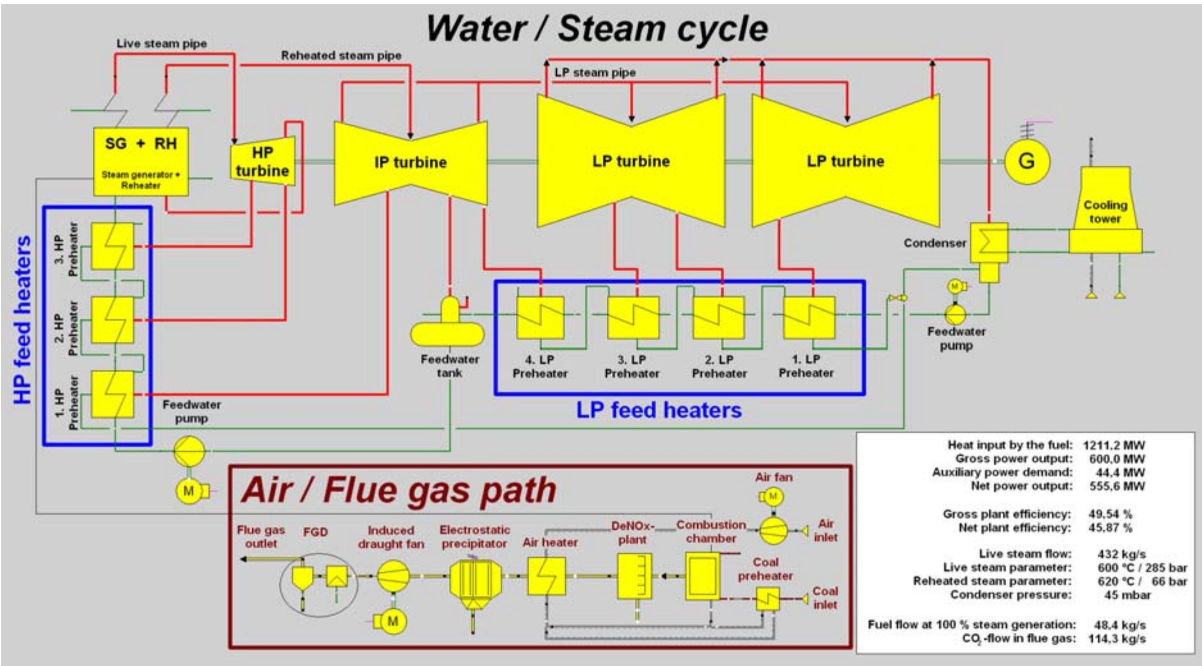

Figure 1: Process flow diagram of RPP-NRW in EBSILON®Professional.

Figure 1 shows the main components of the water/steam cycle for RPP-NRW. These are steam generator, turbine set (high, intermediate and low pressure turbines), condenser, pumps and 8 feed water pre-heaters. After having pre-heated the water, it will be evaporated and superheated in the steam generator until it reaches a temperature of 600°C at 285 bar. The steam will then enter the high pressure turbine, where it will be expanded. A part of the mass flow will be extracted in two tappings with the purpose of using them in the second and third HP feed water pre-heaters, the remaining steam will be reheated in a boiler to a temperature of 620°C at 60 bar and led to a double-flow IP turbine. As with the HP turbine, the IP turbine will also be tapped with the purpose of pre-heating the feed water mass flow in the cycle, as will happen with the LP turbines. The remaining stream will be expanded to a condenser pressure of 45 mbar. The feed water coming out of the condenser will be led through the pre-heaters by pumps until it again reaches the steam generator to close the cycle.

Coal combustion

With the purpose of getting reliable results regarding components taking part in the absorption-desorption process the combustion gases were both generated with Aspen Plus and EBSILON®Professional before they were implemented in the capture unit. The composition of the coal used is that of RPP-NRW and can be seen in Table 2. The simulation with Aspen Plus was conducted based on one of the user guides provided by Aspentech [3]. The results of both simulations were compared with each other noting only negligible differences.

Table 2: Coal data used for this study (water and ash free)

Coal composition	**Mass fraction**
Carbon	0,834
Hydrogen	0,045
Oxygen	0,094
Nitrogen	0,0191
Sulphur	0,0076
Chlorine	<0,0001
Sum	0,9998
Ash (raw condition)	0,14
Water (raw condition)	0,075
Volatile matter	0,30
Calorific value (raw condition) [MJ/kg]	25,95
Lower heating value (raw condition) [MJ/kg]	25,00

The combustion air is pre-heated to a temperature of 350°C and delivered to the furnace by a fan. Coal also has to be pre-heated previous to entering the furnace, where combustion takes place and both flue gas as well as ashes are generated. The ashes, or solids as indicated in [3], have a temperature of 300°C. The assumed air ratio is 1,15. The flue gas leaves the furnace with a temperature of 360°C. It was at this point, that the results of both simulations were compared. Given that EBSILON®Professional is a program specialized in power plants it is relatively easy to implement further units for conventional flue gas cleaning technologies such as DeNOx and flue gas desulphurisation (FGD). The advantage of this relies in being able to account for the electrical energy demand of such plants and determining the condition of the flue gas as it follows the conventional cleaning path.

CO_2 capture unit

The flow sheet of the amine scrubbing unit simulated with Aspen Plus version 2006.5 is shown on Figure 2. The process consists of an absorber/stripper configuration. The process was simulated as a rigorous model with the property method electrolyte NRTL and the chemistry package MEA from the same software, as suggested in a document from the company Aspentech [4]. The following reactions belong to the mentioned chemistry package and chemical equilibrium was assumed for all of them.

$$2H_2O \leftrightarrow H_3O^+ + OH^-$$
$$CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^-$$
$$HCO_3^- + 2H_2O \leftrightarrow H_3O^+ + CO_3^{2-}$$
$$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+$$
$$MEACOO^- + H_2O \leftrightarrow MEA + HCO_3^-$$
$$H_2O + H_2S \leftrightarrow HS^- + H_3O^+$$
$$H_2O + HS^- \leftrightarrow S^{2-} + H_3O^+$$

In order to avoid degradation and corrosion problems the flue gas has to be pre-treated before it enters the absorber column. In this case a maximum content of 10 ppmv SO_2 is used [5]. This represents a significant reduction of current SO_2 levels held by FGD plants (200 ppmv) and thus represents an extra energy penalty for the power plant. In this study it was assumed that the flue gas leaves the FGD at a temperature of approximate 47°C and will be directed to a blower, which will increase its pressure by 80 mbar to compensate for pressure losses within the absorber. The flue gas will then be led to a direct contact cooler (DCC) to reduce its temperature to 40°C previous to enter the absorber column. The flue gas is then ready to enter the absorber column at the bottom, while the lean solvent enters the column at its top (counter current), also at 40°C. The absorber is operated at atmospheric pressure. The CO_2 content in the flue gas decreases as the gas flows to the top of the absorber column and at the same time the CO_2 is absorbed in the solvent, which accumulates at the bottom of the column.

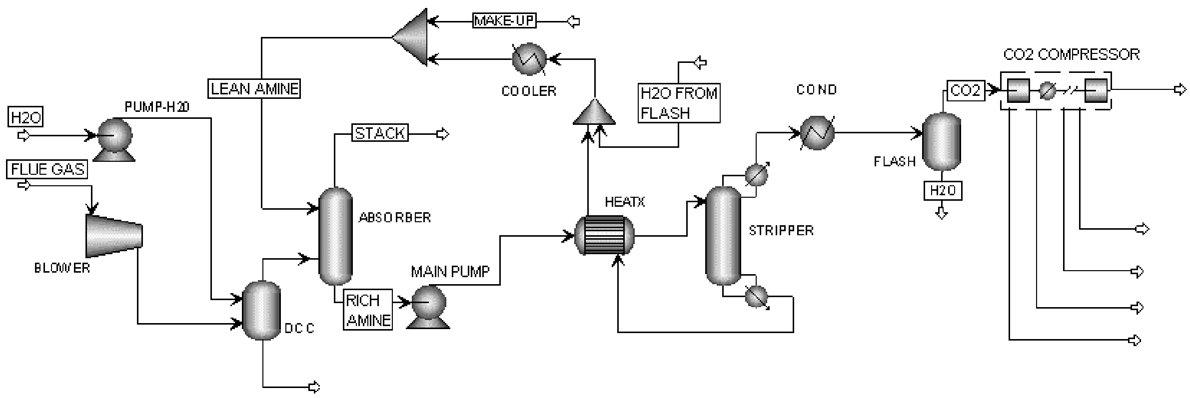

Figure 2: CO_2 capture unit with CO_2 compression.

The cleaned flue gas leaves the absorber column at the top and is released to the atmosphere once it has been washed to retain impurities such as amine rests (this part is not shown in Figure 2), which will be re-injected in the absorber column, contributing to keep amine loses low. The rich solvent is sent to the regeneration column or stripper via a pump and a cross heat exchanger.

The pump fulfills two tasks: on the one hand it will be used to move the big solvent mass flow ($\dot{m}_{solvent}$) required for capturing 90% of the CO_2 from a 600 MW_{el} coal-fired power plant (> 2000 $kg_{solvent}/s$) and, on the other hand it will increase the pressure of this mass flow in order to reach the necessary operating conditions needed within the stripper. This is also the pump within the scrubbing system with the highest electricity demand, which varies depending on the amount of solvent used ($P_{el} = f(\dot{m}_{solvent})$). Here it is important to mention that the value of mass flow used is also a direct function of the lean solvent loading (α_{lean}), as has been mentioned in previous publications [6, 7], and hence it will be considered in the overall analysis of energy demand for the presented CO_2 capture unit. α is defined as follows:

$$\alpha = \frac{mol_{CO_2}}{mol_{MEA}}$$

In the heat exchanger the heat of the lean amine from the stripper column is transferred to the rich amine from the absorber, as a measure to prepare both solvent flows for the operating conditions within the two columns of the process. The assumed temperature difference between rich and lean solvent was 10 K.

The regeneration of the solvent takes place in the stripper column at elevated temperatures (100-140°C) and pressure (1,6 bar at the top and nearly 2 bar at the bottom of the column). This unit requires the highest amount of thermal energy from the scrubbing cycle and thus from the power plant itself. Steam is extracted from the power cycle and supplied to the reboiler in order to both heat the solvent for the purpose of reversing chemical reactions that took place in the absorber and evaporate part of it, to act as stripping gas. As with the pump, the precise amount of required energy in MJ_{th}/kg_{CO2} depends on several parameters such as level of regeneration of the amine, kind of solvent used, content of amine in the solvent, amount of CO_2 to strip, among others. For this study a solvent consisting of 30 % MEA was used. The rich amine is injected to the column at the top and gets in contact with the steam produced by the reboiler at the bottom. As the rich amine finds its way downwards, the reactions that took place in the absorber will be reversed, meaning that the CO_2 content in the amine (α_{rich}) gets reduced until it reaches the desired new loading α_{lean}. The regenerated amine leaves the stripper at the bottom and is directed to the heat exchanger and on its way back to the absorber to close the CO_2 capture loop.

The stripped CO_2 leaves along with some water and a trace of MEA in form of steam at the top of the column. This stream will then be cooled down in a condenser and subsequently separated in a flash drum. A part of the liquid phase consisting of water and MEA will be refluxed to the stripper and the rest can be re-used in the scrubbing unit, to maintain the water balance within the system, which would otherwise have to be compensated with the Make-Up stream. The saturated CO_2 stream leaves the flash drum at the top at an assumed temperature of 50°C and a pressure of 1,6 bar. The initial cooling temperature of the CO_2 stream affects directly the electrical energy requirement of the compressor. It also affects the water content in the CO_2 stream to be compressed.

CO_2 Compression

For the simulation of this step the unit operation model (UOM) MCompr or Multistage compressor from Aspen Plus was used, so that the components and small impurities provided by the absorption-desorption process would also be considered. This UOM offers the possibility of compressing the CO_2 in several stages, without having to model every single step of the compression process. It is also possible to enter the isentropic and mechanical efficiencies, pressure ratio (2,287 being kept constant for all stages). The temperature of the CO_2 stream within the compressor increases with every stage and has to be cooled down, in order to minimise the energy demand and to dry the CO_2 at the same time, which is a necessary step if corrosion within the CO_2 pipeline is to be avoided.

From a previous study performed at LUAT [8] it was determined that the required specific energy demand in kW/kg_{CO2} decreases with an increasing number of stages in a compressor and the minimum number of stages recommended should be 4. It was therefore decided to use 5 stages for this simulation. In the study it was also said that how many stages would actually be used in a compression process was all a matter of economics, since the reduction in specific energy demand would be less pronounced with every further stage. For this study 5 stages were used and the property method applied was PENG-ROB [9]. For the simulations an isentropic and mechanical efficiencies of 72 % and 97 % were respectively assumed. The final pressure of the CO_2 stream is 100 bar (supercritical). For transport purposes the CO_2 pressure has to be further increased up to about 200 bar.

Process integration

With the purpose of retrofitting a coal-fired power plant like RPP-NRW with a CO_2 capture plant, it is imperative to first detect the links between these two units. It is indeed important to guarantee for the steam supply from the power cycle to the CO_2 scrubbing plant, to provide the required energy for regeneration of the solvent and stripping of CO_2 from it, though this is not the only focus of the study.

It was previously mentioned that the amount of required energy depends on several factors. Since it was decided to work with a solvent consisting of 30 % MEA and a conventional absorber-stripper configuration as shown in Figure 2, the alternatives to reduce the energy demand have already been limited by the conditions established in "CO_2 capture unit". Under these circumstances, the steam from the power plant would have to be extracted before it is led to the LP Turbines at p=3,6 bar and re-injected in the water/steam cycle between the third and fourth feed water pre-heaters at T=140°C and constant pressure. In order to avoid pressure instabilities that would end in an imbalance within the power cycle, a pump would have to be built in.

If coal-fired power plants are to be conventionally retrofitted with a CO_2 capture unit, a specific energy demand of 3 MJ/kg_{CO2} or lower must be reached. An alternative to reduce the energy demand from the capture plant while still using MEA was suggested by [7]. In that case the concentration of MEA in the solvent would be 40%, but it was also mentioned that this might not be a feasible solution, due to limitations established by corrosion and solvent degradation.

Results

Throughout the simulations performed with Aspen Plus an MEA content of 30 % in the solvent, as well as a capture rate of 90 % CO_2 were kept constant.

Figure 3 shows the reboiler heat duty in MJ/kg_{CO2} and rich solvent mass flow in kg/s as a function of $\Delta\alpha$, which represents the difference from rich and lean solvent loading.

In this case the lean loading is represented by the solvent entering the top of the absorber column, while the rich loading usually represents the solvent leaving at the bottom. As previously mentioned, the solvent is regenerated in the stripper. Running the simulation in an open loop offers the opportunity of getting a model to converge faster; though, there are certain dependencies that might get lost, unless a scrubbing system is run in a closed loop, like in this case. One important dependency is the effect $\Delta\alpha$. Figure 1 shows how much thermal energy was used to regenerate the solvent. As can be seen, there is also a direct dependency on the amount of solvent used within the scrubbing process. The higher the difference $\Delta\alpha$ is the more energy will be used in the reboiler to regenerate the solvent. This also means that the intake capacity of the solvent will be higher, making it possible to use less solvent to capture the same amount of CO_2 (90% in all cases). Reducing $\Delta\alpha$ increases the amount of solvent used in order to be able to absorb the same amount of CO_2, since the capture rate is supposed to be kept constant at all times. On the other hand, reducing $\Delta\alpha$ means the reboiler duty also decreases, as shown in Figure 1. In the sensitivity analysis

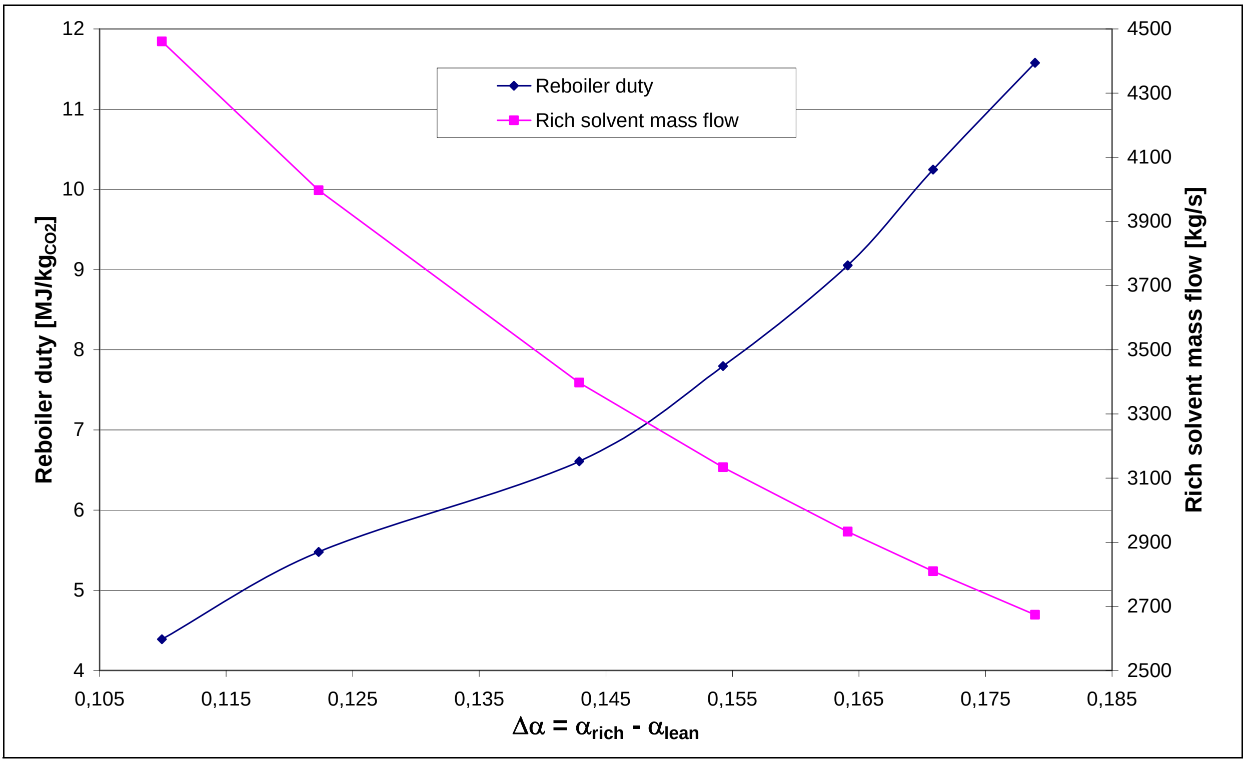

Figure 3: Reboiler duty and rich solvent mass flow as a function of $\Delta\alpha$ (rich and lean loading difference).

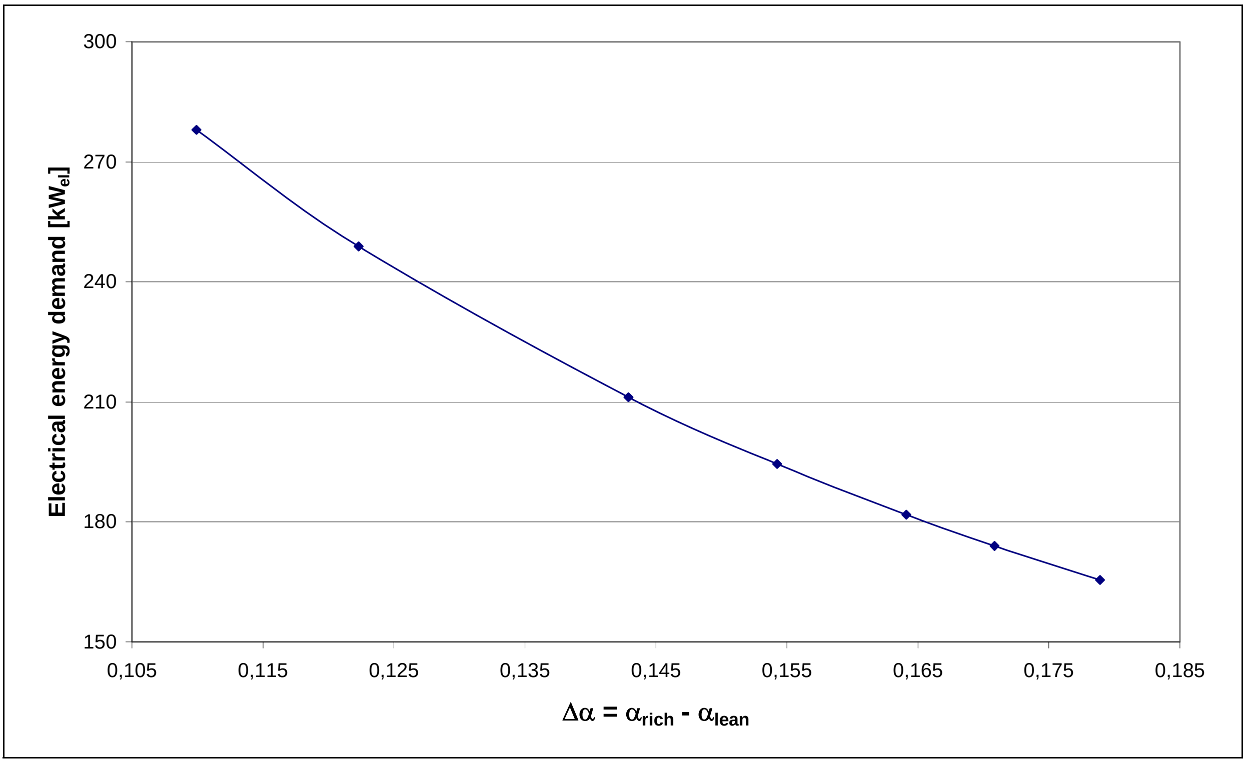

Figure 4: Electrical energy demand of the main pump as a function of $\Delta\alpha$ (rich and lean loading difference).

conducted during simulations, the lowest reboiler duty accounted for was 4,39 MJ/kg$_{CO2}$ at a loading of α_{lean} = 0,25. This value coincides with the data from previous publications [6, 7, 10]. The trend of the reboiler duty curve also implies that the duty could, in theory, further be decreased and can be subject to future analysis. It would also imply that a considerable increase of solvent mass flow would be expected. At this point it is important to remark that the columns used for the scrubbing system would also have to be dimensioned.

From Figure 3 a decrease of solvent in kg/s was observed with an increasing $\Delta\alpha$. As it was to be expected Figure 4 shows the decrease of electrical energy used for the main pump as $\Delta\alpha$ increases. The main pump has in this case two main tasks: to increase the pressure of the rich solvent from the absorber operating at almost atmospheric pressure to reach operating conditions in the stripper and, to pump the solvent to the stripper for its regeneration. There are two more important units in the capture unit that are not represented in Figure 4: blower and CO_2 compressor. The reason for this is the fact that their energy requirement remains constant, since the flue gas mass flow is not changed and neither is the mass flow of the CO_2 captured. The electrical energy demand for the compressor with an initial temperature of 50°C for the CO_2 stream is 36,2 MW_{el} and for the blower 4,14 MW_{el}. Plotting all three results in Figure 4 would not make sense, as the trend of the pump curve would get lost due to its small dimension compared with the other two mentioned units.

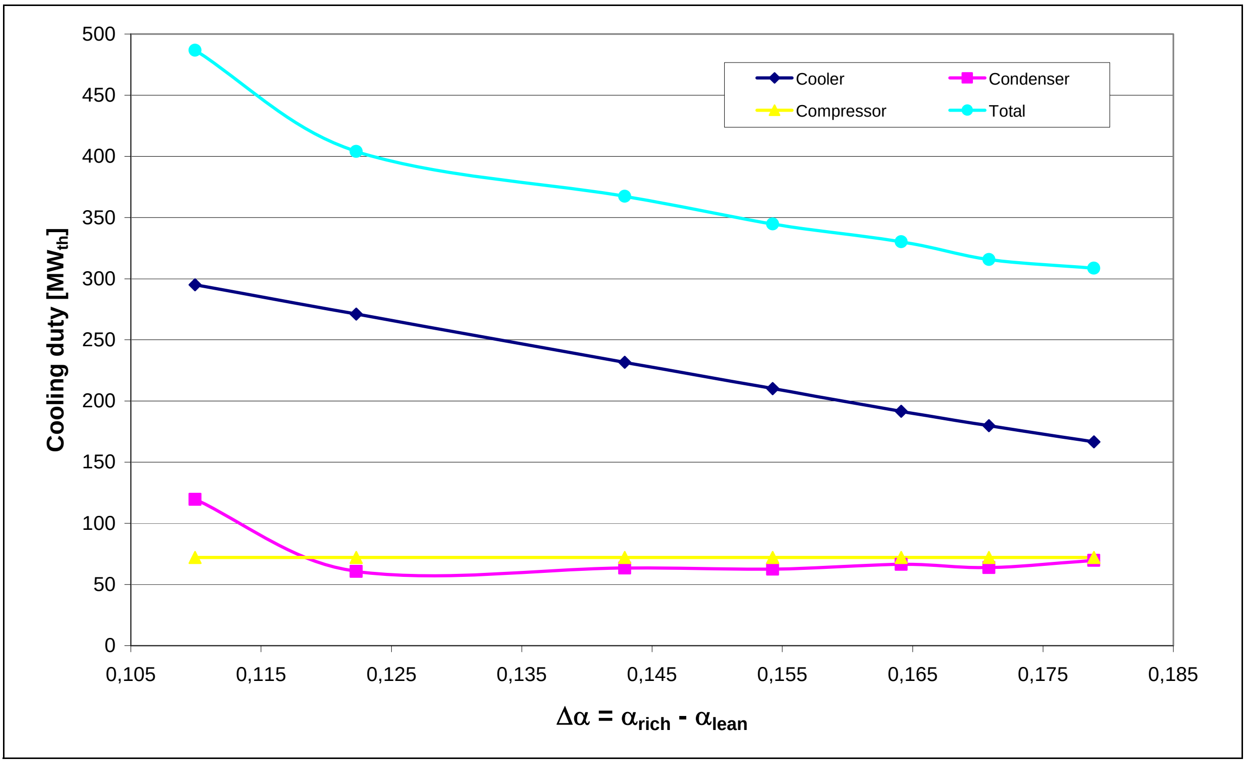

Figure 5: Cooling duty as a function of $\Delta\alpha$ (rich and lean loading difference).

Figure 5 shows the increase of cooling duty as a function of $\Delta\alpha$. The three main components for cooling duty demand are represented there: Cooler (conditioning of lean amine from stripper back to absorber), condenser (after stripper column to separate CO_2 from water with MEA before entering the compressor) and CO_2 compressor. In Figure 5 there is a curve representing the total cooling duty in MW_{th}. The trend of this curve seems to be linear starting at a $\Delta\alpha$ value of approximately 0,12. The reason for the change of trend lies in the cooling duty of the condenser for $\Delta\alpha < 0{,}12$. An option to increase the lean loading (α_{lean}) is to vary the reflux ratio (RR) within the stripper. The RR represents the amount of moles returned as liquid to the column divided by the amount of moles of final product. In other words, the smaller RR is, the more product will have to be cooled down. Furthermore, as could also be seen in Figure 3 the amount of solvent circulating within the scrubbing cycle also increases as $\Delta\alpha$ decreases, so that more product has to be cooled down to get the same amount of CO_2 to be compressed.

The trend from the cooler curve was to be expected, given that with a decreasing $\Delta\alpha$ the solvent mass flow increases, making it necessary to increase the cooling duty to maintain a constant temperature of the lean solvent before entering the absorber.

Regarding the compressor curve, the cooling duty remains constant because the amount of CO_2 was not increased.

According to simulations' results a minimum pressure of 3,6 bar would be required for the steam that would be extracted from the power plant (RPP-NRW) to be able to reach the solvent's temperature of regeneration. An approximate steam rate of at least 194 kg/s would be needed to supply 4,39 MJ_{th}/kg_{CO2}. This corresponds to a 90 % capture of CO_2. Furthermore, in order to avoid a pressure drop within the steam pipeline a throttle would have to be built before the low pressure turbine, which would be the location of steam extraction. The throttle would bring losses along with it so that the overall efficiency of the power plant would irreversibly be affected. The steam rate could also decrease to a range of 132-177 kg/s if the reboiler duty would be reduced to 3-4 MJ/kg_{CO2} respectively.

Conclusions

The simulation of the scrubbing process and a coal-fired power plant (RPP-NRW) with Aspen Plus and EBSILON®Professional respectively helped to determine main conditions required to integrate both processes. It was identified that the lean solvent loading alone does not guarantee the reduction of thermal energy required for the regeneration of the solvent. The difference between rich and lean solvent loading ($\Delta\alpha$) is a key parameter to increase or decrease the thermal energy demand as it dictates, how much energy will be invested in regenerating the rich solvent. The results showed a minimum reboiler duty of 4,39 MJ/kg_{CO2}, although the presented trends show that an even lower reboiler duty could be reached. Besides the loading there are more aspects that have to be considered if a specific energy requirement from the reboiler of 3MJ/kgCO_2 or lower is to be reached. An important role play the heat integration within the scrubbing cycle and the regeneration energy requirement of the solvent. In addition, a solvent should also be tested under real conditions to see if it will be suited to be implemented in coal-fired power plants. That is the reason why at LUAT a small mobile pilot plant will be constructed and implemented directly in a power plant. The expected information will help to optimise simulations as well as the real scrubbing process itself.

An increase in the solvent mass flow was noted with decreasing $\Delta\alpha$ and the involved increase-decrease for both cooling duty and electrical energy demand were presented. In this case, the main pump showed an increase of demand but was found to be very small compared to the electrical energy demand from both blower and CO_2 compressor. The electrical demand and cooling duty for the CO_2 compressor was kept constant. Regarding the cooling duty the lean amine cooler and condenser showed a higher cooling water demand for small $\Delta\alpha$ values.

With respect to the power plant it was noted that a throttle would have to be built in order to maintain the pressure of the extracted steam at 3,6 bar to guarantee for the right temperature of regeneration needed in the stripper column. This would nevertheless affect the power plant irreversibly, due to losses caused by the throttle. The steam rate for a 90% capture of CO_2 was calculated to be approximate 194 kg/s. This is not a final number, due to the fact that the steam rate is directly proportional to the reboiler duty. This means, that the steam rate can be decreased, as soon as the reboiler duty gets reduced.

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