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Derivation of power loss factors to evaluate the impact of post-combustion CO_2 capture processes on steam power plant performance

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Abstract

When integrating a post-combustion CO_2 capture process and a CO_2 compressor into a steam power plant, the heat duty for the regeneration of the solvent (and the corresponding steam extraction) shows to be the largest contributor to the overall net efficiency penalty of the power plant. One parameter which varies from plant to plant and which significantly affects the impact of steam extraction from the steam turbine on the power plant efficiency is the pressure in the IP/LP crossover. In this work, the dependency of the energy penalty on the quantity and quality of the heat duty is analysed and quantified for three state-of-the-art hard coal fired power plant configurations with different pressure levels in the IP/LP crossover.

Keywords: post-combustion; CO_2 capture; power plant; integration; compression

1. Introduction

In a post-combustion CO_2 capture process the CO_2 is separated from the flue gas of the power plant. There is a large number of concepts for post-combustion CO_2 capture from coal-fired power plants, but it is agreed that the implementation of an absorption-desorption-process using a chemical solvent is the most developed and most adequate process for deployment in the near- to middle-term [1; 2]. In recent years the number of selected solvents and proposed process configurations for post-combustion CO_2 capture has strongly increased aiming for the lowest energy penalty of the overall steam power plant process. To identify the most promising new solvents and most energy efficient process configurations, an evaluation on a consistent basis is necessary.

Independent of the solvent or the process configuration, the main interface quantities between power plant, CO_2 capture unit (CCU) and CO_2 compressor which are affecting the net power output are:

1. The heat needed for solvent regeneration in the reboiler of the CCU;
2. The electrical duty of pumps and blowers within the CCU and of the CO_2 compressor ;

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3. The auxiliary power of additional cooling water pumps due to the large amounts of cooling water needed in the capture and compression process.

The heat is commonly provided by extracting low-pressure steam from the water-steam-cycle of the power plant. The magnitude of the energy penalty is not only determined by the amount of extracted steam (quantity) but also by the quality of extracted steam (pressure). When optimising process parameters of the CCU such as the solution circulation rate or the desorber pressure, the variation of these parameters can have opposing effects on the required steam quantity and quality. Hence, an overall process optimisation requires the consideration of the impact of process parameters not only on the CCU in an isolated manner but on the overall process in a holistic approach.

To determine the impact of the CCU on the power plant, detailed modelling and analysis of the water-steam-cycle of the power plant is necessary. Such work is done by several research groups [3; 4; 5]. As the development and evaluation of such models is a time consuming and complex task one possibility to evaluate the overall process is to use simplified correlations.

Oyenekan and Rochelle introduced a correlation referred to as “equivalent work” [6]. With this expression, the amount of steam extraction for solvent regeneration is transformed into an equivalent electrical power loss. Additionally, the power duty of the CO_2 compressor is taken into account. In later publications the power duty of pumps within the capture plant are also included as an electrical power loss [7].

Liebenthal et al. introduced a methodology which enables to estimate the power loss due to steam extraction for solvent regeneration in case of a CCU retrofit to an existing plant via a set of correlations derived from detailed power plant models [8]. Additionally, correlations were provided to estimate the energy penalty attributed to the additional cooling and power duties of the CCU and the CO_2 compressor. By using these correlations researchers involved in the development of new solvents and/or process configurations for post-combustion CO_2 capture processes can evaluate their findings with respect to the integrated overall process (“steam power plant” + “CO_2 capture unit” + “CO_2 compressor”) with a high degree of accuracy.

The correlations derived in [8] are based on a specific power plant model with a fixed IP/LP pressure of 3.9 bar. The pressure in the IP/LP crossover significantly affects the steam extraction for a CCU and varies for different power plants. Consequently, the intention of this work is to extend the analysis in [8] by analysing power plant configurations which differ in terms of the IP/LP crossover pressure.

2. Modelling methodology

Today, rigorous models are capable to provide accurate predictions for the heat, cooling and power duty of a CCU. To evaluate the overall process it is not sufficient to represent the steam power plant and CO_2 compressor in a simplified manner. Instead, the intricate interaction of the CCU with the steam power process demands adequate models of similar accuracy for the steam power plant. In this work the commercial software tool EBSILON®*Professional 8.00* is applied.

To allow comparisons to currently planned power plant projects, the power plant model used in this work is based on a state-of-the-art supercritical power plant [8]. The hard-coal fired power plant with high steam parameters (280 bar, 600 °C) has a net power output of 1015.4 $MW_{el,net}$ (1100 $MW_{el,gross}$) and a net efficiency of 45.49 % at its design point (full load without CO_2 capture). The schematic flow diagram of the reference power plant is shown in Figure 1. The flue gas parameters are listed in Table 1. In [8] it was concluded that a CO_2 capture process which is retrofitted to an existing power plant with a design pressure of 3.9 bar in the IP/LP crossover causes the lowest negative impact on the overall process if operated at or close to open valve conditions. If the IP/LP crossover design pressure, i. e. the pressure at full load without steam extraction for CO_2 capture, would be larger for such a power plant, the pressure that attunes with steam extraction is also higher.

Therefore, in this work three power plants with different crossover design pressures (PP1: 3.9 bar; PP2: 5.5 bar, PP3: 7 bar) are analysed. Live steam and reheat parameters as well as condenser pressure and feed water temperature at the boiler inlet for the power plant at full load without CO_2 capture are kept constant. To provide for a fair comparison of power plants with different crossover design pressures, all steam bleed pressures of the water-steam-cycle must therefore be optimised with regard to a maximal net efficiency. Thereby the choice of steam bleed pressure is a trade-off between energetic (maximal amount) and exergetic (maximal temperature increase) utilisation of the enthalpy of the steam. This n-dimensional optimisation problem, where n is the number of steam bleed points to be optimised, was solved by using a nested one-dimensional iterative solution method. As the flue-gas-side remains unmodified, the flue gas parameters (pressure, temperature, flow, composition) remain unchanged for the power plants with different IP/LP crossover pressure.

If the power plant is retrofitted with a CCU certain components of the steam power plant are no longer being operated in their design point. Hence, the off-design behaviour of these components is adjusted by using two-dimensional characteristics (for details refer to [5; 8]).

Steam extraction for solvent regeneration represents the largest contributor to the efficiency penalty. The possibilities to adapt the water-steam-cycle for a retrofit integration of a CCU to optimise the overall process are limited. In this work the steam for the reboiler is considered to be extracted from the IP/LP crossover. The reboiler condensate is forwarded to the feed water tank in the water-steam-cycle of the power plant (cf. Figure 1). Advanced integration configurations (e. g. waste heat integration, cf. [9]) are not considered within this work.

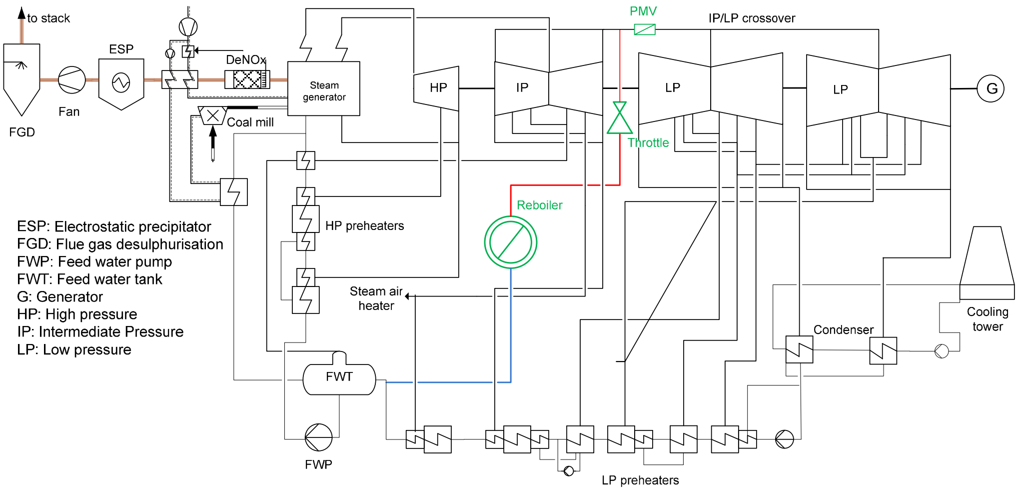

Figure 1: Schematic flow diagram of the reference power plant with integrated reboiler

Table 1: Flue gas parameters downstream of flue gas desulphurisation unit (FGD) for the reference power plant (100 % load)

Temperature (°C)	48.5	N_2	70.70 vol.-%
Pressure (bar)	1.019	O_2	3.29 vol.-%
Volumetric flow (m³/s)	912.64	Ar	0.85 vol.-%
Total mass flow (kg/s)	1021.05	H_2O	11.24 vol.-%
CO_2 mass flow (kg/s)	213.40	CO_2	13.92 vol.-%
		SO_2	<10 ppmv*

*SO_2 concentration with enhanced FGD for CO_2 capture

Due to the expected distance of a retrofitted CO_2 capture unit to the steam turbine of the power plant a pressure loss of 0.4 bar in the branch pipe is assumed. Furthermore, the mean temperature difference in the reboiler between condensing steam and boiling solution is assumed to be 10 K. To avoid hot spots in the reboiler which could lead to thermal degradation of the solvent or increased fouling in the reboiler, the steam for solvent regeneration has to be saturated (e. g. by spray attemperation).

When extracting steam from the IP/LP crossover the pressure level decreases (cf. Figure 6). As a certain steam quality is necessary to regenerate the solvent (depending on the desired reboiler temperature), steam conditioning is required. Taking into account the pressure drop due to steam extraction, it has to be differentiated whether the pressure in the IP/LP crossover is too high or too low for solvent regeneration. To provide the steam at the required pressure a throttle and a pressure maintaining valve (PMV) are necessary (cf. Figure 1).

a) If the resulting pressure in the IP/LP crossover is higher than required for solvent regeneration, the excessive pressure of the extracted steam needs to be throttled to the required level. The throttle is located between the IP/LP crossover and the reboiler.
b) If the pressure is lower than required for solvent regeneration, the pressure maintaining valve needs to be activated in the IP/LP crossover downstream of the extraction point. The pressure in front of the PMV can be held at a certain value while the pressure drops downstream of the PMV.
c) If the pressure in the IP/LP crossover which attunes due to steam extraction matches the pressure as required by the CCU, neither throttle nor PMV are in operation; such conditions are referred to "open valve operation". The latter attunes as a function of the amount (quantity) of extracted steam. A match can be achieved by varying the reboiler temperature in the CCU.

3. Results

The overall loss in net power output of the power plant due to post-combustion CO_2 capture can be expressed as a sum of five terms:

$$\Delta P_{Loss} = \Delta P_{CCU,Steam} + \Delta P_{CCU,el} + \Delta P_{Comp,el} + \Delta P_{CCU,cw} + \Delta P_{Comp,cw} \quad , \qquad (1)$$

where $\Delta P_{CCU,steam}$ is the power decrease due to steam extraction for solvent regeneration, $\Delta P_{CCU,el}$ is the additional auxiliary power of the CO_2 capture unit, $\Delta P_{comp,el}$ is the additional auxiliary power of the CO_2 compressor, $\Delta P_{CCU,cw}$ is the auxiliary power of the cooling water pumps of the CCU and $\Delta P_{Comp,cw}$ is the auxiliary power of the cooling water pumps of the CO_2 compressor.

As the correlations for the CO_2 compressor and the cooling water pumps are not directly affected by different power plant configurations this work focuses on the influence of steam extraction ($\Delta P_{CCU,steam}$) on the efficiency penalty for different power plant configurations. It should be noted that the effect of steam extraction accounts for 50 – 70 % of the overall process efficiency penalty. Therefore it is also mandatory to incorporate the other four terms of Eq. (1) for an optimisation of the overall process. Especially the auxiliary power of the CO_2 compressor which accounts for 20 – 40 % of the overall process efficiency penalty is affected by the desorber pressure of the CCU.

3.1. Power loss due to steam extraction

The impact of steam extraction $\Delta P_{CCU,Steam}$ can be determined by a factor that converts an extracted heat flow $\dot{Q}_{Steam}$ into an equivalent electric power loss:

$$\Delta P_{CCU,Steam} = \dot{Q}_{Steam} \cdot \sigma \text{, where } \sigma = f\left(\dot{Q}_{Steam}, T_{reb}\right) \; . \qquad (2)$$

The factor σ is referred to as "Power Loss Factor". The Power Loss Factor (PLF) is a function of the extracted steam quantity ($\dot{Q}_{Steam}$) and the steam quality by means of the reboiler temperature (T_{reb}).

The required steam quantity $\dot{Q}_{Steam}$ can be determined by:

$$\dot{Q}_{Steam} = \varepsilon \cdot \dot{m}_{CO2} \cdot q_{reb} \qquad (3)$$

where ε is the CO_2 capture rate, $\dot{m}_{CO2}$ is the CO_2 mass flow at the inlet of the absorber (213.4 kg/s) and q_{reb} is the mass specific heat duty of the CO_2 capture unit (e. g. in MJ_{th} / kg CO_2).

The lower the Power Loss Factor, the lower the electrical power loss of the power plant due to steam extraction (Eq. (2)). The behaviour is caused by a combination of effects, where the pressure drop in the throttle or in the PMV has the main impact. For a detailed explanation of the Power Loss Factor for different steam quality and quantity levels refer to [8]. Figure 2 - Figure 4 show the Power Loss Factor depending on the design pressure level in the IP/LP crossover, the reboiler temperature, and the amount of extracted steam. Before the effect of the design pressure level in the IP/LP crossover is explained, an explanation of the qualitative impact of steam extraction at a certain pressure level of the steam power plant is given:

a) Activated PMV: A relatively high reboiler temperature on the solvent side of, for example, 140 °C leads to a required steam pressure of 5.2 bar in the IP/LP crossover (including pressure loss in the branch pipe and temperature approach in the reboiler) for solvent regeneration. If steam is extracted and the pressure in the IP/LP crossover is below the required pressure of 5.2 bar, a pressure maintaining valve (PMV) is necessary to back up the pressure. For PP2 (middle curve in Figure 4), the power loss factor increases for an increasing steam extraction. This effect is caused by a combination of effects, where the pressure drop over the PMV has the main impact. To provide for a constant pressure upstream of the PMV, a decrease in pressure downstream of this component is inevitable (isenthalpic throttling). The PMV therefore increases the pressure of the steam at the IP turbine outlet while the available pressure and exergy level of the steam at the LP turbine inlet decrease. The difference between the increasing PLF (middle curve in Figure 4) and the decreasing PLF (topmost curve in Figure 4) can be attributed to the design pressure in the IP/LP crossover of PP1, which is below the required steam pressure of 5.2 bar. If the design pressure of the IP/LP crossover is below the required pressure, even for a small steam extraction the pressure level of the complete steam in the IP/LP crossover needs to be increased. This pressure increase result in an additional power loss and to a decreasing PLF due to the definition of this factor.

b) **Activated throttle**: A low reboiler temperature of 100 °C on the solvent side leads to a required steam pressure of 1.8 bar (including pressure loss in the branch pipe and temperature approach in the reboiler) for solvent regeneration. For the entire range of steam extraction of PP3 (cf. topmost curve in Figure 2) the pressure in the IP/LP crossover is above the pressure required by the CCU (1.8 bar). The excessive pressure is throttled to the required value. The PLF for a given reboiler temperature decreases slightly as the steam extraction is raised since the required pressure approaches the IP/LP crossover pressure. As the pressure in the IP/LP crossover drops, both the back pressure of the IP turbine and the inlet pressure of the LP turbine decrease. Hence, part of the energy conversion is shifted from the LP turbine to the IP turbine.

c) **Combination of PMV/Throttling:** A combination of a) and b) is shown in Figure 3 for different IP/LP crossover pressure levels (PP1 - PP3) and a reboiler temperature of 120 °C (required steam pressure of 3.1 bar including pressure loss in the branch pipe and temperature approach in the reboiler). For small amounts of extracted steam the pressure in the IP/LP crossover is larger than the required pressure and the excessive pressure has to be throttled (cf. case b)). Extracting more steam would lead to a pressure below 3.1 bar in the IP/LP crossover. Hence, at a certain amount of extracted steam the resulting pressure in the IP/LP crossover matches the pressure required by the CCU and no throttling is needed (open valve operation). For a further decrease of steam extraction, the throttle has to be deactivated and the PMV has to be activated in order to keep the pressure level at 3.1 bar. As long as the throttle is active, the PLF decreases with increasing steam extraction. Further increasing of steam extraction boosts the PLF due to the PMV.

As explained above, the effect of steam extraction on the efficiency of the power plant depends on the amount of extracted steam and on the reboiler temperature. A third important factor is the design steam pressure in the IP/LP crossover. In Figure 5 the IP/LP pressure and the corresponding reboiler temperature is shown when steam is extracted and no steam conditioning is required, thus when an open valve operation is feasible. The diagram is divided into two distinct areas by the lines which represent an operation with open valves for each analysed IP/LP pressure. In this case, neither the throttle nor the PMV are active, i. e. the pressure in the IP/LP crossover drops due to the steam extraction and perfectly matches the steam pressure as required by the CCU. As explained under b) above, throttling would be required, if the pressure lies above the open valve operation line. If the pressure lies below the open valve operation line, the PMV needs to be activated (see case a) above). Taking into account that open valve operation is the most efficient configuration regarding the steam extraction it shows from Figure 5 that the higher the reboiler heat duty in case of retrofit integration, the lower the optimal reboiler temperature to reach open valve operation for which the net efficiency penalty due to steam extraction becomes minimal. It is also notable from Figure 5 that a higher design pressure of the IP/LP crossover leads to a higher resulting pressure level at open valve operation for a given amount of extracted steam.

In Figure 2 the pressure in the IP/LP crossover lays nearly always above the required pressure level of 1.8 bar, which corresponds to a reboiler temperature of 100°C. Only for the IP/LP pressure of 3.9 bar (5.5 bar) at steam extractions above 620 MW_{th} (790 MW_{th}) the PMV needs to be activated resulting in an increase of the PLF. It can be concluded that as long as throttling occurs, the power plant which shows the smallest derivation from open valve operation shows the lowest PLF. In Figure 3 the PMV needs to be activated for PP1 - PP3. The higher the design pressure of the IP/LP crossover, the higher the amount of steam extraction for open valve operation. In Figure 4 the effect of a reboiler temperature of 140 °C on the PLF is shown. As the PMV needs to be activated nearly always for all IP/LP design pressures, PP3 with the highest design pressure in the IP/LP crossover pressure is beneficial.

The results described above result in the following statement:

"As it might be difficult to design a power plant for a given CCU, process configuration, the solvent, and the operating conditions need to be adapted to an existing power plant."

For example: A solvent with a reboiler temperature independent specific heat duty of 3 MJ_{th}/kg CO_2 and a capture rate of 90 % ($\dot{Q}_{Steam}$ ~575 MW_{th}) for the CO_2 capture process of the reference power plant according to Figure 1 is considered. For three different power plants with IP/LP design pressures of 3.9 bar, 5.5 bar and 7 bar, the power loss due to steam extraction is the lowest for reboiler temperature of 100 °C (see PP1 in Figure 2), 120 °C (see PP2 in Figure 3) and 140 °C (see PP3 in Figure 4).

As explained in [8], two equations are necessary to describe the coherences discussed above. The asymptotic curves reveal the operation with a PMV, showing a stringent dependency on the reboiler temperature and can be described by:

$$\sigma' = a' \cdot \frac{(T_{reb} - b')}{\dot{Q}_{Steam}} + c' \quad . \tag{4}$$

The curves representing the operation with a throttle are (nearly) independent from the reboiler temperature and can be described by:

$$\sigma'' = a'' \cdot \dot{Q}_{Steam}^2 + b'' \cdot \dot{Q}_{Steam} + c'' \quad . \tag{5}$$

In order to decide whether Eq. (4) or Eq. (5) has to be used to calculate the Power Loss Factor, a "switch"-function is necessary. Note that the "switch"-function also defines the amount of steam that needs to be extracted for a certain reboiler temperature to achieve an open valve operation.

$$\dot{Q}_{Switch} = a_{Switch} \cdot T_{reb}^2 + b_{Switch} \cdot T_{reb} + c_{Switch} \quad , \tag{6}$$

$$\sigma = \begin{cases} \sigma', & \text{for } \dot{Q}_{Steam} > \dot{Q}_{Switch} \\ \sigma'', & \text{for } \dot{Q}_{Steam} < \dot{Q}_{Sswitch} \end{cases} \quad . \tag{7}$$

Table 2: Coefficients for the power loss calculation

Power Loss Factor					
3.9 bar		5.5 bar		7.0 bar	
a' (MW) =	1.6248	a' (MW) =	1.5937	a' (MW) =	1.6547
b' (°C) =	130.2970	b' (°C) =	141.5615	b' (°C) =	149.8060
c' (-) =	0.2542	c' (-) =	0.2664	c' (-) =	0.2800
a" (1/MW²) =	-5.207E-8	a" (1/MW²) =	-6.79E-8	a" (1/MW²) =	-5.40E-8
b" (1/MW) =	-6.466E-6	b" (1/MW) =	1.25E-5	b" (1/MW) =	-7.00E-6
c" (-) =	0.1955	c" (-) =	0.2200	c" (-) =	0.2400
a_{Switch} (1/°C²) =	-0.2003	a_{Switch} (1/°C²) =	-0.1950	a_{Switch} (1/°C²) =	-0.1787
b_{Switch} (1/°C) =	24.8435	b_{Switch} (1/°C) =	28.9953	b_{Switch} (1/°C) =	28.9469
c_{Switch} (MW) =	138.8601	c_{Switch} (MW) =	-159.1984	c_{Switch} (MW) =	-232.2973
Specific power duty and cooling duty for CO_2 compressor					
a_{el} (MW/bar kg) =	0.3948	a_{cw} (MW/bar) =	0.5736		
b_{el} (-) =	-0.3893	b_{cw} (-) =	-0.2698		
c_{el} (MW/kg) =	0.0301	c_{cw} (MW/kg) =	0.0901		
Specific auxiliary power duty					
φ_{cw} (MJ_{th}/kg CO_2) =	0.3882				

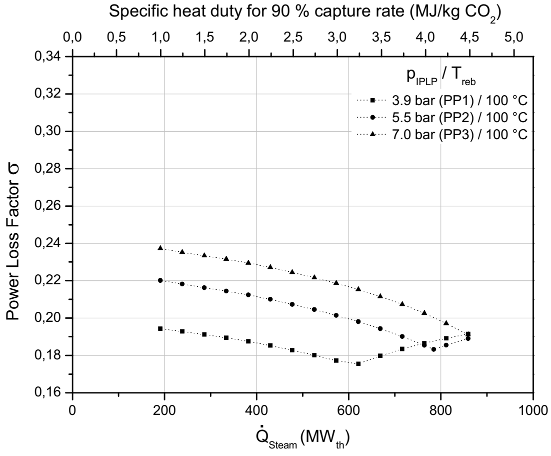

Figure 2: Power Loss Factor for different IP/LP crossover pressures at T_{reb} = 100 °C

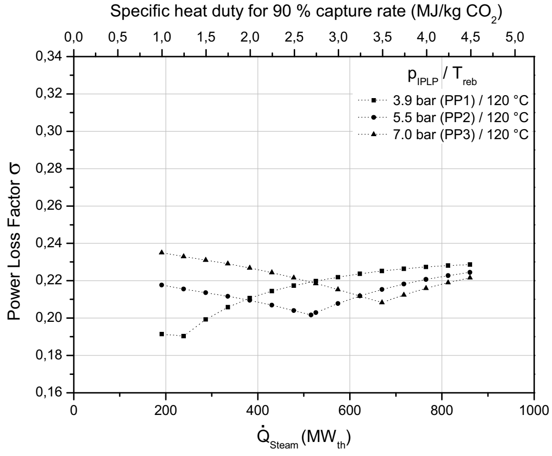

Figure 3: Power Loss Factor for different IP/LP crossover pressures at T_{reb} = 120 °C

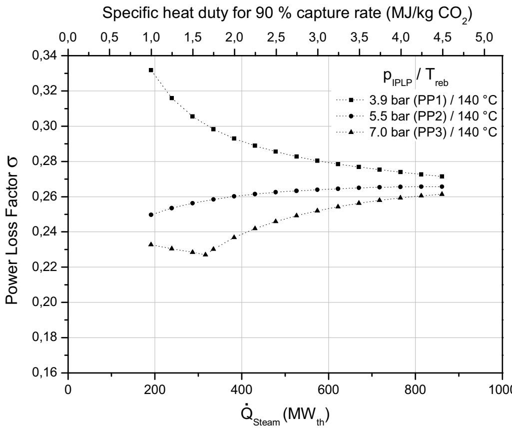

Figure 4: Power Loss Factor for different IP/LP crossover pressures at T_{reb} = 140 °C

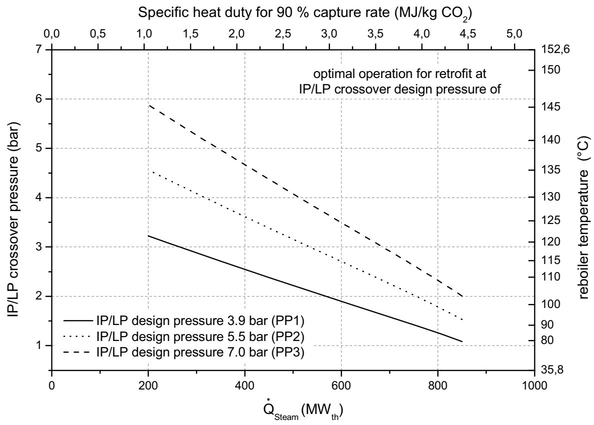

Figure 5: Open valve operation

3.2. Additional power loss terms

As explained above the overall loss in net power output of the power plant due to post-combustion CO_2 capture can be expressed as a sum of five terms (Eq. (1)). As the main focus of this work lies on the evaluation of different pressure levels in the IP/LP crossover only the power loss due to the heat duty is discussed in detail. For the auxiliary power of the CO_2 capture unit, the CO_2 compressor, and the cooling water pumps the required equations are given below. A detailed explanation of these factors is found in [8].

3.2.1. Auxiliary power duty of the CO_2 capture unit ($\Delta P_{CCU,el}$)

The auxiliary power duty of the CO_2 capture unit, mainly attributed to the additional blower and the solvent pumps, can be calculated by:

$$\Delta P_{CCU,el} = \varepsilon \cdot \dot{m}_{CO2} \cdot w_{CCU,el} \quad , \qquad (8)$$

where $w_{CCU,el}$ is the specific power duty of the CO_2 capture unit.

3.2.2. Auxiliary power duty of the CO_2 compressor ($\Delta P_{comp,el}$)

To transport the separated CO_2 to the injection well, a pipeline pressure of 110 bar is assumed. Therefore, a simplified correlation is developed in [8] to evaluate the impact of an integrally-geared (radial) compressor on the overall process. The correlation to determine the corresponding power duty as a function of the inlet pressure is based on an exponential approach:

$$\Delta P_{\mathrm{Comp,el}} = \varepsilon \cdot \dot{m}_{\mathrm{CO2}} \cdot \left(a_{\mathrm{el}} \cdot p_{\mathrm{in}}^{b_{\mathrm{el}}} + c_{\mathrm{el}}\right) \quad , \tag{9}$$

where p_{in} is the inlet pressure. The coefficients and corresponding units are listed in Table 2.

3.2.3. Auxiliary power duty of the cooling water pumps of the CCU and the CO_2 compressor ($\Delta P_{CCU,cw}$ and $\Delta P_{Comp,cw}$)

To provide the cooling duty of the capture plant and the CO_2 compressor additional cooling water pumps are required. The auxiliary power of these pumps results in a reduction of the net power output of the power plant. The following correlation converts a cooling duty into an electric power loss:

$$\Delta P_{\mathrm{CCU(Comp),cw}} = \frac{\dot{Q}_{\mathrm{CCU(Comp),cool}} \cdot \varphi_{\mathrm{cw}}}{c_{\mathrm{p,cw}} \cdot \Delta T_{\mathrm{cw}}} \quad , \tag{10}$$

where $\dot{Q}_{CCU(Comp),cool}$ is the cooling duty of the CCU (compressor), $c_{p,cw}$ is the specific heat capacity of the cooling water, ΔT_{cw} is the temperature gain of the cooling water and φ_{cw} is the specific auxiliary power duty. The cooling duty of the CCU can be calculated by:

$$\dot{Q}_{\mathrm{CCU,cool}} = \varepsilon \cdot \dot{m}_{\mathrm{CO2}} \cdot q_{\mathrm{CCU,cool}} \quad , \tag{11}$$

where $q_{CCU,cool}$ is the specific cooling duty of the CO_2 capture unit.

The correlation for the specific cooling duty is similar to the correlation for the determination of the power duty of the CO_2 compressor (cf. Section 3.2.2):

$$\dot{Q}_{\mathrm{Comp,cool}} = \varepsilon \cdot \dot{m}_{\mathrm{CO2}} \cdot \left(a_{\mathrm{cw}} \cdot p_{\mathrm{in}}^{b_{\mathrm{cw}}} + c_{\mathrm{cw}}\right). \tag{12}$$

The coefficients of Eqs. (10) to (12) are listed in Table 2.

3.3. Accuracy and valid parameter range

Using the detailed power plant model to derive the correlations discussed in Section 3.1, the amount of extracted steam has been varied from 200 to 850 MW_{th} which corresponds to specific heat duties for solvent regeneration between 1.0 and 5.0 MJ/kg CO_2 for a capture rate of 90 %.

All correlations are developed targeting the lowest deviance between the power plant model with steam extraction for solvent regeneration and the correlations in order to reach the highest degree of accuracy. The largest discrepancy between modelling results and correlations in the given parameter range is below 6 %.

It has to be mentioned that depending on the quality and quantity of the extracted steam, the pressure level in the IP/LP crossover and thus at the outlet of the IP turbine might drop below the nominal pressure. In this case, the relative volume flow in the last stage of the IP turbine (actual volume flow/nominal volume flow) increases for the full load operation, examined in this work. For a relative volume flow in the IP turbine larger than approx. 1.4 this might lead to a limitation as damages in the last turbine stages of the IP turbine might occur. Therefore a retrofit of the IP turbine might become necessary to provide for a safe operation with steam extraction for the CCU. This can be done by redesigning the last stages of the IP turbine or by installing additional turbine capacity [10]. The losses associated to an IP turbine retrofit are likely to be within normal design variations. In this work changes in turbine efficiency due to modified steam flow patterns are therefore neglected. To evaluate if the operation of the turbine is still feasible or a retrofit of the IP turbine is necessary detailed turbine analysis is required. For a retrofit of the turbine, additional integration effort and investment costs have to be considered.

3.4. Example Calculation

In Table 3 a step-by-step example calculation is given for the case of a IP/LP crossover pressure of 3.9 bar. This calculation should serve as a guideline for the application of the presented methodology.

Table 3: Example calculation

Input values		Pre-calculation steps		Results for solvent evaluation	
q_{reb} (MJ/kg CO_2) =	3.5	$\dot{Q}_{\mathrm{Steam}}$(MW_{th}) =	672.21	$\Delta P_{\mathrm{CCU,Steam}}$ (MW_{el}) =	154.15
$w_{\mathrm{CCU,el}}$ (MJ/kg CO_2) =	0.1	$\dot{Q}_{\mathrm{Switch}}$ (MW_{th}) =	235.40	$\Delta P_{\mathrm{CCU,el}}$ (MW_{el}) =	19.21
$q_{\mathrm{CCU,cool}}$ (MJ/kg CO_2) =	4.0	$\dot{Q}_{\mathrm{Switch}} < \dot{Q}_{\mathrm{Steam}}$	$\sigma = \sigma'$	$\Delta P_{\mathrm{Comp,el}}$ (MW_{el}) =	62.77
T_{reb} (°C) =	120	σ (-) =	0.23	$\Delta P_{\mathrm{CCU,cw}}$ (MW_{el}) =	7.13
$p_{\mathrm{des}} = p_{\mathrm{in}}$ (bar) =	2.1	$\dot{Q}_{\mathrm{CCU,cool}}$ (MW_{th}) =	768.24	$\Delta P_{\mathrm{Comp,cw}}$ (MW_{el}) =	1.00
ε (-) =	0.9	$\dot{Q}_{\mathrm{Comp,cool}}$ (MW_{th}) =	107.48		
ΔT_{cw} (K) =	10.0			**ΔP_{Loss} (MWel) =**	**244.25**
$c_{\mathrm{p,cw}}$ (MJ/(t K)) =	4.18				
$P_{\mathrm{el,nom}}$ (MWel) * =	1015.44			**η_{net} (%) =**	**34.55**
$\dot{Q}_{\mathrm{in}}$(MWth) * =	2232.06			**$\Delta\eta_{\mathrm{net}}$ (%-pts.) =**	**10.94**
$\dot{m}_{\mathrm{CO2}}$ (kg/s) * =	213.40				

* from reference power plant (fixed values)

4. Conclusions

In this work, the overall loss in net power output due to the retrofit of a post-combustion CO2 capture process was analysed and quantified for three state-of-the-art hard-coal-fired power plants with different pressure levels in the IP/LP crossover (PP1 – PP3). The simulations are carried out using the simulation tool EBSILON®Professional 8.00. The overall loss in net power output can be expressed as a sum of five terms (Eq. (1)); in this work, empirical correlations were given to determine each of the five terms and the resulting overall power loss of one of the three power plants.

The impact of steam extraction was determined by the Power Loss Factor σ that converts an extracted heat flow for solvent regeneration into the equivalent electric power loss. To provide the steam at the required pressure (heat quality), a throttle and a pressure maintaining valve are necessary. For the three evaluated power plants in this work it was shown that the optimal design pressure in the IP/LP crossover depends on the amount of extracted steam and the reboiler temperature. In general, for a high reboiler temperature of the capture process, a power plant with a high design pressure in the IP/LP crossover is beneficial in terms of power loss.

Furthermore, correlations for the specific power duty of the CO_2 compressor, the additional auxiliary power of the CO_2 capture unit, and the auxiliary power of the cooling water pumps of the CCU and the CO_2 compressor were provided to allow a complete evaluation of new solvents and/or process configurations for post-combustion CO_2 capture processes in a holistic approach.

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