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## Post-Combustion $CO_2$ Capture for Combined Cycles Utilizing Hot-Water Absorbent Regeneration

**Klas Jonshagen***
Dept. of Energy Sciences
Lund University
SE-22100 Lund
Sweden
klas.jonshagen@energy.lth.se

**Majed Sammak**
Dept. of Energy Sciences
Lund University
SE-22100 Lund
Sweden
majed.sammak@energy.lth.se

**Magnus Genrup**
Dept. of Energy Sciences
Lund University
SE-22100 Lund
Sweden
magnus.genrup@energy.lth.se

### ABSTRACT
The partly hot-water driven $CO_2$ capture plant offers a significant potential for improvement in performance when implemented in a combined-cycle power plant (CCPP). It is possible to achieve the same performance with a dual-pressure steam cycle as in a triple-pressure unit. Even a single-pressure plant can attain an efficiency competitive with that achievable with a triple-pressure plant without the hot-water reboiler. The underlying reasons are better heat utilization in the heat recovery unit and less steam extraction to the absorbent regenerating unit(s).

In this paper, the design criteria for a combined cycle power plant utilizing hot-water absorbent regeneration will be examined and presented. The results show that the most suitable plant is one with two steam pressure levels. The low-pressure level should be much higher than in a conventional combined cycle in order to increase the amount of heat available in the economizer. The external heat required in the $CO_2$ capture plant is partly supplied by the economizer, allowing temperature optimization in the unit. The maximum value of the low-pressure level is determined by the reboiler, as too great a temperature difference is unfavourable.

This work evaluates the benefits of coupling the economizer and the reboiler in a specially designed CCPP. In the $CO_2$ separation plant both monoethanolamine (MEA) and ammonia are evaluated as absorbents. Higher regeneration temperatures can be tolerated in ammonia-based plants than in MEA-based plants. When using a liquid heat carrier the reboiler temperature is not constant on the hot side, which results in greater temperature differences. The temperature difference can be greatly reduced by dividing the regeneration process into two units operating at different pressures. The possibility of extracting more energy from the economizer to replace part of the extracted steam increases the plant efficiency. The results show that very high efficiencies can be achieved without using multiple pressure-levels.

### INTRODUCTION
Carbon dioxide emissions can be reduced by implementing technology for carbon dioxide capture. The emission of carbon dioxide can be avoided or mitigated either by removing the carbon from the combustion process, i.e. pre-combustion techniques, by collecting the carbon dioxide from the flue gases after combustion, i.e. post-combustion techniques or by avoiding dilution of the exhaust with nitrogen, i.e. oxy-combustion. Pre-combustion is based on that carbon is removed or separated from the fuel before the combustion. The principle of the oxy-combustion cycles (also called oxy-fuelled cycles) is that nitrogen is removed from the air before the process resulting in that the flue gas consists mainly of $CO_2$ and water. After the steam generator (a boiler or a heat-recovery steam generator (HRSG)), the steam is separated by condensation of the water vapour in the flue gases. Two major concepts for oxy-fuel cycles have emerged: the semi-closed oxy-fuel combined cycle [1-3] and the Graz cycle [4].

Post-combustion is based on that $CO_2$ is separated from the flue gases in an absorbent-based $CO_2$ capture unit after the power plant. Compared with the other $CO_2$ capture techniques, absorbent-based $CO_2$ capture does not require a new power plant concept; hence proven technology can be used. This makes the method very suitable for retrofitting to existing plants. Two absorbents were investigated in this study: monoethanolamine (MEA) and ammonia.

Monoethanolamine is an alkanolamine that has been used for many years in the petroleum industry. Kohl and Nielsen

*Corresponding author

have described the method of $CO_2$ capture with MEA [5], and there are numerous publications concerning the integration of MEA with CCPPs [6-14].

Eli Gal developed and patented the method of using ammonia to capture carbon dioxide, referred to as the chilled ammonia technique [15]. The patent is today owned by Alstom power. Darde has presented a detailed study of the chilled ammonia process [16], and Dave later compared the performance of chilled ammonia and MEA [17]. Common to all post-combustion techniques is that heat is required to regenerate the absorbent. In previous studies in this field steam extracted from the turbine has been used to regenerate the absorbent.

This paper describes a method of utilizing low-grade energy to regenerate the absorbent. The theoretical study was designed to investigate the utilization of low-grade energy in two post-combustion $CO_2$-sequestration processes employing chilled ammonia and MEA. A single-pressure cycle with and without reheat, a dual- and a triple-pressure cycle including reheat has been tested with a MEA capture plant. The single-pressure reheat cycle has also been tested with a chilled ammonia capture unit. The purpose of the study was to evaluate the benefits of recovering excess energy from the economizer to provide a part of the reboiler heat duty.

## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| CCPP | Combined Cycle Power Plant |
| EGR | Exhaust Gas Recirculation |
| GT | Gas Turbine |
| HP | High-Pressure |
| HRSG | Heat Recovery Steam Generator |
| IP | Intermediate-Pressure |
| LP | Low-Pressure |
| MEA | Monoethanolamine |

## CARBON CAPTURE ON A CCPP

The flow of flue gas per unit power produced in a CCPP is much higher than that from a steam-boiler-based power plant as combustion is performed in the former with a large surplus of air. This results in a need for very large, and thus very expensive, absorption columns. The volume of the columns can be reduced by utilizing exhaust gas recirculation (EGR), which is described in a later section. The size of the column is determined by the maximum possible velocity of the flue gas. This is to ensure that none of the liquid absorbent is swept away with the flue gas at the top of the column.

A post-combustion $CO_2$ capture plant requires heat to regenerate the absorbent (to break the $CO_2$–absorbent bonds). The temperature required for absorbent regeneration depends on the absorbent used. If a higher temperature can be used, the pressure in the regenerator can be increased. A high regenerator pressure means that the absorbent can absorb the $CO_2$ at ambient pressure, and then be pumped to a higher pressure. The result of this is that the energy required for the compression of gaseous $CO_2$ can be reduced.

The energy required in the carbon capture plant is generally supplied by steam from the low-pressure part of the steam cycle. In a combined cycle there is no other low-temperature heat sink than the feedwater from the condenser. If part of the water is condensed at a higher pressure, and hence at a higher temperature, the heat sink will be reduced. The result of this is that less energy can be recovered from the gas turbine exhaust gas.

### Exhaust gas recirculation, EGR

The working principle of a gas turbine with large amount of excess air in the combustion results in that the concentration of $CO_2$ in the exhaust gas is lower than for a conventional steam boiler. This, in combination with the higher specific flue gas flow for the gas turbine, makes the separation plant large and costly. (The specific flue gas flow in a gas turbine plant is of the order of 1.5 kg/MWs, compared with approximately 0.95 kg/MWs for a normal steam boiler.) To limit the flow, the concentration of carbon dioxide in the gas turbine working fluid can be increased by utilizing EGR. This will reduce the volume of flue gas to be treated in the separation plant. It should be noted that the energy required in the $CO_2$ capture plant, apart from some minor pumping requirements, consists of the absorbent regeneration energy, which is not affected by the concentration of $CO_2$ in the flue gas. In other words, the amount of $CO_2$ dissolved in the absorbent determines the energy required, and this is the same regardless of whether EGR is used or not. The limit on how much EGR can be utilized is, in principle, determined by the combustor. The limitation is in general caused by a lack of oxygen, which reduces the efficiency of the combustor, resulting in high CO levels [9, 18].

Experimental studies by Elkady et al. showed that the dry low $NO_X$ (DLN) combustor used in General Electric’s F-class, heavy-duty gas turbines can be operated at 30–35 % EGR without modification, and they predicted that such turbines could be operated with EGR levels above 40% with only minor modifications [18]. Bolland and Mathieu used an EGR rate of 40 % in a GE-109FA gas turbine. This was possible provided that the concentration of $O_2$ before the combustion can be kept above 16 %vol.

EGR will change the properties of the gas turbine working fluid and will therefore affect the performance. First of all, EGR requires exhaust gas cooling in order to reduce the volume flow. This is usually done with a flue gas condenser using direct contact with water at ambient temperature. The temperature difference in the flue gas condenser results in that EGR will increase the compressor inlet temperature. This will reduce the density of the working fluid and therefore have a negative effect on the compressor mass flow. On the other hand the purpose of EGR is to increase the $CO_2$ content of the working fluid and as $CO_2$ has a higher density than oxygen, the density at a given temperature will increase. These two effects will cancel each other out and the compressor mass flow will only be marginally affected due to EGR. The increased amount of $CO_2$ in the working fluid will also reduce the isentropic exponent resulting in a reduced temperature difference over both the turbine and the compressor. This will have two main effects, both negative for the GT efficiency; more fuel is required for maintaining the combustor outlet temperature and the exhaust gas temperature will increase. The reduced GT efficiency means that more energy is available for the steam cycle and the power output will increase. For the combined cycle the result of EGR is that the power output will increase at a more or less unchanged efficiency but this is to the cost of a large flue gas condenser requiring large amount of cooling water. In a previous study the author has performed a theoretically study of the effects of EGR on the turbomachinery, in terms of Mach numbers, resulting from changes in the gas properties of the working fluid [19]. It was found that the change in Mach number was very small at 40 % EGR.

The current model gives a $CO_2$ concentration of just below 8 %vol with 40 % EGR, which corresponds to the value suggested by Elkady et al. for the GE 109FB burner [18], therefore, 40 % EGR was used in this work. EGR requires exhaust gas cooling in order to reduce the temperature at the compressor inlet. This is done with water at ambient temperature, which is sprayed through the exhaust in an exhaust gas condenser.

## THERMODYNAMIC MODELLING

This study is based on a combined cycle using the General Electric 109FB gas turbine, a 300 MW, single-shaft machine, as topping cycle. With no available data from using EGR it was necessary to use an off-design gas turbine model. The gas turbine model is modelled as described by Walsh and Fletcher [20] and uses fully dimensionless parameter groups. The compressor map is based on a publication by General Electric [21]. The map is actually for a Frame 7 unit, which is the 60 Hz version of the Frame 9 type. It is assumed that the Frame 9 compressor is a direct scale-up of the smaller Frame 7 unit. The turbine uses a standard turbine map (choking occurs in the stator).

**Table 1: Calculation assumptions**

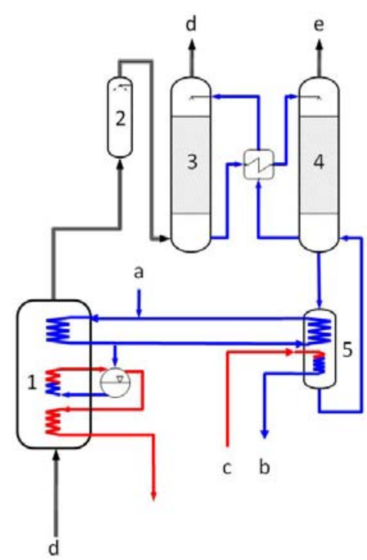
| | | |
|---|---|---|
| $\eta_{HP}$ | 85.0 | % |
| $\eta_{IP}$ | 90.0 | % |
| $\eta_{LP}$ *(dry)* | 88.0 | % |
| $\eta_{GT}$ *(at 40 % EGR)* | 37.7 | % |
| *EGR rate* | 40 | % |
| *Compression work per kg* $CO_2$ | 300 | kJ/kg |
| *Pressure loss in HRSG* | 40 | mbar |
| *Evaporator pinch point* | 8 | °C |
| *Ambient temperature* | 15 | °C |

The purpose of this study is not to make a retrofit but to design a new CCPP, therefore the steam turbine calculation only will concern the design point. The wet efficiency is modelled according to Baumann as described by Traupel [22] and the exhaust loss in the low-pressure turbine is set to 30 kJ/kg. Parasitic losses and transformed step-up losses are not included in the presented efficiencies. The heat- and mass-balance program IPSEpro by simtech [23] have been used for the calculation. The key figures for all calculated cycles are displayed in Table 1.

### $CO_2$ capture plant modelling

Two types of absorbent-based $CO_2$ separation techniques were studied. In both cases the capture rate was set to 90 %vol. The first separation plant uses MEA as absorbent. The separation unit model was developed by Fredriksson Möller [6], based on the concept described by Kohl and Nielsen [5]. The absorbent consists of a solution of 30 %wt MEA and 70 %wt water. The absorbent regeneration temperature is set to 120 °C to limit the degradation of the amine.

The second separation unit is based on the chilled ammonia concept developed by Alstom. This process involves many different chemical reactions, and the reaction path depends on the process settings. ASPEN was used to generate the tables needed to make a simplified model in the heat- and mass-balance program IPSEpro [21]. The tables required for the IPSEpro model were created by fixing most of the process parameters in ASPEN and varying the pressure in the regenerator column. The regenerator was modelled with the ASPEN component RadFrac assuming equilibrium. This limited the IPSEpro model to one particular solvent mixture. The purpose here was to test the possibility to utilize a higher temperature for regenerating the absorbent which characterized the choice of mixing ratio of the solvent. To evaluate a chilled ammonia separation unit in a CCPP which supplies the reboiler with energy at a lower temperature, a different solvent should be used and this has not been done in this work.



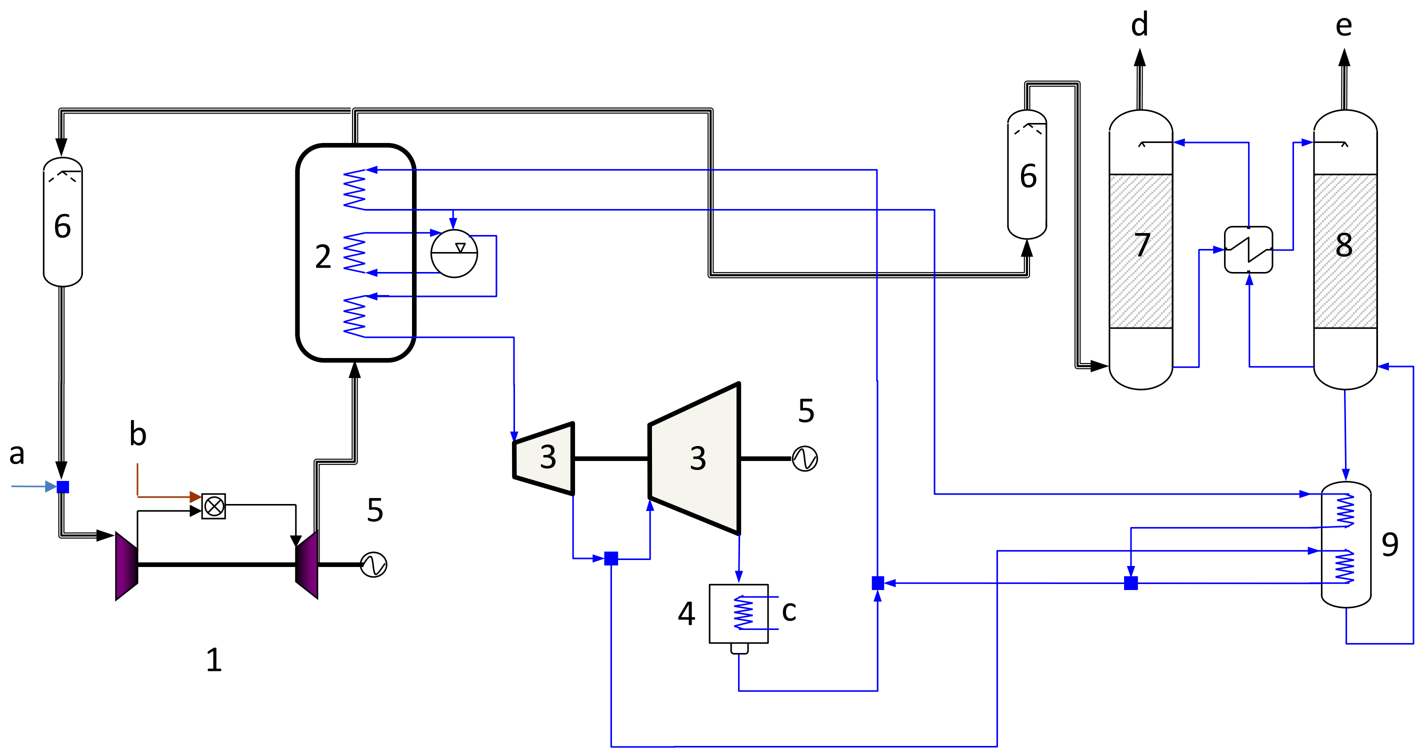

*1. HRSG* — *4. Regenerator* — *b. To fuel preheating*
*2. Flue gas condenser* — *5. Reboiler* — *c. From steam turbine*
*3. Absorber* — *a. Feedwater* — *d. GT exhaust*

**Figure 1: The proposed circuit between the economizer and the reboiler**

The lean solvent used consisted of 11 %wt ammonia, 88 %wt water and 95 ppm $CO_2$. The rich solvent consisted of 11 %wt ammonia, 63 %wt water and 26 %wt $CO_2$. The separation unit includes an absorption column, a low-pressure and a high-pressure regeneration column, and an ammonia stripper. The ammonia stripper prevents ammonia from escaping to the atmosphere. It was assumed that an ambient heat sink could be used to cool the absorption process to 20 °C and that an electric refrigerator with a coefficient of performance (COP) of 4 was used for further cooling to 5 °C. The energy required for electric cooling was calculated to be 21.2 MW.

## INTEGRATION OF $CO_2$ CAPTURE

The transfer of heat from the gas turbine exhaust to the steam cycle is essential for the efficiency of a CCPP. When absorbent-based $CO_2$ capture is integrated with the cycle the heat recovery unit will inevitably be drastically affected. A significant amount of steam is extracted from the steam cycle to cover the heat requirement of the carbon capture plant. This steam is returned at a much higher temperature than the feedwater leaving the main condenser resulting in a reduced heat recovering.




1. Gas Turbine
2. HRSG
3. Steam turbine
4. Condenser
5. Generator
6. Flue gas condenser
7. Absorber
8. Regenerator
9. Reboiler
a. Air
b. Natural gas
c. Water
d. Lean gas
e. $CO_2$

**Figure 2: Schematic simplified picture of the CCPP with $CO_2$ capture utilizing the economizer-reboiler loop**

The design of any CCPP is a compromise between the first and second law of thermodynamics. The first law states that as small amount of energy as possible should leave the system, i.e. the stack temperature should be as low as possible. The condensation temperature of the flue gas limits this temperature. To avoided exhaust gas condensation on the economizer surface, some of the water is circulated to increase the surface temperature on the gas side. The second law states that the amount of entropy generated in the process should be minimized. This means that the irreversibility of the process should be as small as possible. For an HRSG this means that the mean temperature difference on the hot and cold side should be minimized.

The most straightforward method of integrating a $CO_2$ separation unit into a CCPP would be to supply the heat via steam extraction. The condensate returned from the reboiler outlet of the separation plant is mixed with the feedwater before it enters the HRSG. This result in the water entering the HRSG being warmer, and thus less heat can be recovered from the flue gas.

## HOT WATER ABSORBENT REGENERATION

The nature of a CCPP is such that the temperature difference between the hot and cold side of the economizer is larger on the cold end of the HRSG. By applying the equation below to both sides of the economizer, it can be seen that if the mass flow on the cold side is increased the temperature difference will be smaller. By introducing a water loop between the economizer and the reboiler, according to Figure 1, to cover part of the reboiler duty, the water mass flow through the economizer is increased and hence more energy can be recovered.

$$\dot{Q} = \dot{m}\bar{c}_p(T_2 - T_1)$$

The new reboiler consists of two heating coils, one heated by pressurized water and one by condensing steam. The energy supplied by the economizer replaces some of the steam extracted from the turbine, and more power will be produced in the low pressure steam turbine. When more heat is recovered from the flue gas, the requirement of exhaust gas cooling prior to the EGR and the carbon capture plant is reduced.

The control strategy for the economizer–reboiler loop is to control the water mass flow so that the temperature of the water at the economizer outlet is close to the saturated state at all loads. This will provide extra control, preventing evaporation and drying-out of the economizer.

## DESIGNING A CCPP WITH $CO_2$ CAPTURE

When the carbon capture plant is integrated into the CCPP and the economizer-reboiler loop is used, some new aspects should be considered in the plant design. The extra heat extracted from the economizer reduces the temperature difference at the exit of the HRSG. This means that the first law of thermodynamics is fulfilled, more or less independently of the temperature rise in the economizer. Thus, the LP pressure level of the plant can be increased, and the benefit of introducing multiple pressure levels is significantly reduced. The cycle configuration in this work uses the uses the condensate leaving the reboiler for feedwater deaeration, see Figure 1, and fuel preheating (not shown in the figure).

In the first case a single-pressure CCPP is designed with a carbon capture unit utilizing a MEA with an absorbent solution of 30 % MEA and 70 % water regenerated at 122 °C. Figure 2 shows a schematic picture of the plant and the characteristics of the CCPP are given in Table 2.

The compression of $CO_2$ is performed with 8 compressor stages with intercooling to 25 °C. The $CO_2$ leaving the capture unit has a pressure of 1.4 bar, and is compressed to 200 bar. The power consumption for compression is 300 kJ/kg $CO_2$.

**Table 2: Key parameter of the single-pressure cycle**

| | | |
|---|---|---|
| *Admittance pressure* | 100.0 | bar |
| $\eta_{LP}$ *(wet)* | 83.4 | % |
| $\eta_{CC,net}$ *excl. $CO_2$ comp.* | 52.36 | % |
| $\eta_{CC,net}$ *incl. $CO_2$ comp.* | 50.80 | % |
| *Reboiler heat supplied via water* | 17.1 | % |

Figure 3 shows a temperature vs. heat flux diagram for a single-pressure CCPP in which the proposed water-reboiler loop, described in Figure 1, has been integrated. The small temperature difference between the hot and cold side of the economizer results in that more heat can be recovered from the exhaust and very efficient heat recovery. A reduced temperature difference in the economizer means that the thermodynamic driving force is reduced and thus an increased heat transferring area is required. The temperature difference in the economizer used in the cycles in this work is 10 °C. The approach point i.e. the margin to the boiling point at the economizer is maintained at all loads by controlling the flow in the economizer-reboiler loop. The output of the Rankine cycle is limited by a pressure of 100 bar, which was set to keep the moist content at the LP outlet at a reasonable level.

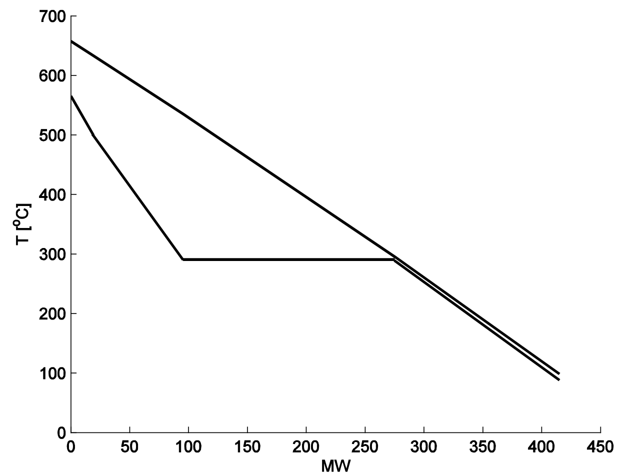



**Figure 3: Temperature vs. heat flux for the single-pressure CCPP with carbon capture and the economizer–reboiler loop. Note the small temperature difference in the economizer**

By introducing a reheat circuit between the HP and LP turbine the moist content at the end of the LP is reduced and the admittance pressure can be increased further. Reheat circuit will increase the mean temperature of the supplied heat, which is beneficial for the Rankine cycle, but at the same time will reduce the cycle mass flow. The reheat heat is extracted before the evaporator and will therefore restrict the energy available for steam production. In a conventional CCPP, a reduction in mass flow would result in less energy being recovered in the economizer, and therefore more energy would be lost in the stack. This is the reason why it is very rare to see single-pressure plants with reheat Rankine cycles. However, this is not a problem with the economizer–reboiler loop as the excess energy is supplied to the reboiler. Thanks to the proposed coupling, the temperature difference in the economizer is not affected when a reheat circuit is introduced. This means that the amount of recovered energy in a single-pressure CCPP is almost independent of if a reheat circuit is used or not.

The optimum pressure for the reheat is 110 bar, but this gives a pressure ratio of 1.45 in the high-pressure turbine, which is very small. This pressure ratio is too small to be considered for a separate turbine cylinder and therefore, the reheat pressure is set to 50 bar. The steam turbine consists of three sections and is configured so that the steam required for the regeneration of the absorbent is extracted from the cross-over pipe between the intermediate and low pressure turbines. The results for the single-pressure CCPP with reheat are presented in Table 3.

**Table 3: Key parameters for the single-pressure cycle with reheat**

| | | |
|---|---|---|
| *Admittance pressure* | 160.0 | bar |
| $\eta_{LP}$ *(wet)* | 84.8 | % |
| $\eta_{CC,net}$ *excl.* $CO_2$ *comp.* | 53.06 | % |
| $\eta_{CC,net}$ *incl.* $CO_2$ *comp.* | 51.50 | % |
| *Reboiler heat supplied via water* | 28.7 | % |

With the new heat exchanger, i.e. the reboiler, another temperature difference must be considered. The cold side in the reboiler is the absorbent/water solution in which some of the water is evaporated at an essentially constant temperature. The implication of this is that the temperature difference will increase when water is used on the hot side instead of condensing steam. For a single-pressure plant the distribution of heat carried by steam and water is determined by the cycle pressure. A dual-pressure plant has an extra degree of freedom in the additional pressure, which can be adjusted to suit the temperature difference in the reboiler.

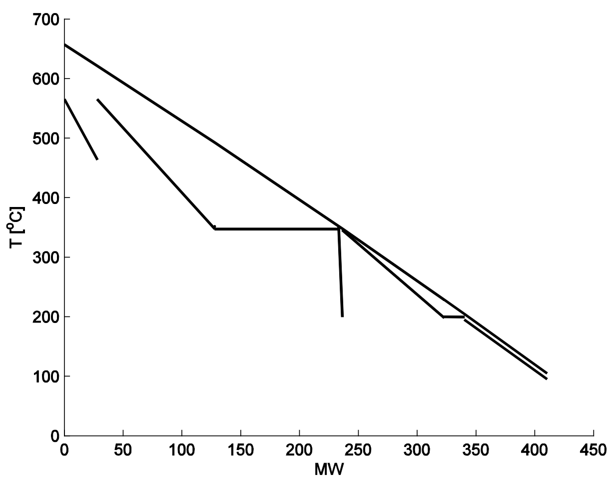



**Figure 4: Temperature vs. heat flux for the dual-pressure reheat CCPP with carbon capture and the economizer–reboiler loop**

The steam turbine already consists of three cylinders due to that the large volume of steam extracted to supply heat to the reboiler must be extracted between two cylinders. A fourth turbine cylinder is not an option for economical reasons, and therefore steam at the second pressure level in inserted at the point of the reheat in the dual-pressure plant. For the GE 109FB gas turbine, a steam cycle with an admittance pressure of 160 bar with reheat and a final superheating temperature of 565 °C, optimal efficiency is obtained with a second pressure level at 50 bar. The cycle parameters are presented in Table 4, and the corresponding temperature vs. heat flux diagram is shown in Figure 4.

**Table 4: Key parameters for the dual-pressure cycle with reheat**

| | | |
|---|---|---|
| *Admittance pressure* | 160.0 | bar |
| $\eta_{LP}$ *(wet)* | 84.7 | % |
| $\eta_{CC,net}$ *excl.* $CO_2$ *comp.* | 53.35 | % |
| $\eta_{CC,net}$ *incl.* $CO_2$ *comp.* | 51.81 | % |
| *Reboiler heat supplied via water* | 43.8 | % |

Although it is unrealistic, a fourth turbine cylinder was introduced to show theoretical maximum efficiency. The fourth cylinder allows the second pressure level to be chosen independently of the reheat pressure. The result show a maximum if the low pressure is set to 21 bar, which is much higher than in a conventional dual-pressure CCPP, which would have a low pressure of 3–8 bar. The efficiency of this rather unrealistic cycle is 51.88 %, including the compression of $CO_2$.

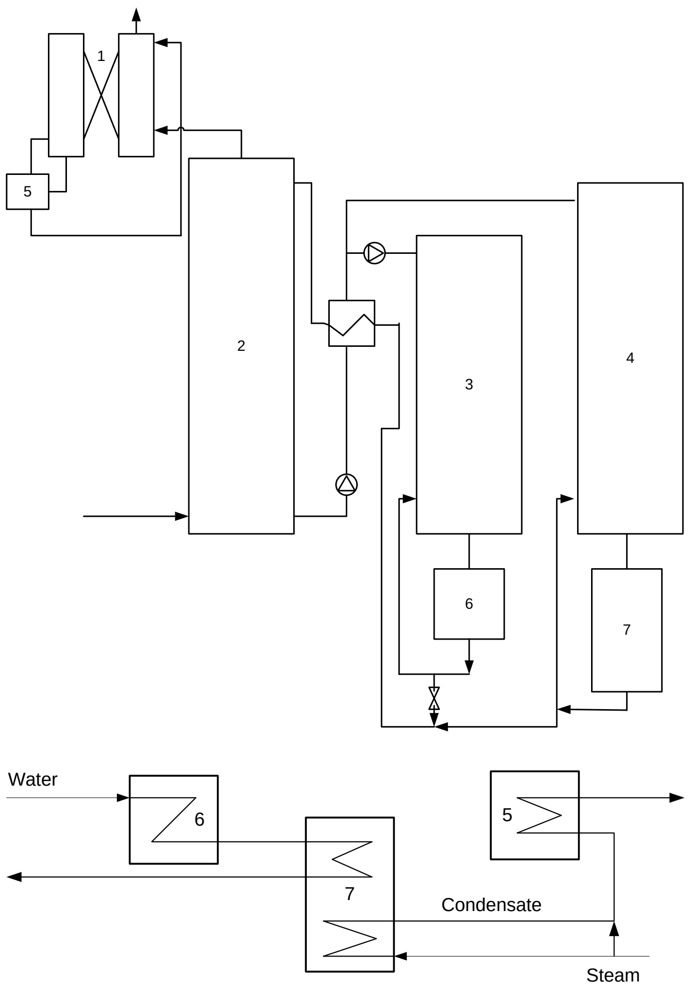
## CHILLED AMMONIA

One limitation of a MEA-based separation unit is its sensitivity to high temperatures, which limits the pressure in the regeneration column. A higher pressure in the regenerator reduces the energy required for $CO_2$ compression as it allows for pumping between the absorber and the regenerator. However, it also requires heat at a higher temperature. The economizer–reboiler loop makes high-temperature heat available, especially if the CCPP is a single-pressure unit.

**Table 5: Key parameters for the single-pressure cycle with reheat using chilled ammonia**

| | | |
|---|---|---|
| *Admittance pressure* | 160.0 | bar |
| $\eta_{LP}$ *(wet)* | 84.8 | % |
| $\eta_{CC,net}$ *excl.* $CO_2$ *comp.* | 52.88 | % |
| $\eta_{CC,net}$ *incl.* $CO_2$ *comp.* | 52.27 | % |
| *Pressure in HP regenerator* | 21 | bar |
| *Pressure in LP regenerator* | 10 | bar |
| *Electric cooling duty* | 21221 | kW |
| *Compression work per kg* $CO_2$*,HP* | 84 | kJ/kg |
| *Compression work per kg* $CO_2$*,LP* | 136 | kJ/kg |
| *Mass flow* $CO_2$*, HP* | 14.8 | kg/s |
| *Mass flow* $CO_2$*, LP* | 24.5 | kg/s |
| *Reboiler heat supplied via water* | 43.8 | % |

With the chilled ammonia process, a higher temperature and a higher pressure can be used in the regeneration column. One drawback of including the economizer–reboiler loop in a single-pressure reheat plant using MEA was the large temperature difference in the reboiler. If a chilled ammonia unit is used instead, the high-temperature water can be utilized in a high-pressure regenerator, and further regeneration can then be performed in a regenerator at a lower pressure with additional steam. The dual-pressure also offers the possibility to flash the solvent between the two columns which reduce the heat requirements as described by Tomasi [24]. The ammonia stripper in which ammonia is recovered from the lean gas (exhaust) is operated at ambient pressure. The energy for ammonia stripping is supplied by the condensate complemented with steam. The configuration of the heat supply to the reboilers is shown in Figure 5. The pressure level for steam extraction is set to suit the temperature in the low pressure regenerator. Therefore, it is preferable to use a low regeneration temperature in the low-pressure column.




*1. Ammonia stripper*
*2. Absorber*
*3. HP regenerator*
*4. LP regenerator*
*5. Reboiler 1*
*6. Reboiler 2*
*7. Reboiler 3*

**Figure 5: The chilled ammonia $CO_2$ separation unit and the reboiler heat configuration**

The dual-pressure chilled ammonia $CO_2$ separation unit was investigated in the same single-pressure reheat plant as for the MEA unit (described in Table 3). The energy required to compress the $CO_2$ from the LP regenerator is 136 kJ/kg $CO_2$, and for the HP column 84 kJ/kg $CO_2$. The temperature in the reboiler is a function of the ammonia/water ratio in the absorbent solution and the amounts of $CO_2$ in the lean and rich absorbent Table 5 gives some of the most important results. For a large-scale plant the height of the columns is a problem, and both the absorber and the regeneration columns are usually divided into two or more units (including two regenerators at different pressures does not necessarily increase the initial plant cost).

## Summary of results

Combined-cycle power plants have been modelled to accommodate absorbent-based $CO_2$ capture using hot water to partly cover the reboiler duty. When the economizer–reboiler loop was included, the mean temperature difference in the economizer was reduced. The result of this is that the HRSG efficiency is no longer dependent on the number of pressure levels. On the other hand, if the $CO_2$ separation unit employs an absorbent that cannot withstand high temperatures, a second pressure level can improve the total efficiency. This is a consequence of the increasing amount of entropy generated in the reboiler with increasing temperature difference. The low pressure of such a plant should be much higher than in a conventional dual-pressure CCPP.

If the absorbent can be regenerated at a higher temperature, a single-pressure CCPP is preferable. By dividing the regeneration column into a high- and a low-pressure section, the steam extracted from the turbine can still be extracted at a low pressure level. A chilled ammonia separation unit offers the possibility of using a high regenerator temperature.

The possibility of better utilizing the potential of the hot water in a chilled ammonia $CO_2$ separation unit appears very promising. To fully evaluate the possibilities and the problems that may be associated with a chilled ammonia unit using a dual-pressure regenerator, more work should be devoted to finding the appropriate composition of the absorbent, i.e. the water/ammonia ratio and lean/rich $CO_2$ loading.

## DISCUSSION

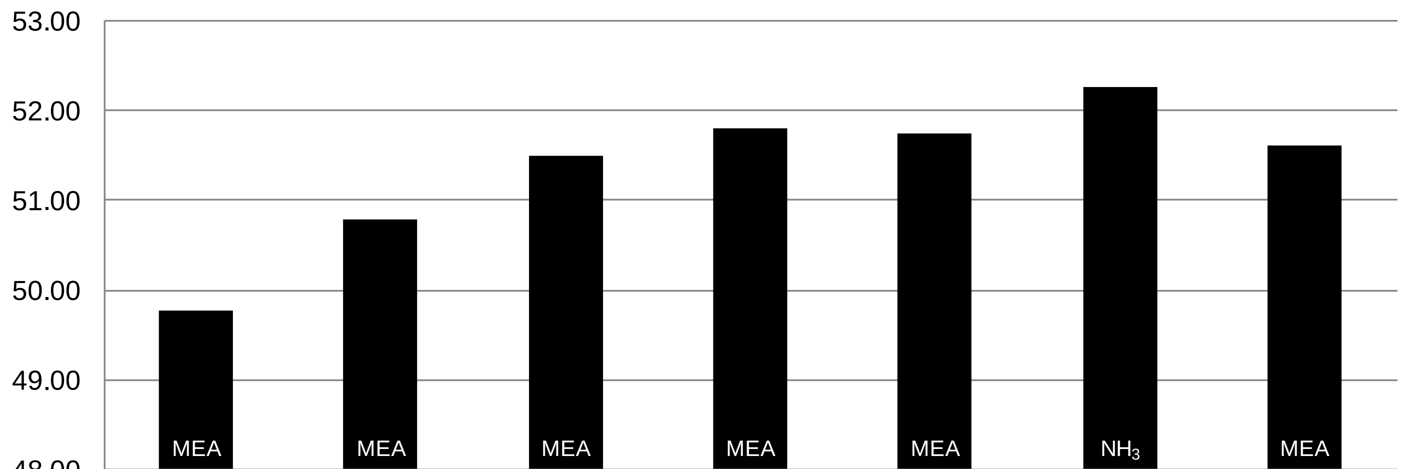
The economizer–reboiler loop provides hot water for the regeneration of the absorbent. The hot water is supplied by the economizer and does not affect the steam production. However, on the other side of the process, i.e. in the reboiler, a liquid heat carrier will not provide heat at a constant temperature. Therefore, it is better for the heat to be supplied at two stages at different temperatures. This will give a process in which less entropy is generated, according to the second law of thermodynamics.

MEA decomposes rapidly when heated above about 120 °C, and lowering the temperature would result in reduced pressure in the regenerator column. This will lead to a large expensive column and increased consumption of power in the compression of $CO_2$. Ammonia is not as sensitive to high temperatures, and a higher temperature can be used in the reboiler, allowing the regeneration column to be divided into a high-pressure and a low-pressure unit. The amount of energy required to regenerate the absorbent in the chilled ammonia

process increases with increasing pressure. This must be weighed against the saving in the energy required for compression as the $CO_2$ is pumped in a liquid state dissolved in the absorbent.
The concept of a dual-pressure regeneration process has, to the best of the author's knowledge, not previously been modelled in the open literature. The configuration investigated here is such that the concentration of ammonia in the solvent is the same in both columns. Therefore, the concentration is a compromise between the concentrations most suitable for the two regeneration pressures/temperatures. The same applies to the $CO_2$ loading. In order to find the optimal $CO_2$ separation plant for the proposed configuration more modelling in ASPEN is required.

The results show that the dual-pressure plant with reheat has the highest efficiency. From Figure 4 it can be seen that the scope for an additional pressure level is very small, but this was investigated for the sake of completeness. To provide a comprehensive overview of the potential of the proposed method, the efficiencies of a single-pressure and a triple-pressure plant with a conventional steam-heated reboiler were calculated. Figure 6 shows the efficiency of a number of CCPPs with carbon capture. All the values include $CO_2$ compression to 200 bar and care was taken to make the comparisons as fair as possible. A conventional triple-pressure CCPP with same losses has an efficiency of 59.44 % (parasitic losses and transformer step-up losses not included).

A single-pressure plant is much cheaper to construct than a multi-pressure plant, and it is also more flexible. With only one steam drum, the plant is quicker to start, and responds more rapidly to load variations. This is an important factor in the power market today. The carbon capture process consists of chemical reactions and has a large heat storage capacity, and is therefore very sluggish to control. The single-pressure plant has the ability to adapt to very rapid load changes when operated without the $CO_2$ separation unit, and is still able to compete with regard to efficiency when the $CO_2$ separation plant is in operation.




| | Single-pressure conventional reboiler | Single-Pressure | Single-Pressure Reheat | Dual-Pressure Reheat | Triple-Pressure Reheat | Chilled Ammonia Single-Pressure with Reheat | Triple-Pressure Reheat conventional reboiler |
|---|---|---|---|---|---|---|---|
| % | 49.79 | 50.80 | 51.50 | 51.81 | 51.76 | 52.27 | 51.62 |

**Figure 6: Efficiencies of different CCPP with $CO_2$ capture. The pile to the most left and to the most right does not use the economizer-reboiler coupling. All plants except the sixth from the left uses MEA as absorbent**

## CONCLUSIONS

This study shows the benefits of using excess energy from the economizer to regenerate the absorbent in a combined cycle with post combustion $CO_2$ capture. It has been shown that by using the economizer-reboiler loop high efficiencies can be achieved without the need of a third pressure level. If a MEA carbon capture unit is used the highest efficiency is achieved with a dual-pressure reheat plant. The single-pressure reheat plant only suffers 0.3 % units to the dual-pressure reheat plant.
The single-pressure reheat plant supplies high temperature water to the reboiler and this can be better utilized by a chilled ammonia separation unit. By designing a chilled ammonia separation unit using a dual pressure regenerator the hot water could be better utilized. The result shows that the chilled ammonia process greatly benefits from the economizer-reboiler

coupling and shows higher cycle efficiencies than for the MEA unit.
A single-pressure plant is cheaper to construct and offers better flexibility in terms of rapid response to changes in load. Since the load control of a $CO_2$ capture plant is slow, the latter is more important when the plant is operated without $CO_2$ capture.

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