Thermodynamic analysis on post combustion CO_2 capture of natural gas fired power plant

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Abstract

A chemical absorption, post-combustion CO2 capture unit is simulated and an exergy analysis was conducted, including irreversibility calculations for all process units. With pinpointing major irreversibilities, new proposals for efficient energy integrated chemical absorption process were suggested. Moving further to the whole natural gas combined cycle plant with a CO_2 capture unit, it has been analyzed on an exergetic basis. By defining exergy balances and black-box models for plant components, investigation has been made to determine effect of each component on overall exergy efficiency. Simulation of chemical absorption plant was done using UniSim Design software with Amine Property Package which maintains thermodynamic data. For overall power plant design, GT PRO software (Thermoflow, Inc.) was used for simulation of a natural gas combined cycle. For exergy calculations, spreadsheets were created with Microsoft Excel by importing data from UniSim and GT PRO. Results show that for current chemical absorption plant, the exergetic efficiency compared to the reversible separation work lies between 9% to 21%.

Keywords: CO_2 capture, Absorption, Exergy analysis

1. Introduction

For a natural gas-capture from flue gases using chemical absorption with aqueous monoethanolamine (MEA), is one of the most near-term technologies.
Flue gas containing CO_2 is flowing through absorber while contacting with MEA solvent counter-currently. Meanwhile reaction is happening between MEA solvent and CO_2 forming a water soluble salt. A rich MEA stream which contains the chemically bound CO_2, preheated in a heat exchanger is entered to a stripper column to reverse the reaction by means of heat maintained by a reboiler and lose CO_2 content as a stream leaving at the top of the column. The lean MEA is recycled back to the absorption column while the CO_2 stream is going to compression section.
Although it is a well-established separation method, the energy consumption and the costs of CO_2 separation are substantially high and lead to consumption of more fossil fuel for the same power generation. In order to increase the energy efficiency and prevent forced extra costs and energy consumption, it is necessary to optimize the process and evaluate the performance of the whole system by means exergy analysis

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which identifies the energy consumption potential improvements and thermodynamic irreversibility amounts.

2. Exergy analysis

The exergy method of evaluating energy-intensive systems integrates the first and second laws of thermodynamics at the state of particular environmental conditions. Exergy analysis with its own certain methods of process evaluation has proven to be an efficient method to define the second law efficiency of processes. It combines the principles of conservation of mass and conservation of energy together with the second law of thermodynamics to characterize the thermodynamic losses of each component of a system through the whole design and it enables to make possible improvements of work and energy consumption. This is an advantageous method to approach the goal of more efficient energy-resource use, since it specifies the locations, types, and real magnitudes of irreversibilities either to be recovered or inevitably lost.

In absence of potential and kinetic energy, exergy of stream is divided into physical exergy and chemical exergy. Physical exergy equals to maximum amount of work obtainable when the stream of substance is brought from its actual state to the environmental state defined by P_0 and T_0 (Szargut et al., 1988) by physical processes involving only thermal interaction with the environment. It is depicted as:

$$\varepsilon_{ph}=(h-h_0)-T_0(s-s_0) \quad (1)$$

Where h and s are the specific enthalpy and entropy and $h_0=h\ (T_0, P_0)$ and $s_0=s\ (T_0, P_0)$ for the flowing matter.

The chemical exergy of a substance is the minimum work requirement to deliver it in the environmental state from the environmental substances by means of processes involving heat transfer and exchange of substances only with the environment. There are tables of calculated standard chemical exergy of various substances in literature (Kotas, 1995). molar chemical exergy of an ideal mixture is expressed as

$$\tilde{\varepsilon}_{0M} = \sum_i x_i \tilde{\varepsilon}_{0i} + \tilde{R}T_0 \sum_i x_i \ln x_i \quad (2)$$

Exergy loss of each individual unit can be calculated by finding the difference between the exergy of input and output streams of a unit operation. To pinpoint irreversible losses in each unit operation, the exergy balance for steady state steady flow is used;

$$\underbrace{\sum_{in} \dot{m}_j \varepsilon_j}_{\text{Flow exergy into system}} + \underbrace{\sum_l \dot{Q}_l \left(1-\frac{T_0}{T_l}\right)}_{\text{Heat exchange}} = \underbrace{\sum_{out} \dot{m}_k \varepsilon_k}_{\text{Flow exergy out of system}} + \underbrace{\dot{W}}_{\text{Work}} + \underbrace{\dot{I}}_{\text{Irreversibility}} \quad (3)$$

Exergy analysis can be done when composition and thermodynamic properties of all streams involving in capture process are available. For this purpose, specific simulation

software model is used to simulate the whole CO_2 capture process. By transferring stream physical properties and compositions to excel spreadsheets, exergy calculations are performed and reported.
To calculate the chemical exergy of each stream containing MEA component there is a need of chemical exergy of the MEA molecule in the liquid phase. The value which is used in these calculations is not found directly from literature but estimated. The value is $1.274 \cdot 10^6$ kJ/kmol.

3. Methodology

The plant subsystems that are analyzed include gas turbine, heat recovery steam generator (HRSG), steam turbine and condenser, CO_2 absorption column, main heat exchanger of CO_2 capture plant, stripping section, compression section etc. Each of the processes consists of exergy inputs and exergy outputs with some exergy losses.
Particularly plant has been divided into control volumes with exergy inputs and outputs from each representing the different process flows. The processes were approximated to steady or quasi steady-state flow conditions. Relevant thermodynamic data is taken from UniSim software which is process modeling software and transferring them into Excel spread sheet. Chemical and physical exergy of all streams is functioned in excel spreadsheets. The relevant amount of exergy losses and irreversibility is calculated in each part of process considering the exergy balance in each control volume.
Furthermore, exergy analysis calculations for the designed power plant are derived from GTPro Thermoflow software calculation which is going to be depicted later. The reference environment will be the local environment of the place where the natural gas fired power plant is located which it is assumed in here with ambient temperature T_0= 298.15 K and pressure P_0=101.325 kPa.
As mentioned before, this study is limited to the analysis of the physical exergy and chemical exergy. Other forms of exergy as kinetic and potential are insignificant in these processes so they are ignored. The degradation and consumption of the MEA solvent was neglected in CO_2 capture unit.

4. Base case model

As a base case, the CO_2 separation with MEA absorption model shown in figure1 is designed according to the capture rate that is set to 93%. This capture rate for the base case was attained by MEA wt% of 30%, solvent circulation rate of 2358 t/h and reboiler duty of $6.12 \cdot 10^8$ kJ/h. Reboiler energy consumption is 4.36 (MJ/kg of separated CO_2) which is produced by the steam flow of 76.45 kg/s .Total mechanical work needed for the capture and compression unit is mentioned in Table 1. CO_2 compression was done in 3 stages with adiabatic efficiencies of 85%, 85% and 80% respectively with intermediate cooling after each stage. A pump further raised the pressure from 79.7 bara to 110 bara. The pump adiabatic efficiency was set to 75%.

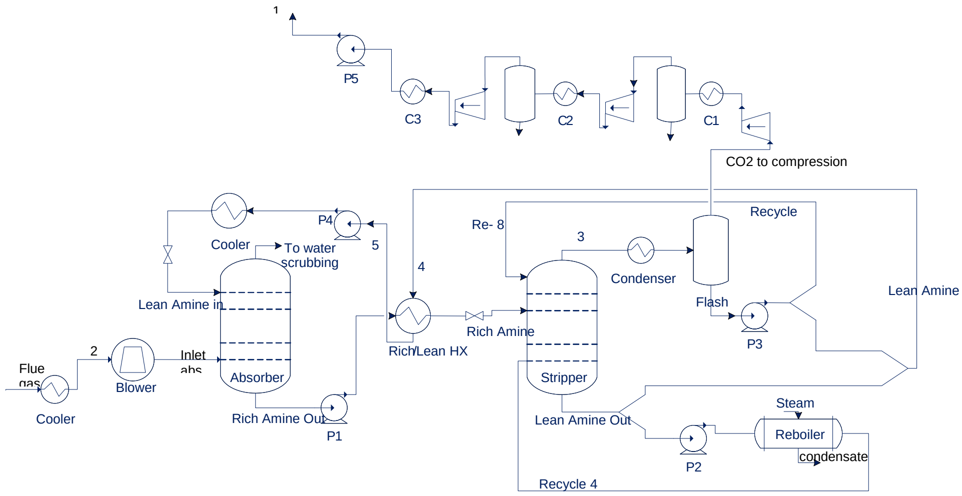

Figure 1: Flow sheet of CO_2 capture and compression units designed by UniSim Design

The virtual power plant that is connected to the CO_2 capture process provides mechanical work to cover the demand of the CO_2 capture unit as well as the steam demand of the regeneration reboiler. A complete schema of the designed combined cycle power plant is shown in Figure 2 with key stream information. The plant key data are shown in table 2.
The fuel was considered as natural gas without H_2S with 722087 kW thermal as lower heating value and flow of stack gas is 686.4 kg/s with molar composition of 3.82% CO_2, 12.54% O_2, 8.24 % H_2O, 75.4% N_2 and temperature of 412.5 K which is going to be cooled in capture unit.

Table 1: Total mechanical work demand for post combustion CO_2 capture plant

Work demand	MJ/kg CO_2 separated
Power production penalty	1.00
compression work	0.30
Auxiliary power	0.16
Total	1.46

Table 2: Power plant summary

	Power Output kW		LHV Heat Rate kJ/kWh		Elect. Eff. LHV%	
	gross	net	gross	net	gross	net
Gas Turbine	291600		8915		40.38	
Steam Turbine	89322					
Plant Total	380922	373761	6824	6955	52.75	51.76

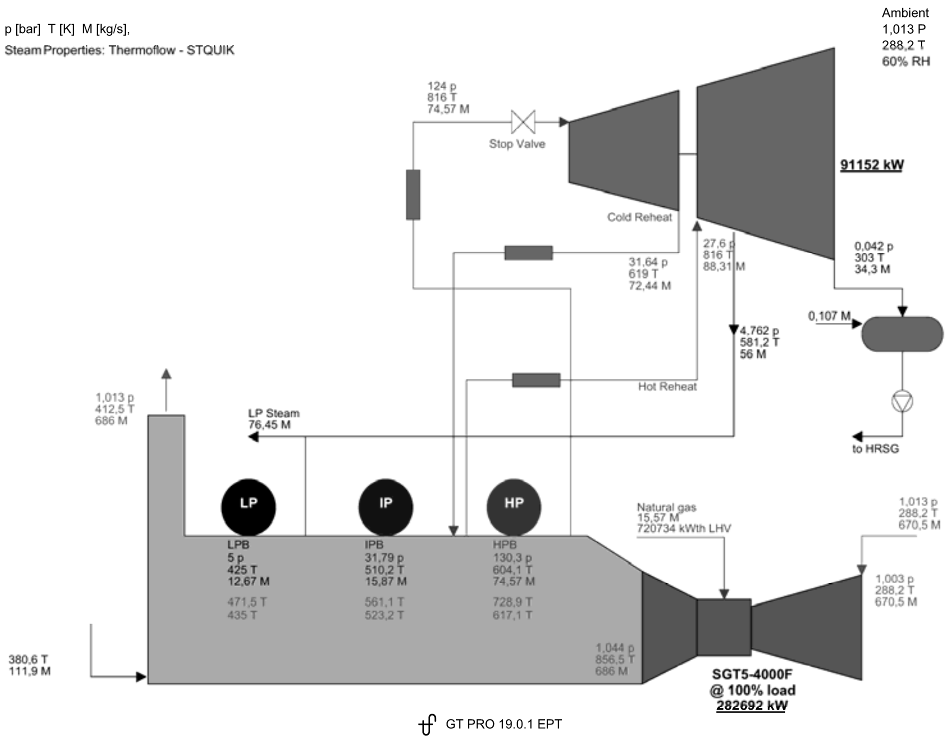

Figure 2: Flowsheet of the designed power plant

5. Results

5.1 Natural gas fired power plant

The results of exergy calculation for specified natural gas fired power plant designed by GTPro Thermoflow software are shown in table 3.

Table 3: Plant exergy analysis

	kW	MJ/kg CO_2 separated
Exergy In	741527	18.88
Fuel exergy	729153	18.56
Ambient air exergy	115.6	0.00
Condenser cooling water in	6228	0.16
Process condensate return	6029	0.15
Makeup water	1.852	0.00
Exergy Out	443391	11.29
Net electric output	373760	9.52
Process steam/water exergy @ delivery	55318	1.41
Condenser cooling water out	1362.8	0.03
Stack gas exergy	12950	0.33

Table 3: Plant exergy analysis (continued)

	kW	MJ/kg CO_2 separated
Exergy Loss	298136	7.59
GT exergy loss	250133	6.37
HRSG exergy loss	20218	0.51
Steam turbine exergy loss	10173	18.88
Condenser exergy loss	6062	18.56
Non-heat balance related auxiliaries	2520.7	0.00
Transformer loss	1904.6	0.16
Miscellaneous exergy loss*	1868.6	0.15
Unaccounted exergy loss**	5257	0.0

* Includes piping loss, ST leakage to external sink, fuel compressor loss, condensate pump loss

** Includes losses from desuperheating, mixing, and throttling, small water streams, misc. aux. and heat rejection

5.2 CO_2 capture plant

The detailed description of CO_2 capture plant has been shown in Figure1. Figures 3a-3c shows a simplified block schema of the absorption unit, desorption unit and compression unit which presents the streams transferring exergy through this subsystems that are material streams and work streams.

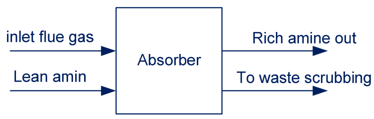

Figure 3.a block scheme for absorption section

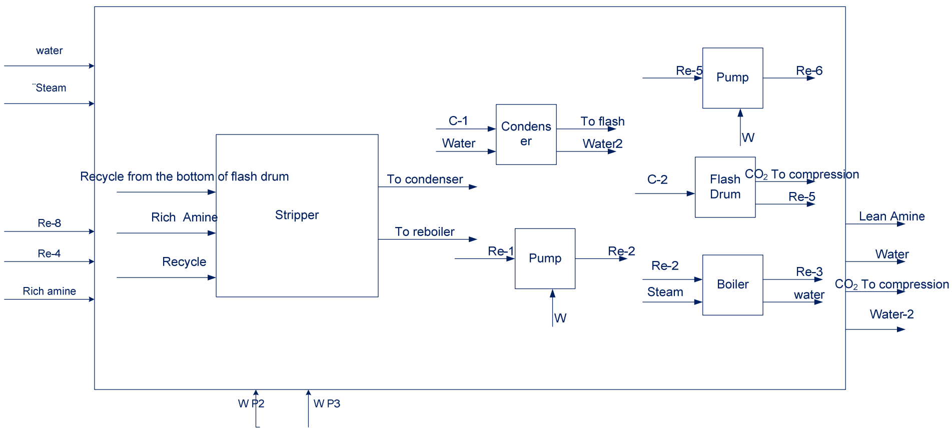

Figure 3.b block scheme for stripping section

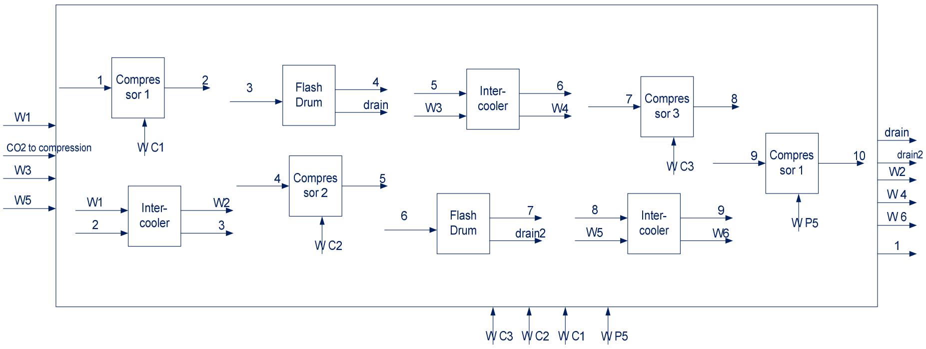

Figure 3.c block scheme for CO2 compression section

In Table 4, physical stream's characteristics and relevant calculated exergy which is used to find irreversibility amounts according to exergy balance formula are shown; it should be noted here that for simulation of streams containing amine component, UniSim Design software (Honeywell 2008) developed a specific property package which predicts behavior of systems containing MEA solvent. For simulation of other streams Peng-Robinson equation of state is used.

Table 4: Themodynamical data and exergy of streams

Stream	Temperature (°C)	Pressure (kPa)	Mass Flow (kg/s)	Exergy (MJ/kg CO_2 separated)
1	24.66	11000.00	39.3	0.49
CO2 to compression	28.00	167.20	39.6	0.49
2	60.00	101.30	686.4	0.39
inlet abs	67.11	107.30	686.4	0.50
Flue gas	100.00	101.30	715.8	0.50
to water scrubbing	46.91	101.30	651.0	0.40
Re-4	150.54	194.00	91.0	16.11
Re-8	28.15	649.97	28.2	0.50
3	103.26	172.37	71.0	1.04
4	119.71	186.20	676.3	115.20
5	57.83	146.20	676.3	112.49
Lean Amine Out	119.74	186.20	764.0	130.69
Steam	176.85	400.00	76.4	2.66
condensate	142.87	392.00	76.4	1.43
Lean Amine in	20.96	107.00	680.5	111.32
Rich Amine Out	49.14	106.30	715.8	112.36
Rich Amine	105.12	180.00	715.8	114.88

Table 5: irreversibility amounts by unit sections

		Irreversibility MJ/kg CO_2
Flue gas cooler		0.14
Blower		0.03
Absorption section		0.42
Rich /lean heat exchanger		0.01
Stripping section:		0.71
	reboiler	0.20
	Flasher(condenser+ flash)	0.69
compression section		0.31
Total		1.62

5. Concluding remarks

Although the exergy loss in CO_2 capture and compression units are rather small comparing to those lost in Gas turbine, HRSG and steam turbine, there are some points of potential improvements. Results show that for current chemical absorption plant, minimum reversible separation work which is calculated based on the approach presented by Cengel et al. (2006) is 0.194 MJ/kgCO_2 and consequently the relevant exergy efficiency is 19.36%. Additionally, current study -as in Table 5- shows that flasher, absorber and reboiler have the most irreversibility amounts and exergy losses. Use of other solvents with lower binding energy is suggested to decrease the exergy loss of reboiler section. In order to minimize the exergy loss, it is important to have uniform exergy degradation along equipments, which can be an optimization idea for the regeneration column, flasher and reboiler. Furthermore in order to divide exergy losses through the absorption column and stripping column, process configuration changes such as stream splitting can be performed (Adisorn, 2005).

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