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Exergy Analysis of Gas Turbine Power Plant with Carbon Capture for Methanation and Storage

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Abstract—*Gas turbine power plants are extensively used due to their capabilities of offering good thermal efficiency and the ability of quick starting. In general, the gas turbine power plants use hydrocarbon type fossil fuels such as natural gas, naptha, methane etc. for combustion and the emissions from them have carbon dioxide as one of the major constituent. The carbon dioxide emitted in combustion leads to the air pollution and global warming. Therefore, it is essential to devise suitable mechanism for handling the carbon dioxide emitted from the power plant. Here, in this paper it is proposed to retrofit the existing gas turbine power plant at Auraiya U.P. with the carbon capture unit to capture the carbon dioxide from the exhaust of the gas turbine and utilize this captured carbon dioxide for the production of methane with the help of methanation unit and polymer electrolyte membrane electrolyzer. Here exergy analysis of gas turbine plant is carried out for quantifying the exergy efficiency and exergy destruction. The study shows that the combustion chamber is one of the critical components of gas turbine plant as it has the highest exergy destruction occurring in it. The energy and exergy efficiency of the gas turbine is found as 40.99% and 38.15% at 12.7 cycle pressure ratio and 1400 K turbine inlet temperature respectively without carbon capture.*

Keywords: Gas turbine, Turbine cooling, Carbon capture and storage, Methanation unit, PEM Electrolyzer.

Nomenclature	
Cp	Specific heat (kJ/kg K)
ex	Specific exergy (kJ/kg)
ex_{ch}	Chemical exergy (KJ/kg)
Ex_d	Exergy destruction (kW)
h	Enthalpy (kJ/kg)
LHV	Low heating value, (kJ/kg)
$\dot{m}_a$	Mass of air, (kg/sec)
$\dot{m}_c$	Mass of coolant, (kg/sec)
$\dot{m}_f$	Mass of fuel, (kg/sec)
$\dot{m}_g$	Mass of gas, (kg/sec)
Nu_g	Nusselt number
Re_g	Reynolds number
s	Entropy (kJ/kg K)
St_g	Stanton number
T	Temperature, (K)
T_b	Permissible blade temperature, (K)
T_c	Temperature of coolant, (K)
T_g	Temperature of gas turbine exhaust, (K)
W_{mcomp}	Compression work of CO2 in methanation unit
x	Molar composition (%)
Z	Fuel air ratio
Greek symbols	
ε_{aw}	Adiabatic wall effectiveness
ƛ	Ratio of cooled surface area to hot gas flow area
η_{II}	Second law efficiency
η_{Pc}	Polytropic efficiency of compressor
η_{Pt}	Polytropic efficiency of turbine
η_c	Transpiration cooling efficiency
η_{cc}	Efficiency of combustion chamber
η_{mech}	Mechanical efficiency
Subscripts	
A	Absorber
C	Compressor
CC	Combustion chamber
CCS	Carbon capture and storage
Con.	Condenser
CO2 Con.	Carbon dioxide condenser
CO2 Comp.	Carbon dioxide compressor
CPR	Cycle pressure ratio
LSP	Lean solution pump
LRHE	Lean rich heat exchanger
PEM	Polymer electrolyte membrane
RSP	Rich solution pump
S	Stripper
T	Turbine
TIT	Turbine inlet temperature

1. INTRODUCTION

Current generation is largely affected by the air pollution and the global warming issues. Apart from various factors, it is significantly contributed by the flue gases from the power plant and the other carbon dioxide generating sources. But the worldwide concern for combating the pollution and global warming the efforts are made for cleaner emissions as well as reducing the emissions. For the existing fossil fuel based power plants, it is quite appropriate to retrofit these power plants with the carbon capture unit. This captured carbon dioxide can be stored under ground to enhance the oil recovery and further this captured CO_2can be utilized for different purposes.

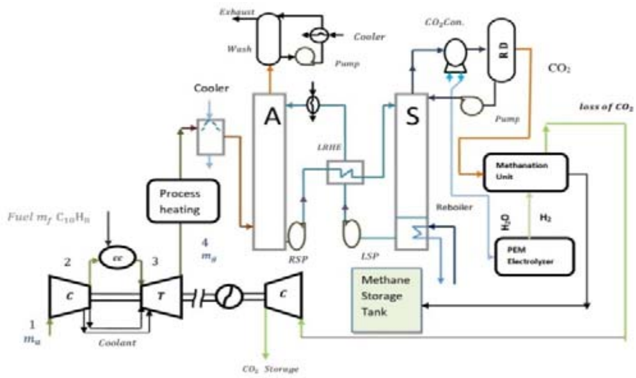
The literature survey shows the effective ways of carbon capture from the gas turbine and suitable utilization of carbon dioxide and the exergetic model of it. Jonshagen et al., [1] studied the use of CO_2 capture unit in a power plant, considering the effect of CO_2 capture and investigated how turbo machinery reacts to exhaust gas recirculation. Boubenia et al. and Stangeland et al. [2], [3] studied the carbon dioxide capture and utilization of captured carbon dioxide, this study also included the polymer electrolyte membrane electrolyzer for conversion of the water into hydrogen and study of CO_2methanation process to convert carbon die oxide to methane. Kumar and Singh [4, 5] presented the investigations on cooling of turbine blades in a gas turbine cycle through the transpiration cooling and film cooling. Ibrahim et. al. [6] showed the exergetic model of gas turbine power plants and comparedit with the energy efficiencies of the power plants. Zare and Hasanzadeh [7] investigated a closed Brayton cycle based combined cycle on the basis of energy and exergy analysis. Nami and Akrami [8] showed the energy, exergy and exergoeconomic analysis of a gas turbine based hybrid system for steam, power and hydrogenproduction.Reddy et. al. [9] showed the exergetic model of natural gas fired combined cycle power plant. Ersayin and Ozgener [10] analyzed the performance of combined cycle gas-steam power plant on basis of energy and exergy analysis.

The objective of the present paper is to analyze the exergy model of the gas turbine unit of the existing combined cycle power plantat Auriaya U.P. with carbon capture and methanation. Study considers the gas turbine unit with carbon dioxide capture system and subsequent utilization of the collected CO_2 for the production of methane by PEM Electrolyzer and Methanation unit. Further, this methane can be used as a fuel to run another gas turbine power plant or for some other purpose.

2. SYSTEM DESCRIPTION

Figure 1 shows the layout of the gas turbine power plant with carbon capture and methnation unit. Gas turbine plant having components as compressor, combustion chamber and turbine is shown in the arrangement. The gas turbine is of cooled type and is cooled through the air transpiration cooling. Air enters to the compressor at state 1 and after compression it goes to the combustion chamber at state 2. This compressed air is sent to combustion chamber with fuel so as to produce high temperature & high pressure combustion products for getting expanded in gas turbine from state 3 to 4.

The exhaust from gas turbine at state 4 is sent to the carbon capture unit for capturing the carbon dioxide and the capture capacity of this carbon capture unit is considered as 90%. This captured carbon dioxide reacts with hydrogen and subsequently methane is produced in the methanation unit. Here the methanation unit compressor is to used to compress this carbon dioxide and hydrogen mixture to a certain pressure and temperature for methane production and polymer electrolyte membrane electrolyzer is used to convert this water in hydrogen. And this produced methane is stored in the storage unit.



C: Compressor, T: Turbine, CC: Combustion Con: Condenser, RSP: Rich Solution Pump, LSP: Lean Solution Pump, LRHE: Lean-Rich Heat Exchanger, A: Absorber, S: Stripper, PEM: Polymer Electrolyte Membrane, C: CO_2 Compressor, RD: Reflux Drum

Figure 1: Layout of gas turbine power plant with carbon Capture unit and methanation unit and PEM electrolyzer

3. THERMODYNAMIC MODELING

Thermodynamic modeling based on first law and second law of thermodynamics involves air compressor, combustion chamber, gas turbine, reboiler, methanation unit, PEM electrolyzer. Mathematical equations involved in thermodynamic modeling of major components of the entire cycle are briefly detailed ahead.

Assumptions for the current study are given as:

- The flow is steady flow.
- Air and combustion products are taken as ideal gas.
- Dead state conditions are taken as P_0=1.3125 bar and T_0=298.15 K.
- Heat transfer between the components of the plant and environment is negligible.

3.1 Gas turbine cycle

Mathematical equations needed for the calculation of performance of components of the gas turbine cycle are given as:

3.1.1 Compressor:

Compressor work is given by energy balance equation:

$$W_{cmp} = \dot{m}_a . h_2 + \dot{m}_c . \dot{h}_c - \dot{m}_a . \dot{h}_1 \quad (1)$$

Exergy destruction by exergy balance equation:

$$Ex_{d1} = W_{cmp} + \dot{m}_a ex_1 - \dot{m}_a . ex_2 - \dot{m}_c . ex_c \quad (2)$$

Where ex_i is specific exergy, given as:

$$ex_i = (h_i - h_0) - T_o(s_i - s_o) \quad (3)$$

3.1.2 Combustion Chamber:

Energy balance for the combustion chamber is given as:

$$m_a . h_2 + m_f . LHV . n_{cc} = m_g . h_3 \quad (4)$$

Exergy destruction for combustion chamber by exergy balance equation:

$$Ex_{d2} = m_a * ex_2 + m_f . LHV . n_{cc} - m_g * ex_3 \quad (5)$$

Chemical reaction in combustion chamber is given as:

$C_{10}H_8 + 12(O_2 + 3.76N_2) \rightarrow 10CO_2 + 4H_2O + 45.12N_2$ (6)

3.1.3 Gas turbine:

Turbine work is obtained by energy balance equation:

$$W_{turb} = \dot{m}_g h_3 + \dot{m}_c \dot{h}_c - \dot{m}_{exh} h_4 \quad (7)$$

Exergy destruction is obtained by exergy balance equation:

$$Ex_{d3} = \dot{m}_g ex_3 - \dot{m}_{exh} . ex_4 + \dot{m}_c . ex_c - W_{turb} \quad (8)$$

Mass of the coolant requirement in transpiration cooling of gas turbine blades is estimated as follows: [4,5]

$$\frac{\dot{m}_c}{\dot{m}_g} = \lambda * St_g * \ln\left[\frac{Cp_g}{Cp_c} * \frac{(T_g - T_o) - \varepsilon_{aw}(T_g - (T_c + \eta_c * (T_b - T_c)))}{\eta_c * (T_{bo} - T_{ci})} + 1\right] \quad (9)$$

3.2 Methanation unit:

Carbon dioxide is converted into methane in the methanation unit and the process is known as Sabatier process.

(Exothermic reaction)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (10)

The conversion reaction is operated at a initial pressure of one atmosphere and temperature of 27 °C. Final temperature and pressure of 300 to 350 °C and 20 bar is required for the process. So compressor is needed to increase the atmospheric pressure and temperature. However an electric heater is also needed for the starting ~~of~~ the procedure.

Compressor work for the methanation process is obtained by the energy balance equation is given as:

$$W_{m,cmp} = \dot{m}_{exit} . \dot{h}_{exit} - \dot{m}_{in} . h_{in} \quad (11)$$

Exergy destruction for the compressor of the methanation unit is given as:

$$Ex_{d,m} = W_{m,cmp} + \dot{m}_{in} ex_{in} - \dot{m}_{exit} . ex_{exit} \quad (12)$$

3.3 PEM Electrolyzer:

Polymer electrolyte membrane Electrolyzer consists of two electrodes, a cathode and an anode and the conversion reactions are given as:

(Anode reaction)

$2H_2O \rightarrow O_2 + 4H^+(aq) + 4e^-$ (13)

(Cathode reaction)

$4H^+(aq) + 4e^- \rightarrow 2H_2(g)$ (14)

H_2O + 237.2 kJ/mole (electricity) + 48.6 kJ/mole (heat) $\rightarrow H_2 + ½ O_2$ (15)

- **Chemical exergies for the combustion gases:**

Chemical exergies of the combustion gases have important role in exergy analysis and the equation used for finding the chemical exergy of the combustion gases is given as [10]:

$$ex_{ch,mixture} = \sum_{i=1}^{n} x_i ex_{ch,i} + RT_0 \sum_{i=1}^{n} x_i \ln.(x_i) \quad (16)$$

To find the molar fraction of gases the following equation is used: [10]

$$Z = \frac{0.058\, \dot{m}_a}{\dot{m}_f} \quad (17)$$

$$x_{N_2} = \frac{7.52 * Z}{1 + 9.6254 * Z} \quad (18)$$

$$x_{O_2} = \frac{2 * (Z - 1)}{1 + 9.6254 * Z} \quad (19)$$

$$x_{CO_2} = \frac{1 + 0.0028 * Z}{1 + 9.6254 * Z} \quad (20)$$

$$x_{H_2O} = \frac{2 + 0.0972}{1 + 9.6254 * Z} \quad (21)$$

- **Second law efficiency of the gas turbine without Carbon capture:**

$$\eta_{II} = \left(\frac{Wnetgt}{Ex_f}\right) \quad (22)$$

TABLE 1 Molar fraction of air [10]

Air components	Molar percentage (%)
N_2	75.67
O_2	20.35
H_2O	3.03
CO_2	0.0345
CO	0.0007
SO_2	0.0002
H_2	0.0005
Others	0.91455

TABLE 2 Molar fraction of combustion product [10]

Combustion product	Molar percentage (%)
N_2	76.31
H_2O	6.765
CO_2	16.91

4. RESULTS AND DISCUSSION:

The results are obtained based on thermodynamic modeling of the considered arrangement with the input parameters given in Table 3

TABLE3 Input parameters [4, 5, 11, 12, 15, 16]

Input Parameters	Value
Compressor polytropic efficiency(%)	90
Compressor inlet temperature (K)	300
Compressor inlet pressure (bar)	1.013
Combustion chamber efficiency (%)	99
Cycle pressure ratio	12.7
Exit pressure of CO_2after carbon capture (bar)	1.013
Exit temperature of CO_2after carbon capture (K)	300
Temperature of CO_2 after compression in methanation unit (K)	623
Turbine inlet temperature (K)	1400
Turbine polytropic efficiency (%)	92
Mass flow rate of air (kg/sec)	400
Mass flow rate of naphtha fuel (kg/sec)	8.055
Mechanical efficiency (%)	99
LCV for naphtha fuel (KJ/kg)	44900
LCV for methane gas (KJ/kg)	50000
Permissible Blade temperature (K)	1080
Transpiration cooling efficiency (%)	0.75
Adiabatic wall effectiveness	0.4
Reynolds number	1.6×10^6
Prandtl number	0.7
Reboiler pressure (bar)	1.2
Reboiler temperature (^oC)	140

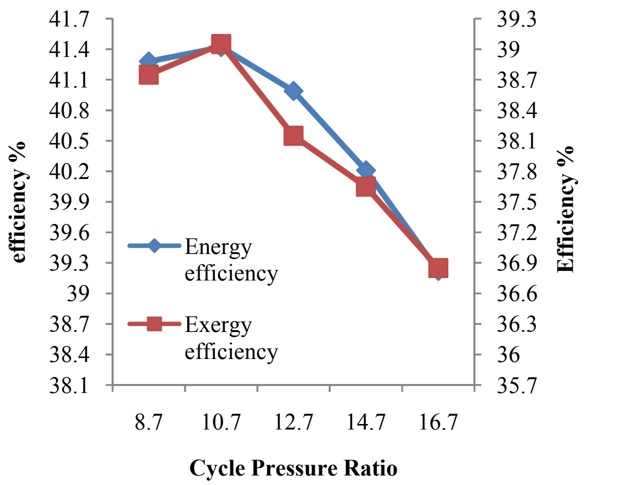


Figure 2: Exergetic efficiency and energy efficiency of gas turbine power plant without carbon capture at TIT 1400 K with varying cycle pressure ratio

Figure 4 shows the energy and exergy efficiency of the gas turbinepower plant at different cycle pressure ratios. The energy and exergy efficiency are found as 40.99% and 38.15% at 12.7 cycle pressure ratio and 1400 K turbine inlet temperature respectively without carbon capture. 10.7 cycle pressure ratio showing optimum point for the energy and exergy efficiency.

Type of stream	Temperature (K)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Specific exergy (kJ/kg)
Air	300	1.01325	300.4	5.7	0.6398
Air	674.5	12.7	686	5.79	359.4
Combustion product	1400	12.7	1593	7.554	979
Combustion product	781.3	1.2	880	7.66	234.4
Mixture for methanation	300	1.01325	1048.94	13.98	611.2492
Mixture for methanation	627	20	431.28	14.002	0.1485
Steam	413	1.2	2755.1	7.48	529.57

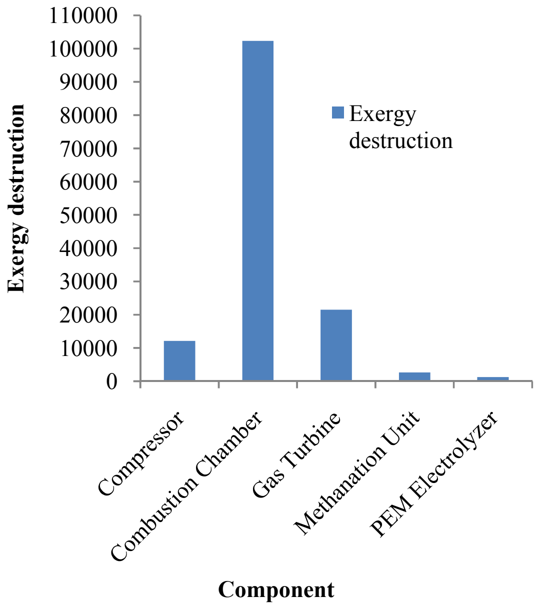


Figure 3: Exergy destruction of different components of the power plant.

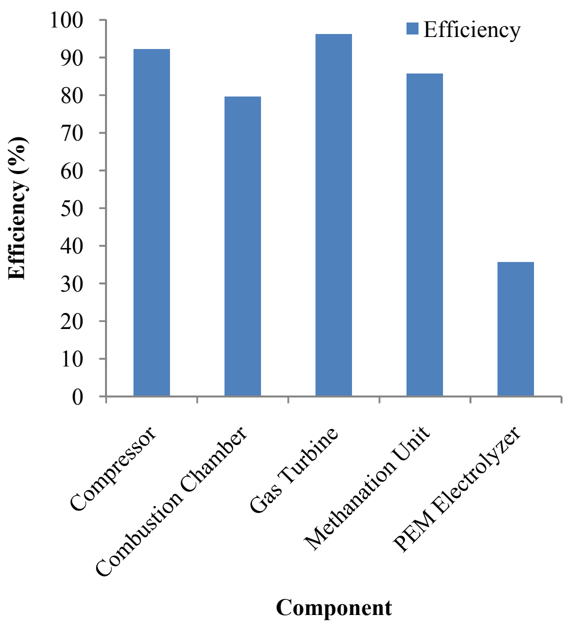


Figure 3: Exergetic efficiency of different components of the power plant.

Figure 2 and 3 show the exergy destruction and exergetic efficiency of different components of the gas turbine power plant with carbon capture for methanation and storage. Results indicate that combustion chamber is one of the critical components of gas turbine plant as it has the highest exergy destruction of 102324 KW occurring in it. The PEM electrolyzer having less exergy efficiency of 35.55 % and exergy destruction of 1349 KW.

5. CONCLUSIONS:

Conclusions obtained on the basis of energy and exergy analysis of the gas turbine power plant with carbon capture for methanation and storage areas under.

- On the basis of exergy analysis, combustion chamber is one of the critical components of gas turbine plant as it has the highest exergy destruction due to high irreversibility during combustion process.
- PEM electrolyzer is having least exergetic efficiency and less exergy destruction.
- Retrofitting carbon capture system in existing power plant reduces the carbon emission to the atmosphere. And utilization of this captured carbon dioxide in methane has the potential to meet the fuel requirement or any other requirement.

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