CHEMICAL ENGINEERING TRANSACTIONS

VOL. 39, 2014

A publication of AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong
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ISBN 978-88-95608-30-3; **ISSN** 2283-9216
DOI: 10.3303/CET1439241

Optimal Design Technologies for Integration of Combined Cycle Gas Turbine Power Plant with CO_2 Capture

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This paper presents a novel design method for optimal integration of Combined Cycle Gas Turbine (CCGT) power plant with CO_2 capture. Different design strategies have been investigated to improve the efficiency of the CCGT power plant, including supplementary firing, steam cycle regeneration, gas cycle regeneration and gas cycle intercooling. Finally, an amine-based post-combustion carbon capture process has been built to capture CO_2 at the exit of the HRSG of the CCGT power plant. The case study shows that, improving the efficiency of CCGT power plant before the integration of carbon capture process will significantly reduce the efficiency penalty caused by integrating carbon capture units into the power plant.

1. Introduction

About 21 % of the world's power production is based on natural gas. One typical gas-fired power plant is combined-cycle gas turbine (CCGT) power plants. In CCGT power plants, a single gas turbine is connected to an electricity generator through a shaft, and the heat contained in gas turbine exhaust is used in a heat recovery steam generator (HRSG) to produce steam that drives a steam turbine and generates extra power. Normally, large CCGT power plants may have more than one gas turbine.

Over the last few years, remarkable development in CCGT technology has significantly increased the CCGT power efficiency. Cihan et al. (2006) used thermodynamic optimization to determine the optimum values of the operating conditions in their considered system to minimize energy losses. The result of Ameri et al. (2008) showed that optimization of the HRSG operating parameters can increase the performance of the plant by reducing the exergy destruction in HRSG arising due to process irreversibility. Moreover, the irreversibility of HRSG can be reduced by increasing the steam temperature at the HRSG outlet, and by reducing the stack temperature and the temperature difference for heat transfer (Bassily, 2007). Casarosa et al. (2004) also showed that optimizing the HRSG could increase the efficiency of existing plants by 1.9 - 2.3 % and the output power by 9 - 11 %. Sanjay (2013) considered combined cycle systems with different bottoming cycle configurations, showing that there was 3.16 % increase in plant efficiency when a bottoming cycle configuration of increased complexity is adopted. An early research on the principles of thermodynamic integration between a gas power plant and a post combustion CO_2 capture based on steam extraction from the power cycle to provide the heat necessary for solvent regeneration was undertaken by Mimura (1995), this was further developed by Gibbins and Cranes (2004) where they modified feed-water heating arrangement to reduce the CO_2 scrubbing efficiency penalty. Harkin et al. (2010) used Pinch analysis to show that heat available upstream of the capture unit may be used to reduce the energy required for solvent regeneration. Although integration principles are now well established, much of the current literature on post-combustion capture system in gas power plant still lacks a comprehensive assessment of their impact on power generation. They did not consider improving the efficiency of the gas power plant before integrating the capture unit into it.

Based on the aforementioned discussion, this paper presents a novel design method for optimal integration of Combined Cycle Gas Turbine (CCGT) power plant with CO_2 capture. First of all, a CCGT power plant is built with the use of ASPEN PLUS, and different design strategies have been investigated to

Please cite this article as: Pan M., Agulonu A., Gharaie M., Perry S., Zhang N., Bulatov I., Smith R., 2014, Optimal design technologies for integration of combined cycle gas turbine power plant with CO_2 capture, Chemical Engineering Transactions, 39, 1441-1446 DOI:10.3303/CET1439241

improve the efficiency of the CCGT power plant. Then, a carbon capture process is considered for integrating into the optimal designed power plant.

2. Modelling of Combined Cycle Gas Turbine (CCGT) Power Plant

The considered CCGT power plant consists of the gas turbine, heat recovery steam generator (HRSG) and steam turbines. The modelling of CCGT can be divided into two parts; the gas cycle and the steam cycle. The gas cycle is based on Brayton cycle where the air from the atmosphere is compressed to desired pressure, the compressed air goes to combustion chamber blend with the natural gas and combustion takes place at constant pressure. The hot gas from the combustion chamber goes to the gas turbine where they are expanded back to 1 bar. The heat of the waste of the exit of the Brayton cycle serves as an entrance to the steam cycle. The steam cycle is based on Rankine cycle. The exhaust gas from the gas turbine goes to the HRSG, which recovers the thermal energy from the exhaust gas to produce 3 levels of steam (HP, IP and LP). Each of the levels of steam generated is used to drive 3 different levels of steam turbines (HP turbine, IP turbine and LP turbine). The last part of the process is the condensation, the steam at the exit of the LP turbine goes to the condenser, where it is condensed and pumped back to the HRSG. Figure 1 shows the flow-sheet of the considered power plant.

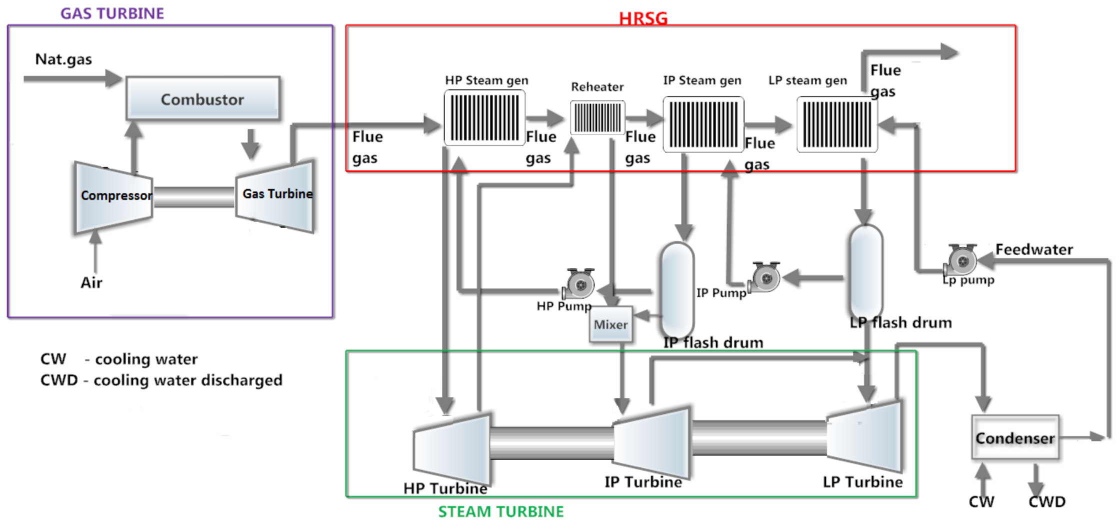

Figure 1: Flow-sheet of a CCGT power plant

2.1 Assumptions

To build the CCGT power plant on ASPEN PLUS, following assumptions have been made:

- The combustion chamber is modelled as reactor in ASPEN PLUS.
- The conversion is 100% in the reactor.
- The compressor efficiency is polytrophic while turbine efficiency is isentropic.
- No losses are assumed in the conversion energy.

2.2 Physical property methods

The choice of appropriate physical property method is always the key decision in determining the accuracy of any simulation. Physical property method is a collection of methods and models that ASPEN PLUS uses to compute thermodynamic and transport properties. The thermodynamic properties includes; fugacity coefficients (k-value), enthalpy, entropy, Gibbs free energy and volume. Transport properties includes; viscosity, thermal conductivity, diffusion coefficient and surface tension. For simulating gas-fired power plant, the gas used for gas cycle consists of light hydrocarbons and the recommended physical property methods for light hydrocarbons are: SRK, PR-BM, RSK-BM and PENG-ROB. The recommended physical property for steam and water in the steam cycle is STEAM-TA.

2.3 Modelling of the gas turbine section

First of all, air enters the compressor (COMPR) at an atmospheric pressure and is compressed to a desired pressure value, increasing the temperature of air entering the combustion chamber. Polytropic efficiency of 0.9 and mechanical efficiency of 0.996 was assumed. The air composition fed to the compressor is given in Table 1.

Table 1: Composition of air

Components	Nitrogen	Oxygen	CO_2	Argon
Moles (%)	77.30	20.74	0.03	0.92

RGIBBS reactor was used to model the combustor in ASPEN PLUS with compressed air and natural gas as feeds. The mass and energy balance around the combustor takes into account the compressed air and the natural gas feeds into the combustion chamber. The composition of the natural gas according to the specifications given by Shoreham gas power plant is given in Table 2.

Table 2: Composition of natural gas

Components	N_2	CO_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}-2	C_4H_{10}-1	C_5H_{12}-1	C_6H_{14}-1
Moles (%)	0.890	2.000	89.000	7.000	1.000	0.050	0.050	0.004	0.001

From Table 2, the two main components of natural gas that takes part in the combustion process are Methane and Ethane. The chemical reaction for the combustion process is given as follows:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{1}$$

$$C_2H_6 + \frac{7}{2}O_2 = 2CO_2 + 3H_2O \tag{2}$$

Finally, COMPR block in ASPEN PLUS was used to model the gas turbine. The hot gas from the combustion chamber enters the turbine where it is expands to 1 bar to produce power. The temperature of the hot gas entering the turbine is a constraint. The turbine type is isentropic. The isentropic efficiency of 0.9365 and mechanical efficiency of 0.996 are assumed.

2.4 Modelling of the heat recovering steam generator (HRSG)

In ASPEN PLUS, several HEATX models were used to model the HRSG. The approach used to model the HRSG in ASPEN PLUS has only one feed-water source for the three pressure level steam generation. The HRSG section consists of heat exchanger (HEATX), pumps and flash separators, as shown in Figure 2. In Figure 2, feed-water is pumped from the LP pump to LP economiser (LPECO), where it is preheated up to saturation point, the saturated water is passed through LP flash separator, where the steam is separated from the liquid. The steam at the vapour outlet of the LP flash separator is passed through the LP evaporator (LPEVAP) where it is evaporated; the saturated vapour is superheated in the LP superheater (LPSPHTR) of the HRSG. The LP superheater steam (LPSPHST) at the outlet of the HRSG will be used at the LP steam turbine to produce power. The IP and HP superheater steams (IPSPHST and HPSPHST) are generated in the same way as LP superheater steam. Note that the source of heat in the HRSG is only the hot gas turbine exhaust (flue gas).

2.5 Modelling of the steam turbine section

The three pressure levels of steam generated from the HRSG in Figure 2 are used to drive three pressure level steam turbines: high pressure (HP) turbine, intermediate pressure (IP) turbine and low pressure (LP) turbine. The steam turbines are modelled in ASPEN PLUS using COMPR blocks. It is assumed that the steam turbine type is isentropic and isentropic efficiency of 0.9 and mechanical efficiency of 0.996. Thus, the efficiency of gas-fired power plant is given by network output of the gas turbine and that of the steam turbine as shown in the expression below:

$$\eta_c = \frac{W_{Gturb_{net}} + W_{Sturb_{net}}}{M_f \times LHV} \tag{3}$$

Where: $W_{sturb_{net}}$ is the total power output from the three steam turbines, M_f is the mass flow rate of fuel and *LHV* is the low heating value of fuel.

2.6 Modelling of the water reuse section

The condenser is used to condense the steam at the exit of the steam turbines before it is pumped through the feed-water tank. The condensate was pumped back to the LP economizer.

The complete design of the power plant with the condensing system is shown in Figure 2.

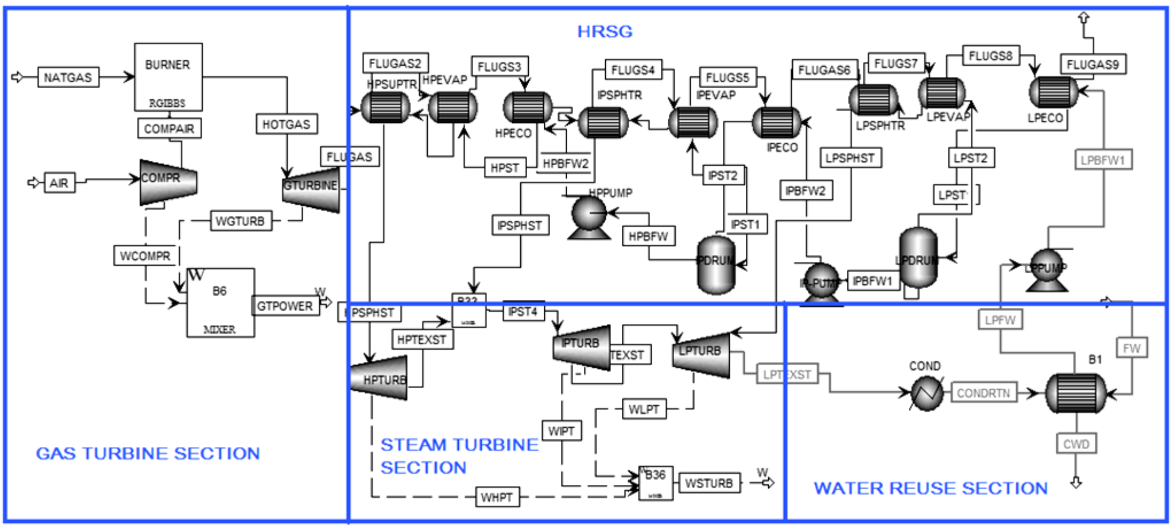

Figure 2: Complete design of CCGT power plant in ASPEN PLUS (base case)

3. Design Strategies of Improving Power Output and Efficiency of Power Plant

Improvements to the basic CCGT power plant design have been made by incorporating the following method: supplementary firing, steam cycle regeneration, gas turbine cycle regeneration, and gas turbine cycle with intercooling.

- **Supplementary firing:** Supplementary firing raises the temperature of the gas turbine exhaust entering the HRSG, using a portion of oxygen in the exhaust. Increasing exhaust gas temperature enhances the quality of steam generated in the HRSG which subsequently increases the power output and efficiency of the steam turbine.
- **Steam cycle regeneration:** The efficiency of the CCGT power plant can be improved by a regenerative Rankine cycle. Steam extracted from the LP turbine can be used to heat up the feed water before it is pumped to the LP economiser (LPECO), which reduces the heat required to heat up the feed-water from ambient temperature.
- **Gas turbine cycle regeneration:** In gas cycle regeneration, all the gas turbine exhaust (flue gas) is not used in the regenerator since the base power plant is CCGT power plant, steam cycle has to be considered for increase in efficiency. Hence the flue gas is split into two parts. One part is used in the regenerator to heat up the compressed air before it is being fed into the combustion chamber. Another part is fed into the second combustion chamber used for supplementary firing; this increases the heat in the flue gas.
- **Gas turbine cycle with intercooling:** This is modelled in ASPEN PLUS using two compressors, the low pressure compressor and higher pressure compressor. The compressed air from low pressure compressor is cooled in an intercooler. The intercooler is modelled in ASPEN PLUS using a heat exchanger (HEATX) and the cooling is supplied by cooling water. The cooled air from the intercooler is fed into the higher pressure compressor where it is compressed further before fed to the regenerator.

Based on the above discussion, the improved CCGT power plant is obtained and presented in Figure 3.

4. Modelling of CO_2 Capture in the CCGT Power Plant

The CO_2 in the flue gas at the exit of the HRSG was captured using a pre-existing simulation model of amine based post combustion carbon capture shown in Figure 4. As shown in Figure 4, lean MEA solvent contacts with flue gas in the absorber and captures CO_2 from the gas; the rich MEA solvent from the absorber exchanges heat with the bottom flow from the stripper, and goes into the stripper; the stripper strips CO_2 from MEA solvent, which includes a partial condenser at the top and a reboiler at the bottom; the mixer mixes the bottom flow from the stripper, new MEA solvent and H_2O to make up lean MEA solvent for the absorber. The proposed process illustrates the use of rigorous rate-based distillation to accurately model the CO_2 capture process by aqueous MEA from a gas mixture of N_2, O_2, CO_2 and H_2O. Key features of this rigorous simulation include electrolyte thermodynamics and solution chemistry, reaction kinetics for the liquid phase reactions, rigorous transport property modelling, rate-based multi-stage simulation with Aspen Rate-Based Distillation which incorporates heat and mass transfer correlations accounting for columns specifics and hydraulics.

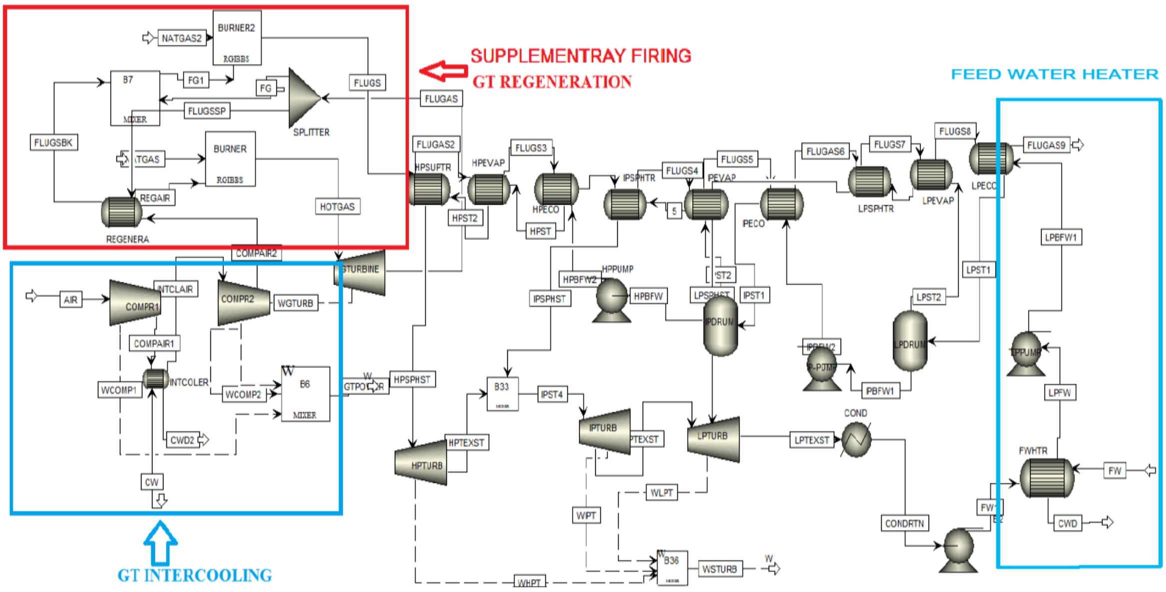

Figure 3: Improved design of CCGT power plant in ASPEN PLUS

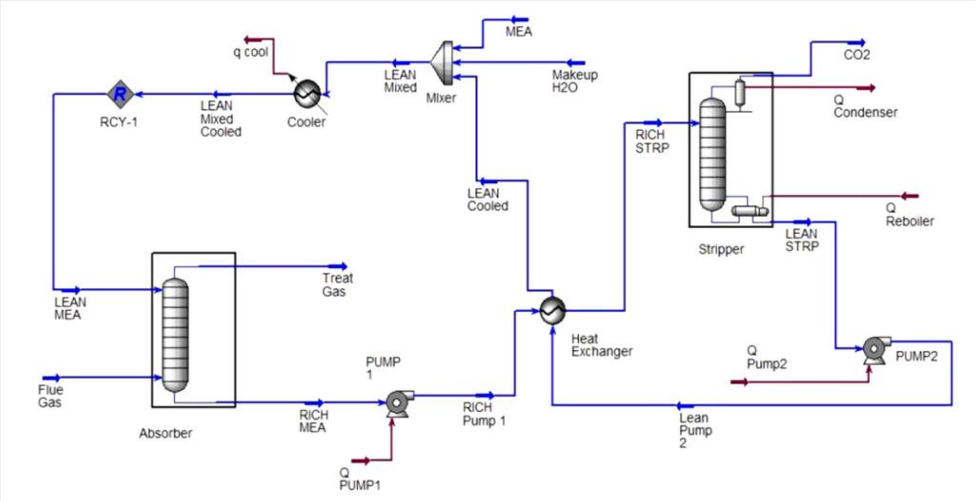

Figure 4: Amine based post combustion carbon capture

5. Case study

The example investigated in this paper is a CCGT power plant producing 420MW of power at the efficiency of 58.29 %. Its original configuration is shown in Figure 2. Based on the proposed improvement procedure for reconfiguring the CCGT power in section 3, the efficiency of the power plant rises to 60.4 % with 5 % fuel flow for supplementary firing; then further configuration of the power plant with steam cycle regeneration raises the efficiency to 60.6 %; finally, the efficiency increases to 63.5 % with gas cycle regenerator and intercooler. The improved configuration of the power plant is presented in Figure 3. The comparison of the base case and the improved case is shown in Table 3.

Table 3: Comparison of the base case and the improved case of the power plant

CCGT Power Plant	Base case	Improved case
Q_{fuel} (MW)	712.30	742.17
Turbine Inlet Temperature(°C)	1,427.90	1,498.30
Compressor Work (MW)	228.47	226.72
Turbine WORK (MW)	563.85	585.67
Gas Turbine Power Output(MW)	335.38	358.95
Gas Turbine Exhaust Temp (°C)	645.00	641.40
Steam Turbine Power Output (MW)	84.75	112.31
Plant Net power Output (MW)	420.13	471.26
Efficiency (%)	58.98	63.50
Stack Temperature (°C)	130.00	150.30

For integrating the CO_2 capture process proposed in section 4 into the CCGT power plant, 186 MW of heat needed by the capture process. It can be found that, in the improved CCGT power plant, 114 MW of heat available in the condenser, which can be recovered and utilized and results in 72 MW of net heat requirement by the capture process. Table 4 shows the integration of CO_2 capture process and power plants (base case and improved case). From Table 4, the result of the improved power plant produces 471.26 MW of power compared to 420 MW of power produced in the base power plant, and the efficiency increases 4.93 % when the capture process is integrated into the improved power plant compared to the integration of the base power plant.

Table 4: Comparison of power plants (base and improved cases) with and without CO_2 capture process

CCGT Power Plant	Base case	Base case + CO_2 capture	Improved case	Improved case + CO_2 capture
Q_{fuel} (MW)	712.30	712.30	742.17	742.17
Power Output (MW)	420.13	348.13	471.26	399.26
Efficiency (%)	58.98	48.87	63.50	53.80

6. Conclusions

This research has investigated various design strategies to improve the efficiency of CCGT power plant, and is able to identify the most efficient design configuration. The effect of integration of carbon capture has been also briefly discussed. However, capital cost is not considered in the modification, the trade-off between the capital and operational cost will be considered for further work.

Acknowledgement

Financial support from EC ENERGY.2011.5.1-1 (282789) CAPSOL Design Technologies for Multi-scale Innovation and Integration in Post-Combustion CO_2 Capture: From Molecules to Unit Operations and Integrated Plants are gratefully acknowledged.

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