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Energy Analysis of Combined Cycle Power Plant Using First Law of Thermodynamics

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Abstract: This paper gives a detailed explanation about the exergy analysis and the energy efficiencies of a combined cycle power plant. Energy analysis of an active CCPP (Combined Cycle Power Plant) is performed with the help of the actual operating data taken from the computer control unit of the plant. For the thermo dynamical performance assessment of the plant, energy analysis, related with the first law of thermodynamics is performed.
Keywords: Exergy, Energy, First law, Combined cycle power plant, condenser

I. INTRODUCTION

Gas-turbines usually operate on an open cycle, A compressor takes in fresh ambient air (state 1), compresses it to a higher temperature and pressure (state 2).Fuel and the higher pressure air from compressor are sent to a combustion chamber, where fuel is burned at constant pressure. The resulting high temperature gases are sent to a turbine (state 3). The high temperature gases expand to the ambient pressure (state 4) in the turbine and produce power. The exhaust gases leave the turbine.

By utilizing the air-standard assumptions, replacing the combustion process by a constant pressure heat addition process, and replacing the exhaust discharging process by a constant pressure heat rejection process, the open cycle described above can be modeled as a closed cycle, called ideal Brayton cycle. The ideal Brayton cycle is made up of four internally reversible processes.

1) 1-2 Isentropic compression (in a compressor)
2) 2-3 Constant pressure heat addition
3) 3-4 Isentropic expansion (in a turbine)
4) 4-1 Constant pressure heat rejection

A. *Steam Turbine*

1) Steam separately coming from H.P. section and L.P. section of HRSG goes seprately to H.P. Turbine and L.P. Turbine. As we know L.P. and H.P. Turbines are both connected in series to each other and they both ar e in series with steam generate.this is the bottom in cycle of plant.
2) Steam entering H.P. turbine at high pressure(48 kg/cm^2) and high temp after coming from and superheater section of H.P. section of HRSG comes out with considerably lower pressure and lower temp. So it requires to increase its temprature for that purpose it is again transferred to Reheater section i.e. super heater and then it is passed through compressors of L.P. turbine at considerably lower pressure than H.P. around (5 kg/cm^2) i.e. four times lower than H.P . In this way L.P. turbine result of this ,starts rotation. since both are connecting in series with each other , steam generator generates power.
3) since we are producing steam which further is used to generate electricity along with electricity generation with Gas turbine, this act is called cogeneration. It help in improving plant efficiency from 35% to approx 60%.

II. LITERATURE REVIEW

The gas turbine engine is characterized by its relatively low capital cost compared with steam power plants. It has environmental advantages and short construction lead time. However, conventional industrial engines have lower efficiencies especially at part load. One of the technologies adopted nowadays for improvement is the combined cycle. Hence, it is expected that the combined cycle continues to gain acceptance throughout the world as a reliable, flexible and efficient base load power generation [1]. Combined-cycle systems utilizing the Brayton Cycle gas turbine and the Rankine Cycle steam system with air and water as working fluids achieve efficient, reliable, and economic power generation. Flexibility provided by these systems satisfies both utility-power generation and industrial-cogeneration applications. Current commercially available power- generation combined-cycle plants achieve net plant thermal efficiency typically in the 50–55% LHV range. Further development of gas turbine, high-temperature materials and hot gas path, metal surface cooling technology show promise for near-term future power generation combined-cycle systems capable of reaching 60% or greater plant thermal efficiency. Additional gas turbine technological development, as well as increases in steam-cycle pressure and temperature and steam-turbine stagedesign enhancement, is expected to achieve further STAG™ combined cycle efficiency improvement. Current General Electric STAG™ (trade name designation for the GE product line of combined- cycle systems) product line offerings, combined-cycle experience, and advanced system development are used to demonstrate the evolution of combined-cycle system technology [2].

III. DIFFERENT OPERATING PARAMETERS AFFECTING PERFORMANCE OF CCPP

The major operating parameters which influence the combined

A. Cycle performance
B. Turbine inlet temperature
C. Compressor pressure ratio
D. Pinch point
E. Ambient Temperature
F. Pressure levels

IV. PERFORMANCE ANALYSIS OF DCCPP

In this study. Currently GT 1 and HRSG#1 are active while GT 2 and HRSG#2 are both inactive, so thermo-physical properties is available only for GT1 and HRSG#1. Energy analysis of an active CCPP (Combined Cycle Power Plant) is performed with the help of the actual operating data taken from the computer control unit of the plant. For the thermo dynamical performance assessment of the plant, energy analysis, related with the first law of thermodynamics is performed.
Some assumptions are made during the calculations. These assumptions can be given as,

A. The flow is steady state.
B. Air and combustion products are assumed as ideal gas. Molar fractions of the components of air and combustion products are shown in Tables2 and 3 respectively.
C. Dead state conditions are taken as P_0 =101.325kPaand T_0=298.15K.
D. Heat transfer between the components of plant and environment is negligible.

In the following section, performance analysis methods are explained. The equations, thermo physical properties of the working fluids and the thermo dynamical analysis of the components of power plant are given in the following parts. Given equations are used for parametric analysis of the system and obtained results are compared with actual operating results.

V. ENERGY ANALYSIS (USING FIRST LAW OF THERMODYNAMICS)

Thermodynamical performance analysis of the DCCPP can be evaluated by dividing the system into two discrete section. First section is called as top cycle and second section is called as bottom cycle.

A. Top cycle

In the studied system, top cycle works according to **Brayton cycle** principle. Required equations for the calculation of the components of top cycle are given below [28].

1) Compressor

$$T_2 = T_1\left(1 + \frac{1}{\eta_{AC}}\left(r_{AC}^{\frac{k-1}{k}} - 1\right)\right) \tag{1}$$

$$\dot{w}_{AC} = \dot{m}_a C_{pa}(T_2 - T_1) \tag{2}$$

$$C_{pa}(T) = 1.048 - \left(\frac{1.83}{10^4}\right)T + \left(\frac{9.41}{10^7}\right)T^2 - \left(\frac{5.49}{10^{10}}\right)T^3 + \left(\frac{7.92}{10^{14}}\right)T^4 \tag{3}$$

In Eq. (1), T1 and T2 denote the temperature of the air at the intet and outlet sections of the compressor respectively. r is the pressure ratio of compressor while k is the ratio of specific heats. Eq. (2) is used to calculate consumed power by the compressor. Eq. (3) gives the specific heat of the air according to the changing temperatures.
using data:T_2=345ºC=618K, T_1 =39ºC=312K, r=8.1/1.013=7.99, k=1.4 and $\dot{m}_a$=165.5 kg/s

using equation 1 and 2 , It is found out that, η_{AC}(efficiency of air Compressor)= 82.8%.
First we calculate heat capacity at constant pressure with changing temperature from equation 3 which comes out to be 1.005 kj/kg-K ,then by using equation 3,power consumed by air compressor(17 stages) is calculated. Hence,
Work done by compressor on air = 50.70 MW. Since it is having stage no=17. A few KWs something approx. 298.25 KW motor is required for intially make Compressor start working ,then it is not required to provide power, it would be running continuously.

2) Combustion chamber

$$\dot{m}_a h_2 + \dot{m}_f\, LHV = \dot{m}_g h_3 + (1 - \eta_{CC})\, \dot{m}_f LHV \quad (4)$$

In Eq. (4), LHV(lower heating value)has variable values with regard to the specification of the fuel provided by the supplier. It is found that LHV(Lower Heating Value) for Natural Gas is 47,141kj/kg.
using following data, $\dot{m}_a$=165.5 kg/s, $\dot{m}_f = 3.3 kg/s$, h_2=627, h_3=1381.27 kj/kg, C_{pg}=1.08 kj/kg-^{0}C, $\dot{m}_g = 168.8 kg/s$
$using\ equation$ 4, $\eta_{I,CC}$ = 83.17%

3) Gas Turbine

$$T_4 = T_3\left(1 - \eta_{GT}\left(1 - \left(\left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}\right)\right)\right) \quad (5)$$

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \quad (6)$$

$$\dot{w}_{GT} = \dot{m}_g C_{pg}(T_3 - T_4) \quad (7)$$

In Eq. (5), T3 and T4 are the turbine inlet and outlet temperatures of combustion gases respectively. From equation,We can calculate with what efficiency thermodynamically, gas turbine is working. using data:T_4=574^{o}C=618K, T_3 =1150^{o}C=1423K, $\frac{P_4}{P_3}$=1.013/8.1=1/7.99=0.1251, k=1.4 and $\dot{m}_a$=165.5 kg/s, $\dot{m}_f$ = 3.3 kg/s, $\dot{m}_g$ =168.8 kg/s, C_{pg}=1.09 kj/kg-^{0}C, from equation 5,
$\eta_{GT,ideal}$ = 90.37%
from equation 7,design capacity of GT=110MW, $\dot{w}_{total,GT}$ =power which is supposed to be generated by Gas Turbine=105.98 MW
$\dot{w}_{net,GT=}$ Actual Power generation from Gas Turbine=74MW

B. Bottom Cycle

In the analyzed system, heat recovery steam generators, steam turbine, pumps and condenser are the main equipments of the bottom cycle. Working principle of the bottom cycle is Rankine cycle. Required equations for the calculation of the components of the bottom cycle are given below.

1) HRSG

$$\dot{m}_{w,HP}(h_9 - h_{13}) = \dot{m}_g C_{Pg}(T_4 - T_b) \quad (7)$$

$$\dot{m}_{w,LP}(h_{10} - h_{14}) = \dot{m}_g C_{pg}(T_b - T_{17}) \quad (8)$$

In Eq. (7), subscript numbers 9 and 13 denote the temperature of water that enters and leaves the high-pressure section, b subscript denote the flue gas. In Eq. (8), subscript numbers 10 and 14 indicate the temperature of water for inlet and outlet of the intermediate/low pressure section.
using following data, $\dot{m}_{w,HP} = 44.77 kg/s$, $\dot{m}_{w,LP} = 4.5\ kg/s$, h_9=3430, h_{13}=572.6 kj/kg,
, h_{10}=2855 kj/kg , h_{14}=551.8kj/kg , C_{pg}=1.08 kj/kg-^{0}C, T_4=574^{o}C, T_{17} = 195.7°C
By solving both equation 7 and equation 8 for two variables $\dot{m}_g\ and\ \dot{m}_g T_b$, we get solution
T_b =224.36^{o}C, $\dot{m}_g = 338 kg/s$

2) Steam Turbine

$$\dot{w}_{ST} = \dot{m}_{w,HP} h_9 + \dot{m}_{w,LP} h_{10} - \dot{m}_{w,total} h_{19} \quad (9)$$

using following data , $\dot{m}_{w,LP} = 4.5\ kg/s, \dot{m}_{w,HP} = 44.77 kg/s,$, h_{10}=2855 kj/kg , h_9 = 3430 kj/kg
$\dot{m}_{w,total} = 49.27 kg/s\ and\ h_{19}$= 2708.7 kj/kg , from equation (9),
$\dot{w}_{total,ST=}$Total power supposed to be generated from steam turbine= 68.35 MW
$\dot{w}_{net,ST}$ =actual power generation in Steam Turbine =34.82MW

3) Condenser

$$\dot{Q}_{Cond} = \dot{m}_{19}h_{19} - \dot{m}_{20}h_{21} \quad (10)$$

By using following data, $\dot{m}_{19} = 49.2 kg/s$, $\dot{m}_{20} = 49.2 kg/s$, $h_{19} = 206.03 kj/kg$ and $h_{20} = 201.2\ kj/kg$

heat loss from cooling towers= Heat exchange rate in condensor =119KW(As Waste heat)

4) Pump

$$\dot{w}_{pump,HP} = \dot{m}_{w,HP}h_{23} - \dot{m}_{w,HP}h_{22} \quad (11)$$

$$\dot{w}_{pump,LP} = \dot{m}_{w,LP}h_{23'} - \dot{m}_{w,LP}h_{22'} \quad (12)$$

Using data, $\dot{m}_{w,HP} = 44.77\ kg/s$, $h_{23'} = 203.04\ kj/kg$, $h_{22'} = 201.7 kj/kg$, $h_{23} = 213.5 kj/kg$ and $h_{22} = 201.7\ kj/kg$, from equation (11)and equation (12),

power consumption by H.P. pumps=527.46 KW

power consumption by L.P. pumps=6.03KW

As well as realizing energy analysis for the components of the CCPP, first law analysis of the whole CCPP can be carried out by using the following equations.

5) First law Efficiency

$$\eta_{I,GT} = \frac{\dot{w}_{net,GT}}{\dot{m}_f LHV} \quad (13)$$

$$\eta_{I,CCPP} = \frac{\dot{w}_{net,ST} + \dot{w}_{net,GT}}{\dot{m}_f LHV} \quad (14)$$

using data, $\dot{w}_{net,GT} =$ 74 MW(actual power output), $\dot{m}_f = 3.3\ kg/s$, $LHV = 47{,}141\ kj/kg$, $\dot{w}_{net,ST} = 34.82$ MW(actual power output)

Overall Gas Turbine Efficiency according to First Law of Thermodynamics ,$\eta_{I,GT}$ =46.74%

Overall Combined Cycle Efficiency according to First Law of Thermodynamics ,$\eta_{I,CCPP}$ = 69.8% .

V. RESULTS AND DISCUSSIONS

According to the calculations first law efficiencies of the top cycle and CCPP system are found as 46.74and 69.8% respectively. Figure depicts the first law efficiencies of top cycle and whole CCPP system.

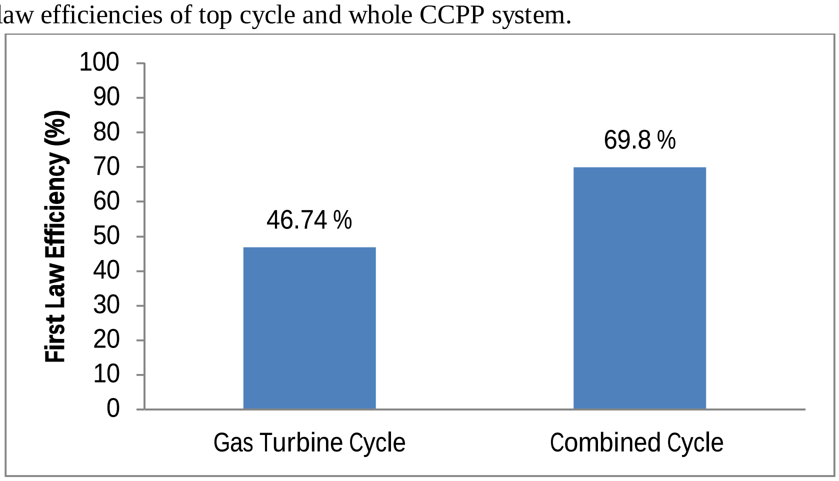

Fig 1: Comparison between First Law efficiencies of Gas Turbine and Combined Cycle

VI. CONCLUSION

Combined cycle power plants meet the growing energy demand, and hence special attention must be paid to the optimization of the whole system. Developments for gasification of coal and use in the gas turbine are in advanced stages. Once this is proven, Coal as the main fuel can also combined cycle power plants meet the growing energy demand, be used in the combined cycle power plant. The advances in cogeneration-the process of simultaneously producing useful heat and electricity from the same fuel source-which increases the efficiency of fuel burning from 30% to 90%, thereby reducing damage to the environment while increasing economic output through more efficient use of resources.

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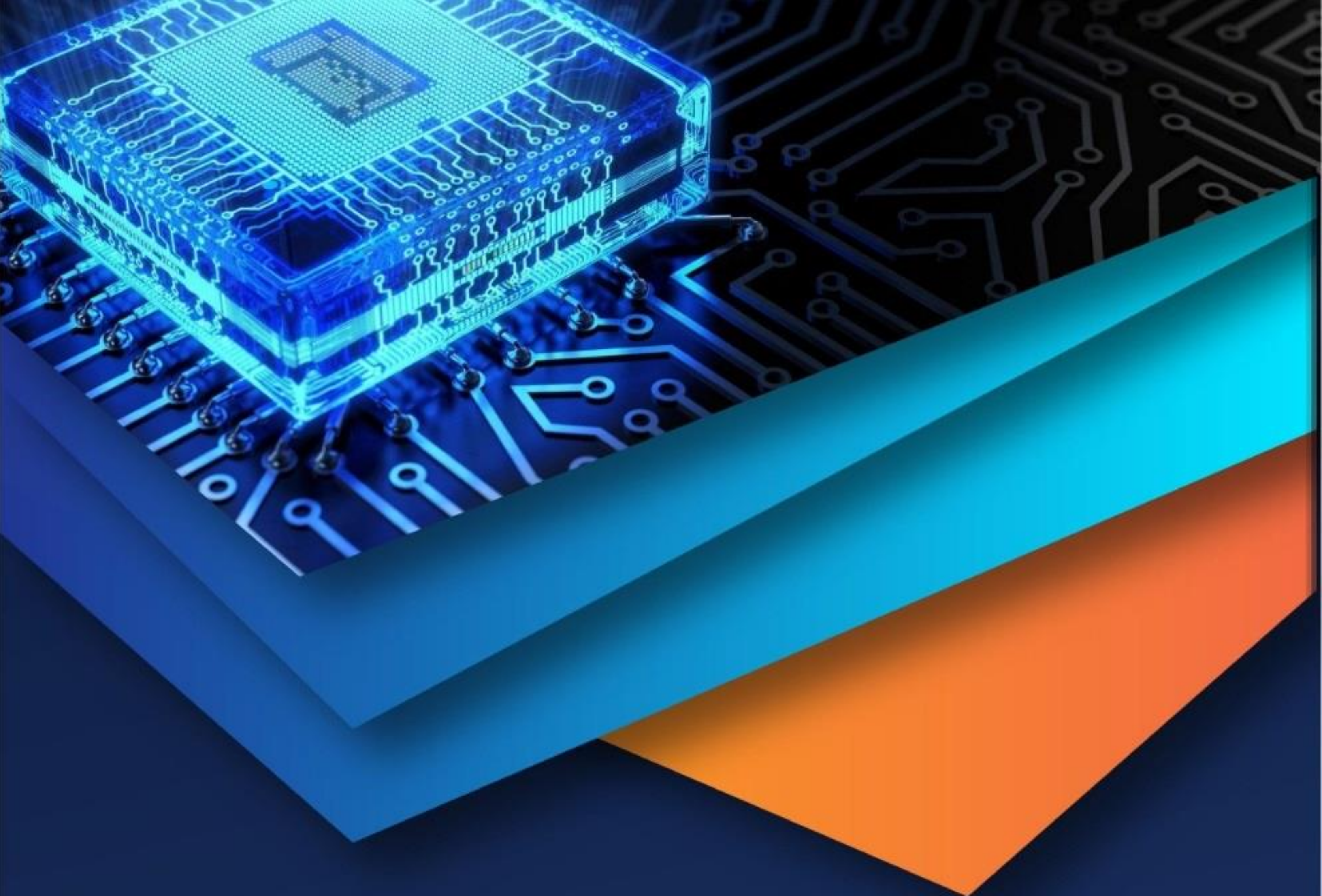

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