Exergy Analysis of a Natural Gas-Fired Gas Turbine Combined Cycle Power Plant with Post-Combustion Carbon Capture

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Post-combustion carbon capture (PCC) plays an important role in reducing the greenhouse gas emissions. In the present study, an exergy analysis is conducted to assess the exergy destruction and exergetic efficiency of a natural gas-fired combined cycle gas turbine (CCGT) system coupled with the PCC unit. The overall exergetic performance of the system is compared against the baseline CCGT by using realistic data. The working temperature and composition of the exhaust flue gas are two critical parameters that have significant impact on the performance of the absorption liquid and equipment operation. Results show that the highest exergy destruction occurs in the combustion chamber and condenser are 15.69 MW and 11.78 MW, occupying more than 45 % of the exergy destruction of the overall system for the conventional CCGT system. For the CCGT system with PCC unit, the exergy destruction of absorber is relatively high with an exergetic efficiency of 56.18 %. The highest exergetic efficiency is found in the units of combustion chamber and heat recovery steam generator (HRSG), which are 90.23 % and 87.01 %, while the condenser has the lowest efficiency. Identification of the low efficiency component presents an opportunity for improvement of the system.

1. Introduction

Post-combustion CO_2 capture (PCC) is a promising technology to reduce CO_2 emissions from the power plant, mostly via the use of monoethanolamine (MEA) to absorb CO2 (Huang, 2018). Since PCC requires only few modifications, it is currently considered as the most practical approach to capture CO_2. Although Combined Cycle Gas Turbine (CCGT) power plant performs with high thermodynamic efficiency, the CO_2 produced from the combustion process needs to be removed or captured before the flue gas is exhausted to the atmosphere. This study examines the exergy flow of CCGT with PCC to identify the opportunity for CO_2 to be recycled and captured. Herraiz et al. (2018) analysed the impact of selective exhaust gas recirculation (SEGR) on the power output of CCGT cycle with PCC, without analysing the exergy flow of the system. Olaleye et al. (2015) analysed the exergy flow of a supercritical coal-fired power plant equipped with a CO_2 capture system. The result shows that the highest exergy destruction occurred in the condenser section, occupying 51.77 % of the total exergy destruction of turbine cycle. Kong et al. (2016) performed an exergy analysis on the main components of CCGT and found that exergetic efficiency increases with increasing turbine's duty, while the exergy destruction increases with increasing ambient temperature. The pressure ratio of gas turbine was found to have great effect on the thermal efficiency and exergetic efficiency, which can be enhanced by 50 % and 47 % when the pressure ratio of gas turbine was increased to 34 % (Reddy and Mohamed, 2007). It was shown that the inlet pressure of gas turbine has a significant effect on the exergetic efficiency, as lower inlet pressure will result in higher exergetic efficiency of gas turbine section. These studies serve as a useful guide to improve the performance of the system. To analyse the chemical exergy of MEA in

the PCC unit, Gharagheizi et al. (2018) proposed the group distribution method to calculate the standard molar chemical exergy of complicated compounds through functional groups.

The present study analyses the exergy flow of CCGT system with PCC unit, with the aim to identify the exergy of each component. Exergy analysis is based on the second thermodynamic law, in which the exergy destruction is determined by exergy balance equation, and exergetic efficiency can be calculated as exergy carried by the products over the exergy carried by fuel. Exergy analysis is a typical way to show the irreversibility of process and quality of energy, where the location, type and quantity of exergy destruction and loss can be identified in the system (Kong et al., 2016). Further, it enables the identification of the section with lowest utilization rate, which is the main target for energy saving measures. Exergy analysis can be utilised to enhance the performance of the overall system in the future. The present study is intended to identify the exergy destruction distribution and exergetic efficiency of each section in the CCGT-PCC system, and to identify the component with the lowest utilization rate.

1.1 CCGT and PCC system

The model combined cycle gas turbine system chosen in this study is shown in Figure 1. The system is based on the proposed model by (Herraiz et al., 2018) developed using ASPEN Plus. The net power output for the gas turbine and steam turbine in this study are 58.225 MW and 10.019 MW. The operating conditions in the systems such as temperature, mass flow rate and pressure are based on the actual CCGT power plant of with rated power 30 MW (Bejan et al., 1996). The CCGT is assumed to operate with natural gas, a widely adopted gaseous fuel due to its clean emissions characteristic and high thermal efficiency. Air and natural gas are mixed and burned in the combustion chamber, while the exhaust gas flow expands through the turbine to generate electricity. Subsequently, the hot gas flows through the preheater and cooled down to 1006 K. Water is converted into steam vapour after absorbing the heat from exhaust flue gas in the HRSG. The steam contains high enthalpy is used to drive the steam turbine to produce work. The expanded vapour then condenses into water to be recirculated back to the HRSG for heat absorption.

The detailed post-combustion carbon capture system is shown in Figure 2. The exhaust gas exiting from the HRSG enters the PCC system. Through booster fan and direct contactor cooler, temperature of flue gas is decreased to 318.15 K while the pressure is increased to 1.05 bar. The exhaust flue gas in the absorber flows from bottom to top, after contacting with the lean solvent from the top of the absorber, CO_2 in the exhaust gas is absorbed. The exhaust flue gas flows out of the absorber at the top. Rich solvent exchanges heat with lean solvent from stripper at heat exchanger, because low temperature is required in absorber, and high temperature is required for stripper. After decreasing the temperature, lean solvent is recycled to the absorber. Rich solvent increases temperature to 378.15 K and enters the stripper to be desorbed. The gases after desorption contains CO_2, water vapor and little MEA. After washing, condensation and separation at the top of stripper, water is condensed and recycled into the stripper. The CO_2 is transported into the compression train and finally be stored or transported. Part of the lean solvent from the stripper will be recycled to the stripper after exchanging heat with steam in the reboiler, while the rest of the lean solvent will be recycled into absorber. In this way, MEA solvent can be utilized more efficiently.
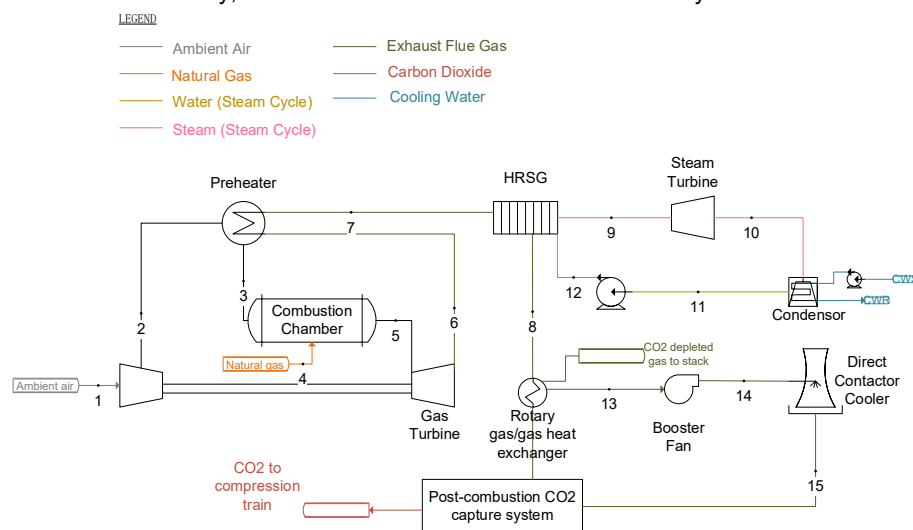

Figure 1: Overall system of combined cycle gas turbine with post-combustion carbon capture system
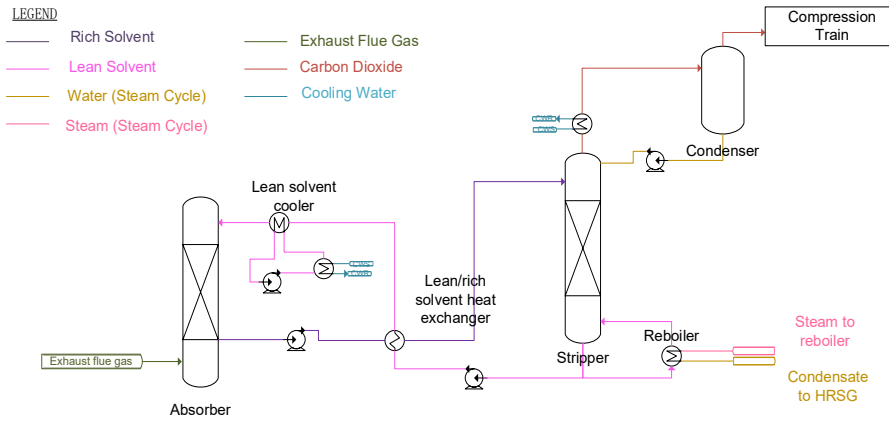
Figure 2: Detailed post-combustion carbon capture system

2. Exergy analysis

2.1 Physical and chemical exergy

Exergy analysis is performed to identify the component with the lowest utilization rate in the overall system, which then enables subsequent measures to enhance the performance of the section with the highest destruction or lowest exergetic efficiency.

In this study, the exergy flow analysis includes the physical and chemical exergy, while the potential exergy and kinetic exergy are not calculated. System is assumed to be operating under steady state condition and natural gas is assumed as pure methane for simplification of calculation. The physical exergy is defined as the maximum amount of work obtainable when the flow of matters is brought from the current state to the environment state (Po and To) (Szargut et al., 1988). The physical processes involve only thermal and mechanical interaction with the environment (Amrollahi et al., 2011). The physical exergy can be shown as Eq(1):

$$E_{ph} = (h_i - h_0) - T_0(s_i - s_0) \tag{1}$$

Where h_0 and s_0 are the specific enthalpy and entropy. $h_0 = h(T_0, p_0)$ and $s_0 = s(T_0, p_0)$. T_0 and P_0 are ambient temperature (298.15 K) and pressure (1.013 bar).

Chemical exergy is associated with the departure of the chemical composition of a system from that of the environment, which is caused by the heat transfer and exchange of substance with the environment (Bejan et al. 1996). The standard chemical exergy of substances in this study are adopted from Bejan et al. (1996), and the standard chemical exergy of gas mixture is calculated as Eq(2):

$$\bar{e}^{CH} = \sum x_k \bar{e}^{CH} + \bar{R}T_0 \sum x_k ln x_k \tag{2}$$

Where x_k and e$^{\wedge}$CH represent the molar fraction and standard chemical exergy of each component in the mixture. R is universal gas constant, which is 8.314 J/(mol·K).

2.2 Group distribution method

For the solvent MEA, the group distribution method is used to calculate its standard chemical exergy. MEA (C2H7NO) is considered to consist of two CH2RX functional groups. Using the method proposed by (Gharagheizi et al., 2018), the standard molar chemical exergy of mixture can be shown as Eq(3):

$$\varepsilon^0 = \Delta H_f^0 - T\Delta S_f^0 + \sum n_j \varepsilon_j^0 \tag{3}$$

Where ΔH_f^0 and ΔS_f^0 are standard enthalpy and entropy of formation, n_j is number of atoms of component j, ε_j^0 is the standard molar chemical exergy of component j. For the organic matter, the formula shown in Eq(4) is calculated using the standard exergy values for different components (Table 1).

$$\varepsilon_{C_aH_bN_cO_dS_eF_fCl_gBr_hI_iSi_j}^0 = \Delta H_f^0 - T\Delta S_f^0 + a\varepsilon_C^0 + \frac{b}{2}\varepsilon_{H_2}^0 + \frac{c}{2}\varepsilon_{N_2}^0 + \frac{d}{2}\varepsilon_{O_2}^0 + e\varepsilon_S^0 + \frac{f}{2}\varepsilon_{F_2}^0 + \frac{g}{2}\varepsilon_{Cl_2}^0 + \frac{h}{2}\varepsilon_{Br_2}^0 + \frac{i}{2}\varepsilon_{I_2}^0 + j\varepsilon_{Si}^0 \tag{4}$$

After replacing the standard molar chemical exergy of the known simple substance, the formula becomes Eq(5):

$$\varepsilon^0_{C_aH_bN_cO_dS_eF_fCl_gBr_hI_iSi_j} = \Delta H^0_f - T\Delta S^0_f + 410.26a + 118.05b + 0.36c + 1.985d + 609.6e + 233.15f + 61.8g + 50.6h + 87.35i + 854.6j \tag{5}$$

Table 1: The experimental standard chemical exergies of different substances

ID	Standard Molar Chemical Exergy	ε^0 (kJ/mol)
1	Carbon (solid, graphite)	410.26
2	$H_2(gas)$	236.1
3	$N_2(gas)$	0.72
4	$O_2(gas)$	3.97
5	$S\,(solid, rhombic)$	609.6
6	$F_2(gas)$	466.3
7	$Cl_2(gas)$	123.6
8	$Br_2(gas)$	101.2
9	$I_2(gas)$	174.7
10	$Si(s)$	854.6

The standard enthalpy of formation is Eq(6):

$$\Delta H^0_f = \Delta H^0_f 0 + \sum_{i=1}^{78} n_i \Delta H^0_f i \tag{6}$$

The standard entropy of formation is calculated as Eq(7):

$$\Delta S^0_f = \Delta S^0_f 0 + \sum_{i=1}^{78} n_i \Delta S^0_f i \tag{7}$$

Where n_i is the number of occurrences of the ith functional group. $\Delta H^0_f i$ and $\Delta S^0_f i$ are the contribution of the i th functional group to the enthalpy and entropy of formation. $\Delta H^0_f 0$ and $\Delta S^0_f 0$ are the coefficients (Gharagheizi et al., 2018). MEA consists of two CH₂RX functional groups. $\Delta H^0_f i$ is -9.1154 kJ/mol, $\Delta S^0_f i$ is -0.079kJ/mol, and $\Delta H^0_f 0$ is -23.9527kJ/mol, $\Delta S^0_f 0$ is 0.0205kJ/mol. Then, ΔH^0_f and ΔS^0_f of MEA is calculated as Eq(8) and Eq(9):

$$\Delta H^0_f = \Delta H^0_f 0 + \sum_{i=1}^{78} n_i \Delta H^0_f i = -23.9527 + 2 \times (-9.1154) = -42.1835 \text{ kJ/mol} \tag{8}$$

$$\Delta S^0_f = \Delta S^0_f 0 + \sum_{i=1}^{78} n_i \Delta S^0_f i = 0.0205 + 2 \times (-0.0798) = -0.1391 \text{ kJ/mol} \cdot \text{K} \tag{9}$$

The standard molar chemical exergy for MEA is shown calculated as Eq(10):

$$\varepsilon^0_{C_2H_7NO} = \Delta H^0_f - T\Delta S^0_f + a\varepsilon^0_C + \frac{b}{2}\varepsilon^0_{H_2} + \frac{c}{2}\varepsilon^0_{N_2} + \frac{d}{2}\varepsilon^0_{O_2} = -42.1835 - T \times (-0.1391) + 410.26a + 118.05b + 0.36c + 1.985d = -42.1835 + 0.1391T + 820.52 + 826.35 + 0.36 + 1.985 \ (kJ/mol) \tag{10}$$

2.3 Exergy destruction and exergetic efficiency

Exergy destruction is from the friction and the irreversibility of heat transfer, which is represented as $\dot{E}_D$. Exergy loss is the rate of exergy transfer related to the heat transfer, which is represented as $\dot{E}_L$. Eq(11) and Eq (12) show the relationship between exergy loss and exergy destruction:

$$\dot{E}_\iota = \dot{E}_e + \dot{E}_D + \dot{E}_L \tag{11}$$

$$\dot{E}_L = \dot{w}_{cv} - \sum_i \dot{E}_i \tag{12}$$

The exergy balance equation is shown as Eq (13):

$$0 = \sum_j \dot{E}_{q,J} - \dot{W}_{cv} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D \tag{13}$$

Exergetic efficiency is another critical value in the exergy analysis. In this study, exergetic efficiency is defined as the exergy of product over the exergy of fuel of a process (Bejan et al., 1996), as shown in Eq(14):

$$\eta = E_{product}/E_{fuel} \tag{14}$$

3. Results and discussion

Applying the basic exergy formulas, the physical exergy and chemical exergy of each critical state are determined. Each section of the system is considered as a control volume, using the inlet and outlet exergy to calculate the exergy destruction and exergetic efficiency.
Result of exergy analysis for each component in CCGT and PCC is shown in the Table 2 and Table 3.

Table 2: Exergy analysis on CCGT system

Equipment	Inlet		Outlet		Exergy Destruction (MW)	Exergetic Efficiency (%)
	Physical Exergy (MW)	Chemical Exergy (MW)	Physical Exergy (MW)	Chemical Exergy (MW)		
Compressor	0.00	0.23	14.36	0.00	15.07	49.18
Combustion Chamber	70.88	85.64	143.43	1.39	15.69	90.23
Gas Turbine	143.43	1.39	80.61	1.39	4.60	56.62
HRSG	64.04	2.39	45.86	11.95	8.63	87.01
Steam Turbine	0.99	10.56	6.23	10.56	4.70	78.14
Condenser	6.23	10.56	0.47	1.00	11.78	11.17

Table 3: Exergy analysis on PCC system

Equipment	Inlet		Outlet		Exergy Destruction (MW)	Exergetic Efficiency (%)
	Physical Exergy (MW)	Chemical Exergy (MW)	Physical Exergy (MW)	Chemical Exergy (MW)		
Absorber	4.55	305.13	4.46	169.52	135.70	56.18
Stripper	0.79	169.99	3.51	172.52	8.26	95.16
Reboiler	54.60	171.60	8.66	171.65	45.89	79.71
Condenser	3.28	0.59	0.59	0.94	5.03	23.30
Compression Train	0.55	0.93	0.04	0.93	0.51	65.37

From the result, it was found that large amount of exergy destruction in the CCGT system occurs in the combustion chamber and condenser, which are 15.69 MW and 11.78 MW, occupying over 45 % of the total destruction of the CCGT system. The exergy destruction of combustion chamber is possibly due to the fuel chemical reactions, as reflected in the chemical exergy changes between the inlet and outlet of the component. It has been reported that the exergy destruction can be reduced by increasing the inlet temperature of combustion chamber (Kong et al., 2016). For the component exergetic efficiency, combustion chamber and HRSG have relatively high efficiency of 90.23 % and 87.01 %. The exergetic efficiency of compressor is considerably lower due to the required work input from the environment.

For the PCC system, the largest exergy destruction occurs in the absorber due to uneven distribution of local driving forces along the absorber (Amrollahi et al., 2011). The present analysis shows that the exergetic efficiency of the absorber is only 56.18 %. The optimal solution is an even distribution of driving forces over unit operation, with the corresponding system designed as such that the stream of solvent is split into two flows, so that these two flows enter the absorber at mid-point and top-point to make the driving force more even (Aroonwilas and Veawab, 2007). Stripper has the highest exergetic efficiency, which is about 95.16 %. The main reason is that the chemical exergy of MEA is quite high and there is only little exergy loss caused by CO_2 and water transfer. Condenser has the lowest efficiency of 23.30 %. The exergetic efficiency of condenser is influenced by the ambient temperature. At 298.15 K, the temperature difference between outlet recycled water and environment is negligible, thus the specific exergy of the outlet recycled water decreases significantly. This means that the exergy of products for condenser is significantly lower than exergy of water inlet, hence the exergetic efficiency for the condenser is very low. This effect can be reduced by decreasing the ambient temperature or increasing the outlet temperature of condenser (Kong et al., 2016).

The exergetic efficiency of the gas turbine operating with the turbine inlet condition of 1520 K and 9.14 bar is 80.01 %, the power to fuel chemical exergy ratio is 68.82 %. Ertesvåg et al. (2005) studied the exergy analysis of CCGT and reported the power to fuel chemical exergy ratio for the turbine was 69.23 %. Their turbine inlet condition used was 15.6 bar and 1523.15 K. Study shows that the inlet pressure of gas turbine has a significant effect on the turbine's efficiency. Decreasing the inlet pressure of gas turbine contributes to higher exergetic efficiency, as higher pressure ratio usually causes an increase inlet temperature, which means more irreversibilities will happen in the component (Reddy and Mohamed, 2007). As the inlet temperatures are fixed almost the same between these two studies, the power to fuel chemical exergy ratios are similar.

4. Conclusions

Exergy analysis for the CCGT with PCC system shows the distribution of exergy destruction in the overall system and the exergetic efficiency of each components. The exergy analysis can be used to identify the component with the highest exergy destruction and the lowest exergetic efficiency. The present study focuses on the exergy analysis of CCGT with PCC unit. Results show that: (1) the lowest exergetic efficiency occurs in the condenser section of the two systems, which are 11.17 % for CCGT and 23.30 % for PCC. (2) Compression train in PCC and compressor in CCGT have low exergetic efficiency due to required work input. (3) Components with the highest exergy destruction in CCGT and PCC are the combustion chamber and absorber, due to the reactions in combustion chamber and high and uneven distribution of local driving forces in the absorber. Identification of the exergetic efficiency of each component in the combined cycle system provides the opportunity to improve the performance of the system. Further exergy analysis will be conducted on the system with selective exhaust gas recirculation to utilise the CO_2 for a more efficient carbon capture process.

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