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Part Load Behaviour of Power Plants with a Retrofitted Post-Combustion CO_2 Capture Process

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Abstract

The flexible and part load operation of fossil-fuelled power plants will increase due to the higher share of fluctuating renewable energies, like wind and solar power. In this work the part load behaviour of the post-combustion CO_2 capture (PCC) process is evaluated. The net efficiency of the conventional hard-coal-fired power plant decreases from 45.6% at full load to 41.5% at 40% load. The net efficiency with PCC using 7 m MEA (monoethanolamine) as solvent decreases to 34.8% at full load and to 30.1% at 40% load. The pressure of the intermediate pressure/low pressure crossover section has major influence on the efficiency. In part load higher pressures are in advantage due to lower throttling losses. The shutdown of the PCC is a possibility to generate balancing power. A reduced capture rate of 75% leads to a generation of 5% additional power.

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Post-combustion Capture; Part Load Behaviour; IP/LP Crossover Pressure; Balancing Power

1. Introduction

As commonly agreed climate change is a serious ecologic and economic challenge in the next decades. To limit the global temperature rise to 2°C a reduction of greenhouse gas (GHG) emissions by 80% until 2050, compared to 1990, is recommend by the IPCC (Intergovernmental Panel on Climate Change) [1]. GHG emissions from fossil-fuelled power plants can be reduced by increasing the energy conversion efficiency or by separating and withholding carbon dioxide (CO_2), commonly referred to as CO_2 capture and storage (CCS).

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Although the contribution of renewable energies is growing significantly worldwide, fossil fuels such as coal will remain central to the world's energy supply for the next decades. The increased share of fluctuating energy sources like wind and solar power will lead to larger amplitudes of load changes of conventional power plants and therefore increase the need for flexible operation of these plants. Energy storage systems in this dimension are not yet commercially available. The installed coal-fired power plants will thus have to operate more frequently in part load than in the past. The coal-fired power plants still operating will have to provide larger amounts of balancing power, to ensure grid stability, so that their frequency of load changes will increase [2].

Post-combustion CO_2 capture (PCC) is a promising possibility to reduce CO_2 emissions of coal-fired power plants. Also these plants must be able to operate under this flexible operation regime in the future and, therefore, for the solvent selection not only the design net efficiencies are of interest but also the part load behaviour has to be taken into consideration. To generate additional balancing power, compared to the coal-fired power plant without PCC, the steam to the reboiler for regeneration of the solvent can be reduced and used in the steam turbine to generate additional power for a certain time interval.

2. Process Description

2.1. Conventional Hard-Coal-Fired Steam Power Plant Process

Conventional state-of-the-art hard-coal-fired power plants burn pulverised coal with preheated air. In the boiler the heat of the combustion process is transferred to the water steam cycle. The raw flue gas contains nitrogen, CO_2, oxygen and water, as well as certain amounts of nitrogen oxides, fly ash (dust) and sulphur oxides. Therefore the flue gas treatment comprises a denitrification system, an electrostatic precipitator and a wet flue gas desulphurisation (FGD) unit.

Up to date power plants have supercritical live steam parameters and reheated steam. The feed water is pre-heated in up to ten feed water pre-heaters with steam tappings from the steam turbine. The maximum overall net electric efficiency of such a hard-coal-fired power plant is today approx. 46.5%. The reference power plant modelled in this paper reaches a net efficiency of 45.6%.

2.2. Post-Combustion CO_2 Capture Process

In the PCC process CO_2 is absorbed by a chemical solvent in aqueous solution from the flue gas of the conventional power plant. The CO_2 content of typical hard-coal-fired power plants lies in the range of 10-15vol% (wet). The reduction of the CO_2 emissions is accompanied by a significant loss in electrical power output and a related net efficiency penalty. In this study 7 m (30wt%) monoethanolamine (MEA) is used as the solvent. The retrofitted PCC with MEA as solvent causes a net efficiency penalty of 10.8%-pts., compared to the conventional power plant at full load. The PCC is already technically mature and applied routinely to gas purification applications, however, under substantially different boundary conditions. Furthermore, the retrofit of existing power plants with PCC is possible due to a low level of integration and downstream application.

Figure 1 shows the schematic of the PCC process and the coupling into the water steam process. The flue gas of the boiler passes through the flue gas treatment, where it is cleaned and cooled, and then enters the absorber column at the bottom, in which the CO_2 is absorbed by a counter-current solution flow. The treated gas is released to the atmosphere, while the rich (CO_2-loaded) solution is gathered at the bottom and pumped to the desorber, passing the rich/lean heat exchanger (RLHX) where it is heated up and enters the desorber column at the top with a temperature close to the desorber temperature level. In the desorber the absorbed CO_2 is stripped from the rich solution and the solvent is regenerated. The required heat duty is provided by a reboiler in which steam from the power plant is condensed and vapour (stripping steam) is generated. The counter-current vapour flow, consisting mainly of steam and CO_2, provides the necessary partial pressure difference as well as the heat for desorption and to heat the solution up. At the head of the desorber the gas is led to the overhead condenser where the CO_2-rich gas is cooled and the water is condensed. The nearly pure CO_2 stream is compressed for transportation. The lean solution is gathered at the reboiler and pumped to the top of the absorber, closing the process cycle, passing the

RLHX where it is cooled and preheats the rich solution. A detailed explanation of the process can be found in [3]. An overview of this process is given in [4].

The goal of the PCC is to capture a certain amount of CO_2, e.g., 90% of the CO_2 emitted by the power plant. The CO_2 capture rate depends on the circulated solution flow rate and the working capacity (difference of lean and rich loading) of the solution. The solution flow rate, and therefore the mass ratio of solution and gas flow (L/G), can be controlled by the pumps in the process. Particularly the heat provided in the reboiler influences the loading of the lean solution, while the rich loading is a result of the entire process. For this reason the working capacity of the solution is adjusted by the heat transferred.

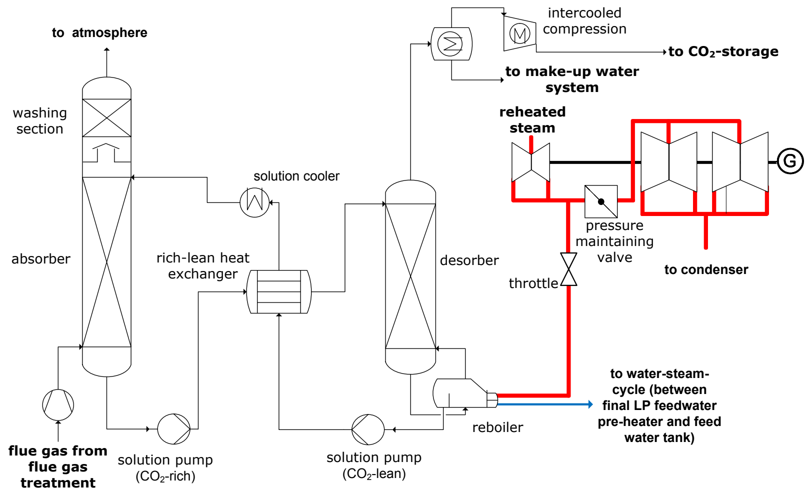

Figure 1. Schematic of the PCC process and the coupling into the water steam process.

The low pressure steam from the power plant is extracted from the intermediate pressure/low pressure (IP/LP) crossover section of the steam turbine [5]. The power output of the power plant is reduced due to the reduced steam flow, the auxiliary power demand of the PCC, blowers and pumps, as well as the CO_2 compressor and the increased cooling water demand, which also results in a higher demand of auxiliary power for the cooling water pumps.

3. Modelling

The overall process comprises the power plant, the PCC process and the CO_2 compression. For each sub-process the most suitable simulation tools for the steady-state simulations are chosen, Ebsilon®Professional for the overall power plant and the CO_2 compression and Aspen Plus® for the CO_2 capture process. Between the simulation tools interface quantities are defined and used to analyse the overall process.

The part load of the power plant is defined as the thermal input at part load divided by the nominal thermal input at full load. Operation below the once-through minimum load (approx. 40%) of the boiler is not considered. All boundary conditions agree well with data obtained from manufacturers, operators and utilities, thus ensuring realistic results.

The specifications for CCS at each load level are a capture rate of 90%, a CO_2 purity of at least 96% and the compression of the CO_2 to 110 bar.

In the field of modelling the part load behaviour are already some publications. Ziaii in [6] modelled the capture process in transient and part load operation and Lucquiaud in [7] analyses the overall process. In this work all three subprocesses are modelled in detail. With these models the part load behaviour is investigated, thereby for example effects like changing temperature differences in the heat exchangers at part load are considered.

3.1. Conventional Hard-Coal-Fired Steam Power Plant

The model is based on data of the concept study “Reference Power Plant North Rhine-Westphalia” [8]. The design of the reference power plant is close to actual newly built power plants in Germany. The gross electric power output is 600 MW with live steam parameters of 600 °C and 285 bar, with reheat steam parameters of 620 °C and 60 bar and a condenser pressure of 40 mbar. Eight feed water pre-heaters, five LP and three HP feed water preheaters, are implemented and induce a feed water temperature of 303.4 °C. The pressure of the steam tappings is optimised for the design point at full load. The pressure in the IP/LP crossover is 5.5 bar at full load.

The once-through steam generator is operated with sliding pressure. The air ratio λ is 1.15 at full load and increases to 1.4 at 40% load. The flue gas temperature downstream the economiser decreases from 380 °C at full load to 320 °C at 40 % load. A part of the high pressure (HP) feed water is led via a steam pre-heater bypass and is heated by heat displacement from the air downstream of the regenerative air pre-heater. The mill outlet temperature is 100 °C and is controlled by adding cold air to the mentioned pre-heated stream, due to the heat displacement the added cold air is minimised at full load. The flue gas temperature behind the air pre-heater is maintained at 115 °C with a steam/air pre-heater that pre-heats the fresh air.

In part load the isentropic efficiencies of the steam turbine sections with dry steam are calculated using characteristic lines in accordance with the corresponding mass flows. In the last stages of the LP turbine the influence of wet steam (Baumann Correlation) and exit losses are taken into consideration. The other turbomachinery (i.e., fans and pumps) is modelled using realistic characteristic diagrams.

Part load behaviour of all heat exchangers is implemented by a realistic characteristic line for the heat transfer. The model of the regenerative heat exchangers considers also a leakage which depends on the load. Pressure loss in part load is calculated using its dependence on mass flow and specific volume.

The composition of the hard coal is 66.1% carbon, 3.83% hydrogen, 6.6% oxygen, 1.6% nitrogen, 0.57% sulphur, 13.5% ash and 7.8% water. The lower calorific value is 25.1 kJ/kg. The temperatures of the environment and coal are 15 °C. The cooling water temperature at the entrance of the condenser is 16 °C. The auxiliary power of the flue gas cleaning equipment is considered using specific power demands. [9]

3.2. Post-Combustion CO_2 Capture

The overall process comprises three sub-processes: power plant, PCC and the CO_2 compression. The design of the power plant island is kept the same as in the conventional plant. The PCC is retrofitted to the power plant, therefore the existing steam power process, especially the steam turbine, is modified as little as possible.

The PCC is modelled with Aspen Plus® and the heat exchangers are designed and modelled with Aspen Exchanger Design & Rating (EDR). The columns are modelled with detailed mass transport (rate-based) and chemical reactions. The columns, heat exchangers, pumps and fans are designed for the lowest overall net efficiency penalty at full load. The PCC consists of two trains each with an absorber of 13.6 m in diameter and with a desorber of 7.9 m in diameter. The packing height in the absorbers is 15 m and in the desorbers 10 m. The RLHXs are designed as plate heat exchanger for a logarithmic temperature difference of 10 K at full load. As reboilers Kettle-type are used and designed for a temperature difference of 10 K between the temperature of condensate and the solution steam. Temperature differences of 10 K are chosen because imitating space for the heat exchangers when retrofitting the PCC into the existing power plant. Lower temperature differences will increase the efficiency of the PCC and the overall process.

As solvent 7 m MEA is used. The L/G is optimised for each part load to reach the minimum net efficiency penalty, taking into account the interface quantities: specific reboiler duty, reboiler temperature, cooling duty and auxiliary power. The constant pressure at the top of the desorber is 2 bar. A reduced pressure of the desorber in part load is not beneficial for the power plant in this work because of the relative high design IP/LP crossover pressure. The advantage of a lower reboiler temperature is overcompensated by the higher specific reboiler heat duty and the higher demand for the CO_2 compression.

The steam for the reboiler is extracted from the IP/LP crossover section. Retrofitting the steam extraction will decrease the pressure in the IP/LP crossover section due to the reduced mass flow. A pressure maintaining valve upstream of the LP turbine has to fulfil two functions: guarantee sufficient steam pressure for the reboiler and therefore sufficient condensing temperature, and prevent the volume flowing out of the last IP stage to exceed a certain level. A throttle upstream of the reboiler reduces the steam pressure if necessary. Figure 1 shows the linked PCC with the IP/LP crossover.

The CO_2 compression is modelled as four parallel trains with integrally geared compressors with six stages and five intercoolers. In part load a bypass operation is used to extend the working range. The choice of four compressor trains will lead to a flexible operation in part load and minimise the bypass operation. Compressor trains are shut down to minimise the power demand for compression as much as possible. [10]

4. Results

4.1. Conventional Hard-Coal-Fired Steam Power Plant

In part load the efficiency of the power plant decreases from 45.6% at full load to 41.5% at 40% load, shown in Figure 2, because of lower steam parameters, higher specific flue gas losses and higher specific demand of auxiliary power. The auxiliary power is shown in Figure 2 as percentage of the gross electric output and is minimal in the region from 70% to 80% load. The auxiliary power is mainly determined by the pumps and fans. Below 50% load one feed water pump of the two trains is shut down so that the specific energy demand decreases for the remaining pump. The pressure loss in the system is reduced, but the efficiency of the turbomachines is reduced, too. These opposing effects lead to a minimum being reached between 70 and 80% load.

At full load the CO_2 content of the flue gas, shown in Figure 3, is 13.6vol% (wet) and reduces in part load due to higher air ratio and higher leakages in the air pre-heater to 10.3vol%. The flue gas mass flow is 564.7 kg/s at full load and reduces to 52.9% at 40 % load.

The IP/LP crossover pressure is 5.5 bar and reduces linearly to 2 bar at 40% load, due to Stodola's law.

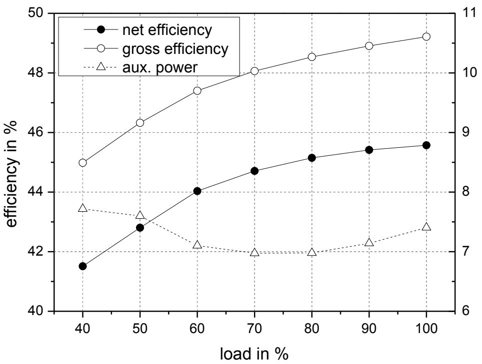

Figure 2. Efficiencies and auxiliary power of the conventional hard coal-fuelled power plant in dependence on the load.

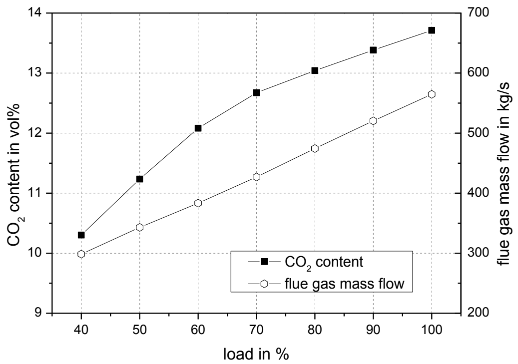

Figure 3. CO_2 content in flue gas and flue gas mass flow in the conventional power plant in dependence on the load.

4.2. Post-Combustion CO_2 Capture

The net and gross efficiency of the power plant with PCC and the overall net efficiency penalty, the difference between the efficiencies of the power plant without and with PCC, are shown in Figure 4. The net efficiency of the process with PCC is 34.8% at full load and decreases to 30.1% at 40% load. The gross efficiency decreases from 41.7% to 37% in the same range of loads. At full load the efficiency penalty is 10.7%-pts. and increases to 11.4%-pts. when reducing the load to 40%. The increase of the efficiency penalty with decreasing load is due to the higher throttling losses in the pressure maintaining valve to guarantee the pressure level necessary for heat transfer in the reboiler. Below 75% load one compressor is shut down, so the specific power demand for compression decreases and leads to lower efficiency penalties.

In Figure 5 the specific CO_2 emissions are shown. When capturing CO_2 the specific CO_2 emissions are 98.4 g/kWh at full load and 113.6 g/kWh at 40% load. The specific CO_2 emissions for the hard-coal-fired power plant are 752.2 g/kWh at full load and increase up to 823.5 g/kWh at 40% load. The rising specific CO_2 emissions are caused by the lower net efficiencies.

In Figure 6 the specific reboiler heat duty for the regeneration of the solvent is shown. The optimised, in context of the overall process, reboiler heat duty is 3.46 MJ/(kg CO_2) at full load. A higher L/G will increase the heat duty to heat the solution to desorber temperature (latent heat). On the contrary, a lower L/G will require a lower lean loading which requires more stripping stream to provide a lower CO_2 partial pressure. This water vapour is condensed in the overhead condenser. In part load the specific reboiler heat duty is reduced because of the decreasing logarithmic temperature difference in the RLHX and a higher rich loading. The rich loading is higher at part load because of an overdesign of the absorber for that load, which induces a better mass transfer and closer approach to equilibrium, although the CO_2 content in the flue gas decreases. The logarithmic temperature difference decreases because of the overdesigned heat exchanger area at part load. The L/G with the minimal heat duty shifts to lower L/G because of the decreasing CO_2 content in the flue gas.

It is notable from Figure 7 that the minimal net efficiency penalty increases under part load. The L/G ratios of the net efficiency minima match the specific reboiler heat duty minima in Figure 6. With reduced load the optimised L/G shifts to slightly lower L/G. This effect occurs below 60% load and is caused by the decreasing reboiler temperature with an increased solution mass flow, which reduces the steam pressure for regeneration.

Figure 8 shows the specific reboiler heat duty for the regeneration of the solvent, the cooling duty and the specific auxiliary power of the PCC for the conditions with minimal overall net efficiency penalty (optimised L/G). The specific reboiler heat duty and cooling duty are reduced at part load because of the effects already explained. The specific auxiliary power is affected mainly by the turbo machines. The opposing effect of a lower pressure loss and a lower efficiency of the turbo machines leads to a minimum between 50 and 60% load.

The breakdown of the net efficiency penalty because of the PCC is shown in Figure 9. The main loss is due to the extraction of steam out of the water steam cycle and is about 70% of the overall loss. At low loads this loss increases because of the higher pressure drop in the pressure maintaining valve and other influences on the water steam cycle. The second largest loss is the electric demand of the CO_2 compression with about 25% of the total loss. The auxiliary power for the fans and pumps in the PCC process decreases with lowering load, in which the fan is the main consumer. The auxiliary power for the additional cooling system, here the cooling water pump (CWP), is roughly half of the power for the PCC. The auxiliary power for the water steam cycle of the power plant is reduced compared to the conventional power plant because of lower mass flows in the cycle between condenser and feed water tank and therefore the pumps, especially the condensate pump consumes less power.

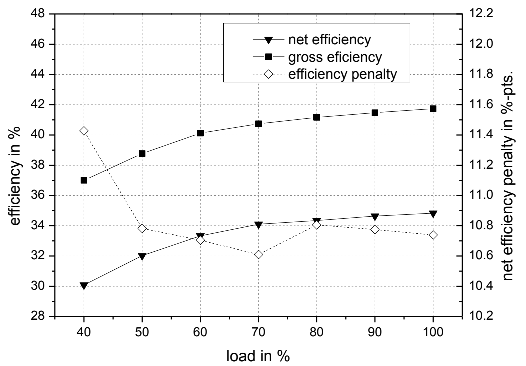

Figure 4. Net and gross efficiency of the power plant with PCC and net overall efficiency penalty in dependence on the load.

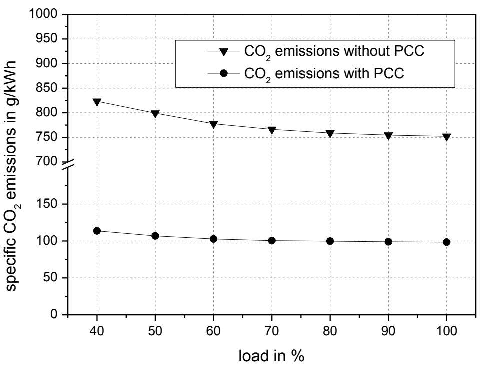

Figure 5. Specific CO_2 emissions of the power plant with and without PCC.

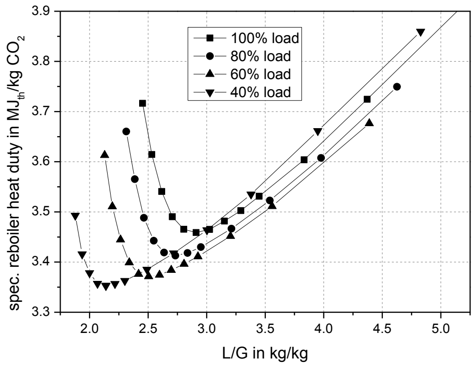

Figure 6. Specific reboiler heat duties for varying L/G and different loads.

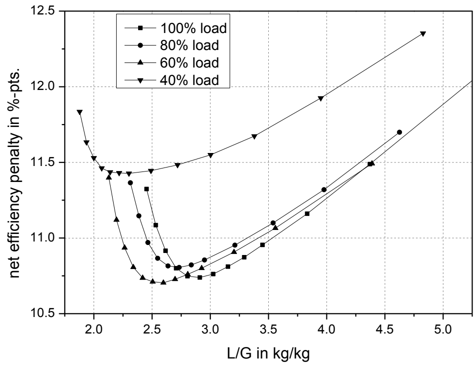

Figure 7. Overall net efficiency penalty for varying L/G and different loads.

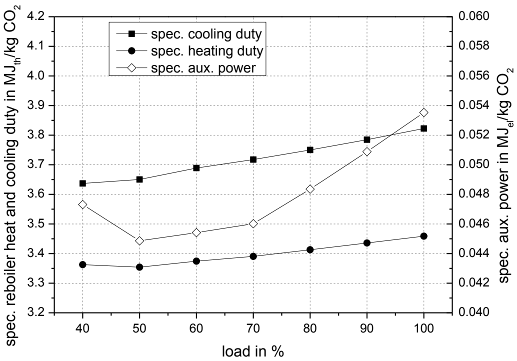

Figure 8. Specific reboiler heat and cooling duty and auxiliary power of the PCC in dependence on the load.

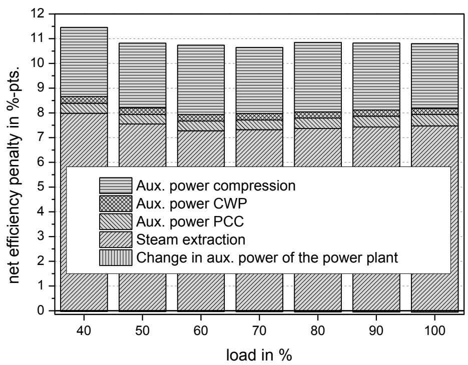

Figure 9. Breakdown of the losses caused by the PCC.

Reducing the pressure of the desorber leads to lower temperatures in the reboiler but higher reboiler heat duties. This reduces the pressure of the extracted steam but increases the power demand of the CO_2 compression and the specific heat duty. In part load this can be a path of optimisation because of high throttling losses to guarantee the pressure level. In the power plant considered, a reduced desorber pressure does not result in a higher efficiency because of the raised power demand of the CO_2 compression. Anyway, especially for IP/LP crossover pressures below 5.5 bar, it could be beneficial. The minimal desorber pressure is limited by the working range of the compressor, the number of compression trains and the mass flow in the compressor.

4.3. Influence of the IP/LP crossover pressure

A major aspect when retrofitting a PCC into an existing power plant design is the IP/LP crossover pressure. This pressure has a significant effect on the efficiency penalty. In Figure 10 the overall net efficiency penalty in dependence on the pressure is shown for full load and 60% load. For 100% load the minimal efficiency penalty of 10.1%-pts. is at 4 bar. Higher pressures increase the throttle losses, steam throttling to the reboiler and pressure maintaining to reduce volume flow through the IP steam turbine. Lower pressures lead to losses due to pressure maintaining. This context is for a reboiler temperature of about 120 °C. Higher temperatures result in a higher optimal pressure. The minimal net efficiency penalty for 60% load is at 5.5 bar. The pressure in the IP/LP crossover already decreases in part load for the conventional power plant. Therefore a higher design pressure is beneficial in part load because of less throttling necessary for pressure maintaining.

The overall net efficiency penalty for the design IP/LP crossover pressure of 3, 5.5 and 9 bar is shown in Figure 11. Lower IP/LP crossover pressures yield higher losses in part load due to pressure maintaining but have advantage in the full load operation. Higher pressures show the opposite behaviour, advantage in part load and higher penalties at full load. When optimising the optimal solvent and design the operation in part load and the part load efficiencies have to be taken into consideration.

A retrofit of the IP turbine can reduce the loss due to the limited volume flow in the turbine. This measure reduces the pressure maintaining, which occurs to downsize the volume flow in the IP turbine. The advantage of a retrofit of the IP turbine to reduce the losses in the reference case is not significant. At full load the advantage is about 0.05%-pts. and below 90% load it is negligible. At higher pressures this measure could be more beneficial.

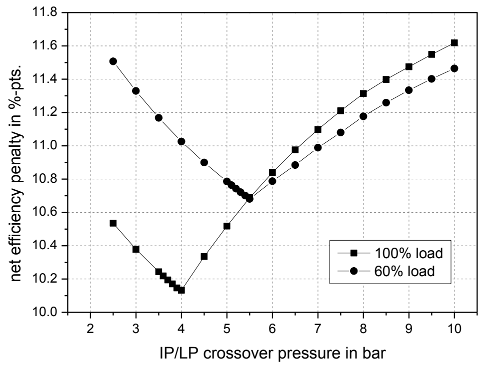

Figure 10. Overall net efficiency penalty in dependence on the IP/LP crossover pressure for 100% and 60% load.

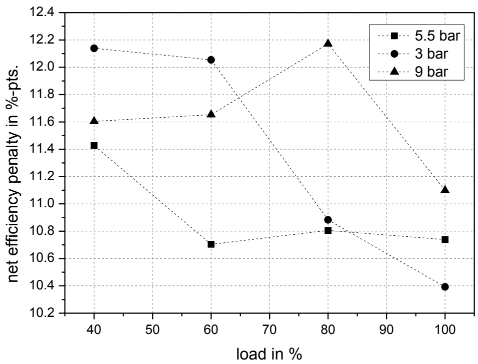

Figure 11. Minimal overall net efficiency penalty in dependence on the load for varying IP/LP crossover pressures.

4.4. Influence of the number of compressor trains

The influence of the number of compressor trains on the specific electric power demand is shown in Figure 12. Using only two compressor trains results in high losses between 50 and 70% load, due to the bypass operation of the two compressors regarding the working range of the compressor. The net efficiency penalty shown in Figure 13 for four compressor trains is less than that for two. Especially in the medium load range the reference configuration with four compressor trains is more advantagous, the maximal efficiency difference is 0.7%-pts. at 60% load.

4.5. Generation of balancing power

An additional generation of power is possible with the PCC. The steam extraction can be shut down, the regeneration of the solvent is stopped and the steam can be used in the LP steam turbine instead. This generates additional power output. In this study the possibilities and influences in steady state operation by varying the capture rate are shown. In Figure 14 the specific reboiler heat duty and the additional power output in dependence on the capture rate at full load are shown. The reference capture rate is 90%; reducing the capture rate leads to lower reboiler heat duties. Higher capture rates increase the reboiler heat significantly. The additional power in the diagram is calculated using also reduced auxiliary demand. To generate additional 5% of the actual power output the capture rate has to be reduced to approximately 75%, 20% additional power leads to a capture rate of 30%.

Figure 15 shows the reduced capture rate in dependence on the load for the generation of a certain amount of additional power. The reduced capture rate to generate additional power is nearly constant over the load. It can be seen in the additional energy, that for higher efficiency penalties at part load the resulting capture rate is little higher than at full load.

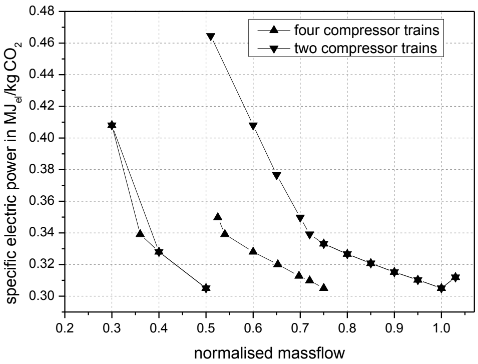

Figure 12. Specific electric power demand of the CO_2 compression in dependence on the normalised mass flow.

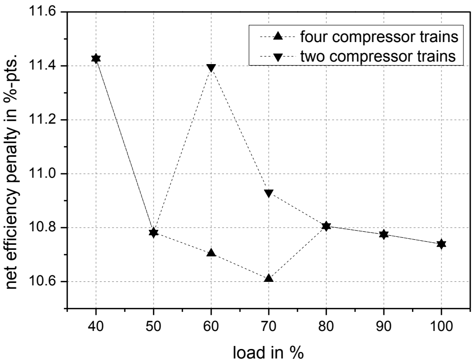

Figure 13. Overall net efficiency penalty in dependence on the load for two and four compressor trains.

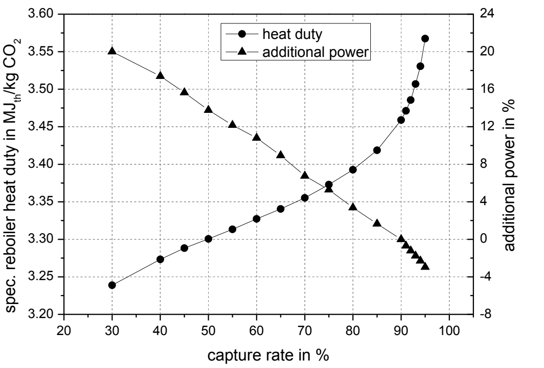

Figure 14. Specific reboiler heat and additional power of the PCC in dependence on capture rate.

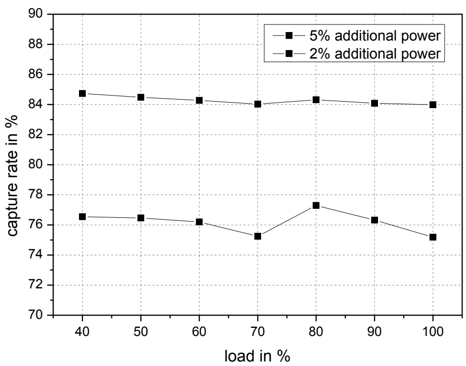

Figure 15. Capture rate in dependence on the load for varying additional power.

5. Summary and Outlook

The steady state part load behaviour of post-combustion CO_2 capture with MEA has been evaluated under realistic boundary conditions. The net efficiency penalty with PCC capture increases from 10.7% at full load to 11.4% at 40% load. The main losses are due to the steam extraction and the CO_2 compression. These dominate the efficiency penalty at part load. For the solvent selection for an existing power plant not only the full load efficiency is relevant, but the whole load region must be optimised.

When retrofitting, the IP/LP crossover pressure is a very important parameter for optimising the process. In part load the optimal pressure increases. The number of compressor trains has been evaluated. The bypass operation has to be avoided by shutting down single compressor trains. The PCC process offers additionally the possibility to generate large amounts of balancing energy by reducing the capture rate.

The results presented here are used within the German DYNCAP research consortium to evaluate the PCC at part load and serve as basis for developing and validating of dynamic power plant and PCC models.

Additional investigations have to be done in the subject of reducing desorber pressure further. A validation of the part load behaviour of the PCC process with pilot plant data will take place in the future.

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