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Energy Integration in an NGCC Plant with Post-Combustion CO_2 Capture – Systematic Methodology for Evaluating Process Alternatives

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Natural gas combined cycles (NGCC) with post-combustion CO_2 capture is expected to be an important part of the solution in the future low-emission energy scenario. An overview of the literature shows that until recently there has been no effort to develop systematic methods to integrate the different units in the process. The CO_2 capture process cannot be optimized without considering its integration into the power plant and the adaptation of existing process units to the new requirements defined by the CO_2 capture process. With this in mind, a systematic energy integration methodology is presented in this work that evaluates the energy targets prior to design. The Sequential Framework for heat exchanger network synthesis is modified to develop the heat exchanger networks including the heat recovery steam generator. Process and component considerations when integrating steam extraction from the bottoming cycle are also discussed. Application of the methodology results in an improvement in efficiency of the overall process by 0.4 % points.

1. Introduction

Natural gas combined cycle (NGCC) power plants with CO_2 capture are expected to play an important role in mitigating carbon emissions. An overview of the different gas turbine cycles with CO_2 capture is provided by Kvamsdal et al. (2007). Post-combustion capture with chemical absorption is the most mature technology for CO_2 capture from natural gas fired power plants and will probably be the first one to be deployed (Wang et al., 2010). A state-of-the-art overview of the research work carried out in post-combustion capture with chemical absorption is provided by Wang et al. (2010). In this work focus will be on natural gas combined cycle with post-combustion CO_2 capture using MEA as the solvent.

2. Description of process units

A schematic of a natural gas combined cycle plant with post-combustion CO_2 capture is shown in Figure 1. The power island is a standard NGCC where natural gas is combusted in compressed air and then expanded to produce shaft work (subsequently converted to electric power). The hot turbine exhaust gases is sent to a heat recovery steam generator (HRSG) where steam is generated for a 3 pressure level steam cycle (with reheat) while cooling the exhaust to 80-100 °C. The steam is expanded in a series of HP, IP and LP steam turbines to 0.048 bar. This steam turbine exhaust is condensed with cooling water and recycled as boiler feed water (BFW) to the HRSG. More information on natural gas combined cycles is available in Kehlhofer et al. (2009).

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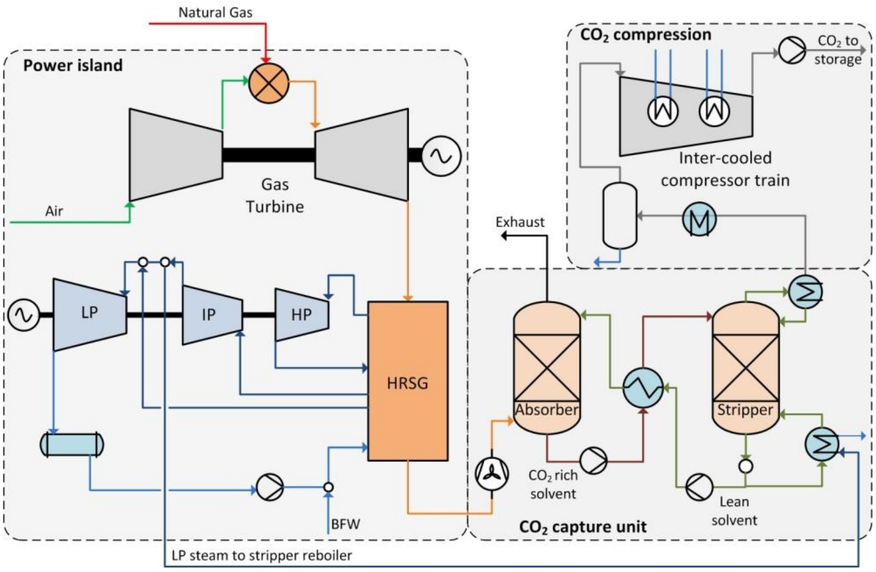

Figure 1: Process flow diagram of Natural Gas Combined Cycle(NGCC) with amine based post-combustion capture unit

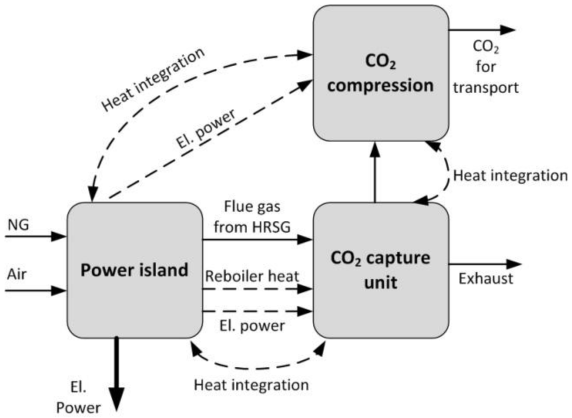

Figure 2: Interaction between different units in an NGCC with post-combustion CO_2 capture

The CO_2 capture unit using MEA as chemical absorbent, is placed downstream of the NGCC power plant. The flue gas from the recovery steam generator (HRSG) is cooled before being sent to the absorber where it is contacted counter-currently with the solvent (MEA). CO_2 is absorbed by the MEA and is sent to the top of the stripper where solvent is regenerated at temperatures of 100 - 120 °C. The heat for solvent regeneration is supplied to the stripper reboiler (LP steam in Figure 1). This heat along with electric power requirement of the flue gas fan and solvent pumps constitute the energy penalty for the CO_2 capture process. More information on amine based CO_2 capture is available in Kohl and Nielsen (1997).

The CO_2 gas from the stripper is cooled to 25 °C to separate water from the CO_2 stream and sent to an inter-cooled compressor train where it is compressed to 80 bar. At this pressure the CO_2 liquifies at 25 °C and pumped to the CO_2 transport pressure of 110 bar. The number of stages in the compressor train varies between 3 to 8.

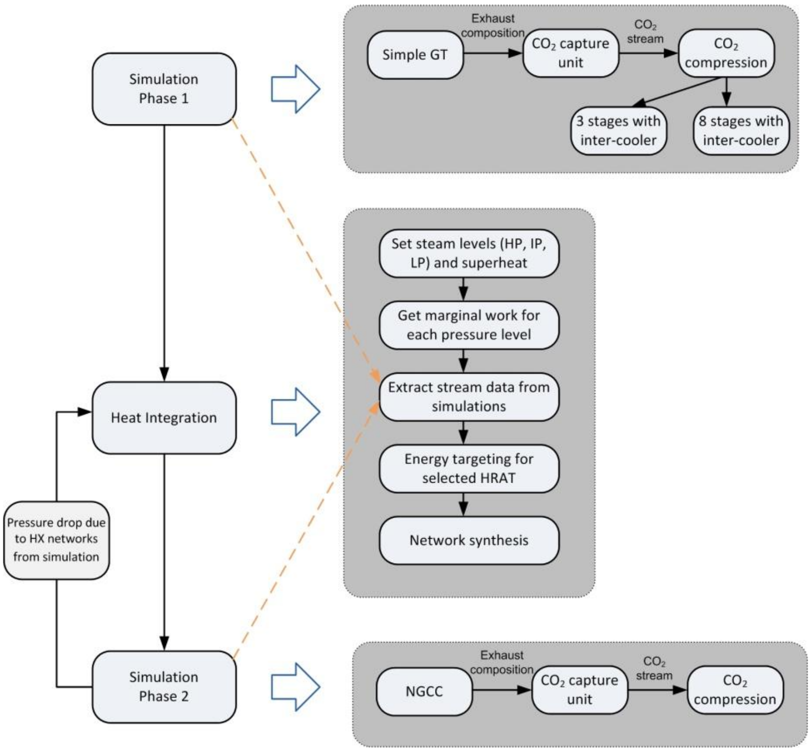

Figure 3: Integration methodology - NGCC with post-combustion CO_2 capture

3. Methodology

A systematic methodology for the integration of post-combustion capture plants with NGCC is an important aspect of ensuring better overall plant efficiency. All process units can be either a heat/work source or sink. Thus it is important when developing a methodology to incorporate all (or appropriate) process streams from each process unit to achieve the best possible integration. A visualization of the interaction between the process units of the NGCC power plant with CO_2 capture is shown in Figure 2.

It is important that the reboiler duty at interface between the power island and the CO_2 capture unit is represented as a heat term rather than a steam flow as this allows the possibility of direct integration of the reboiler in the HRSG.

When integrating the amine process for the capture and compression of CO_2 into a power plant, the net power output is reduced due to the heat requirement for the regeneration of the solvent and additionally due to the required auxiliary power for pumps and blowers in the capture process as well as the CO_2 compression train. As the cooling water demand of the overall process, additional power is also needed to drive the cooling water pumps.

The three main aspects of the plant that affect the overall process efficiency are thus heating, cooling and electric power. In other words the magnitude of the quantities at the interface between the three process units and how they interact with each other determines the overall process efficiency. Rather than evaluate these interactions manually to find the ``best" plant configuration, this work presents a simulation-optimization methodology for process synthesis.

The first step in the methodology is thus to evaluate the magnitude of these quantities at the interface. This is done by using suitable process simulation tools for each of the three process units. This is represented as Simulation Phase 1 in Figure 3. A simple GT cycle simulation provides the CO_2 capture unit with exhaust gas stream information. Based on this stream data simulation for the CO_2 capture unit will evaluate the CO_2 product stream data that is used as input to the CO_2 compression unit simulation. The compression unit is simulated for two extreme cases - with 3 inter-cooled stages and 8 inter-cooled stages. The 3 inter-cooled stages case gives intermediate hot streams at higher qualities for heat integration than the case with 8 inter-cooled stages. However, the 8 inter-cooled stages case requires lower compression work. Both these options will be evaluated with heat integration to compare their overall process efficiency to settle on a final compression train design.

After Simulation Phase 1, heat integration is performed based on stream data extracted from the simulations (see Figure 3). The heat recovery steam generator (HRSG) is the crux of this section. The heat integration models the HRSG and its interaction with other heat sources and sinks in the process. The steam paths in a typical 3 pressure steam cycle with reheat is shown in Figure 4. The superstructure allows stream extraction/addition at all locations in the path. In addition to stream data extracted, the following information is required from the user:

1. Number of steam levels
2. Steam pressures
3. Minimum approach temperature specifications in the HRSG
4. Minimum stack temperature
5. Steam extractions and additions to the HRSG
6. Marginal power generated per kg of steam produced at each level and lost for each kg of steam extracted at the different locations.

The heat exchanger network is generated using the Sequential Framework (Anantharaman et al., 2010). This network is used to perform a new simulation (Simulation Phase 2 in Figure 3). This time the complete NGCC simulation is done based on HRSG design and steam flows provided by the heat integration. As in Simulation Phase 1, CO_2 capture unit and CO_2 compression simulations are carried out. These steps are repeated to generate the optimal process design.

4. Process and component considerations

The earlier presented the methodology developed for process integration in this work. However, along with the methodology, process and component specific considerations are required to ensure a comprehensive and accurate representation of plant components. In this section the various steam turbine configurations for steam extraction to the reboiler are presented separately for a new plant scenario. Ideally, for MEA, steam at 130 °C is required at a saturation pressure of 2.8 bar. However, in most cases it is not possible to extract at this condition.

The steam cycle in a new plant scenario can be designed keeping steam extraction requirements in mind. Thus the LP steam turbine flow can be designed for lower flows than comparable NGCC plants with CO_2 capture. Also, the steam system pressure levels can be set with due consideration given to steam extraction to the reboiler. However, it must be noted that setting the IP/LP cross-over pressure to be as low as 2.8-3 bar could lead to other steam cycle inefficiencies. For a new plant the following schemes can be considered:

1. Steam extraction from LP turbine (Figure 5a): The LP turbine can be designed with an extraction point suitable for reboiler feed. However, extractions from steam turbines are associated with an extraction loss of 5-10 %.
2. Throttling valve at IP/LP cross-over: Extract at the IP/LP cross-over using a throttling valve to keep the pressure constant as discussed in the previous section on retrofit scenario as shown in 5b.
3. Back pressure turbine: Extract at the IP/LP crossover using a backpressure auxilliary LP turbine to expand the steam to conditions required at the reboiler (Figure 5c).
4. Back pressure turbine (Figure 4d): Extract stream from the reheat (RH) and expand it through an IP/LP back pressure turbine to conditions required at reboiler while generating power. This is similar to the IP/LP cross-over back pressure turbine case (Figure 5d).

Steam extracted from the IP/LP cross-over is superheated and requires to be de-superheated before it is fed to the reboiler. An option to de-superheat the steam extracted from the IP/LP cross-over is to mix it with saturated LP steam.

These schematics for integration of the bottoming cycle with the CO_2 capture unit are incorporated in the energy integration model for evaluating among the different options. This could involve more than one run of the methodology. However, the systematic nature of the method will ensure that the results are consistent and can be compared for evaluation.

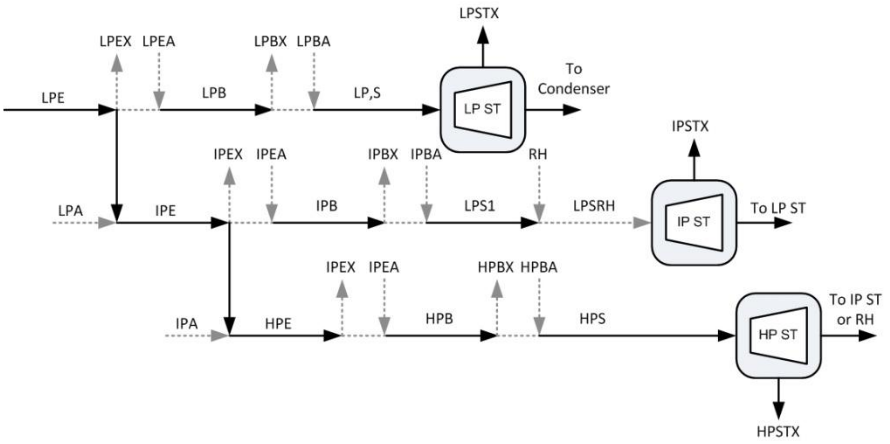

Figure 4: Stream path superstructure for a 3 pressure level steam cycle (with reheat)

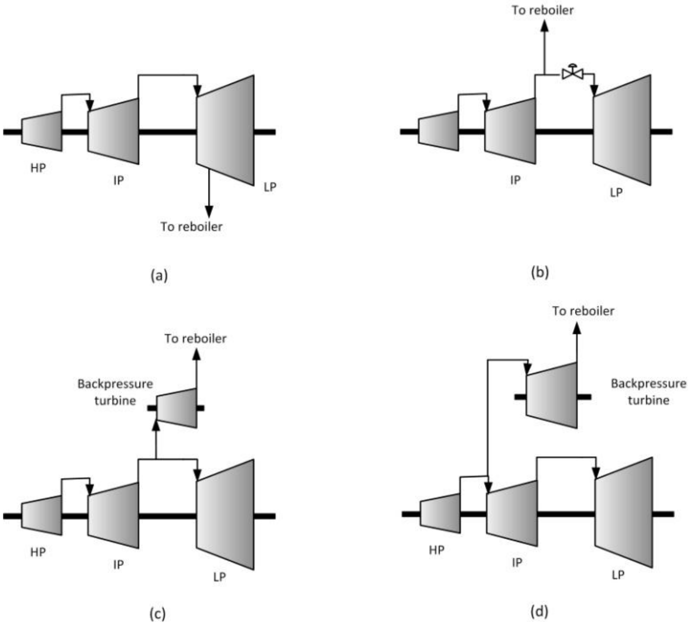

Figure 5: Process and component considerations for steam extraction

5. Results and discussion

The methodology described in this paper is applied on the EBTF Reference Case for NGCC Anantharaman et al. (2011). The net electrical efficiency of the NGCC without capture is 58.3 % and with post-combustion capture is 49.9 % considering stream extraction at the IP/LP crossover.

The integration methodology developed in this work when applied to the reference case gives the complete and direct integration of the reboiler into HRSG as the best integration scheme. This changes the design of the HRSG from a 3 pressure level to a single pressure system. The T-Q diagram of the modified HRSG with complete reboiler integration is shown in Figure 6. The efficiency of the NGCC with post-combustion capture with reboiler integration in the HRSG is 50.3 %. The presents a 0.4 % point improvement in efficiency as compared to the standard way of integration at the IP/LP crossover.

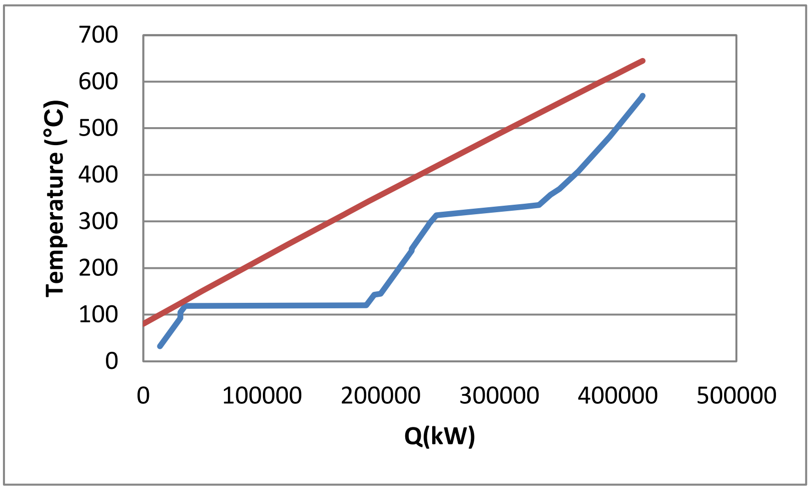

Figure 6: T-Q diagram of HRSG when reboiler is directly integrated with the HRSG

6. Conclusion

Natural gas combined cycles with post-combustion CO_2 capture is expected to be an important part of the solution in the future energy scenario. A systematic energy integration methodology is presented in this work that evaluates the energy targets prior to design. Process and component considerations when integrating steam extraction from the bottoming cycle were discussed.

The methodology results in improved energy efficiency of an NGCC with post-combustion capture due to better integration schemes. The improvement potential is 0.4 % points. This methodology can be extended to use with other solvents in the post-combustion capture process.

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