ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

SIMULATION AND EFFECT OF OPERATING VARIABLES ON THE OVERALL THERMAL EFFICIENCY OF COMBINED CYCLE POWER PLANT

Bijendra Singh[1], K. P. Tyagi[2] and Kishor Patil[1]
[1]MIT-Bulandshahr, India
[2]KIET-Ghaziabad, India
E-Mail: bijendramit@gmail.com

ABSTRACT

Combined cycle power plant of gas turbine topping cycle and steam turbine bottoming cycle, are widely used due to their high efficiencies. Combined cycle cogeneration has the possibility to produce power and process steam more efficiently, leading to higher efficiency and reduction in green house emission. The objective of present work, is to simulate and analyze a natural gas fired combined cycle cogeneration unit and to investigate the effect of operating variables on the overall efficiency. The operating variables include compressor inlet temperature, gas turbine inlet temperature, exhaust temperature of gas, inlet temperature of steam and pinch point.

Keywords: turbines, combined cycle power plants, HRSG, thermal efficiency, temperature, pinch point.

Nomenclature

c = Compressor
CC = Combution chamber
GT = Gas turbine
ST = Steam Turbine
HRSG = Heat recovery steam generator
r_p = Pressure ratio.
T = Temperature K orC°
p = Pressure bar
CV = Calorific value of fuel
f = Fuel
m_g = Mass flow rate of gas
m_s = Mass flow rate of steam
m_a = Mass flow rate of air
C_{pg} = Specific heat of gas
C_{pa} = Specific heat of air
P_{st} = Power output of staem turbine
P_{gt} = Power output of gas turbine
h = Specific enthalpy Kg

Greek Letters

η_c = Efficiency of compressor
η_{st} = Efficiency of steam turbine
η_{gt} = Efficiency of gas turbine
η_o = Overall efficiency of combined cycle

INTRODUCTION

The combined cycle is the combination of two or more thermal cycles, in a single power plant. Normally the cycles can be classed as a "topping" and "bottoming" cycles. The first cycle to which heat is supplied from combustion chamber is called "toping cycle". The waste heat produces, and then it is utilized in a second process which operates at a lower temperature and is therefore referred to as a "bottoming "cycle. Careful selection of the working media makes it possible to create an overall process that makes optimum thermodynamic use of the heat in the upper range of temperatures and returns waste heat to the environment at low temperature level as possible. The topping and bottoming cycles are coupled through a heat recovery steam generator (HRSG).

At present only one combined cycle has found wide acceptance: the combination of gas turbine/steam turbine power plant. In these plants liquid fuels or gases are burnt. There are two main reasons of wide acceptance of gas and steam power plants.

- It is made up of components already existing in power plants with a single cycle. Therefore development costs are low.
- Air is non problematic and inexpensive medium that can be used in modern gas turbine at higher temperature level. That provides the optimum prerequisites for a good topping cycle.

In bottoming cycle, water is used which is inexpensive and widely available. The waste heat from a modern gas turbine has a temperature level beneficial for a good steam process. In recent years have gas turbines attained inlet temperatures that make it possible to design a very high efficiency cycle. Today the installed power capacity of combined cycle gas turbine and steam turbine power plant is more than 30000 MW [1].

METHODOLOGY

In a combined cycle power plant (CCPP), or combined cycle gas turbine (CCGT) plant, a gas turbine generator generates electricity and waste heat is used to make steam to generate additional electricity by a steam turbine. Most new gas power plants in North America and Europe are combined cycle power plant. In a thermal power plant, high-temperature heat as input to the gas turbine, usually from burning of fuel, is converted to electricity as one of the outputs and exhaust from the gas turbine is used as input to the steam turbine through HRSG [2]. The schematic diagram of combined cycle and temperature entropy diagram is shown in Figures 1 and 2.

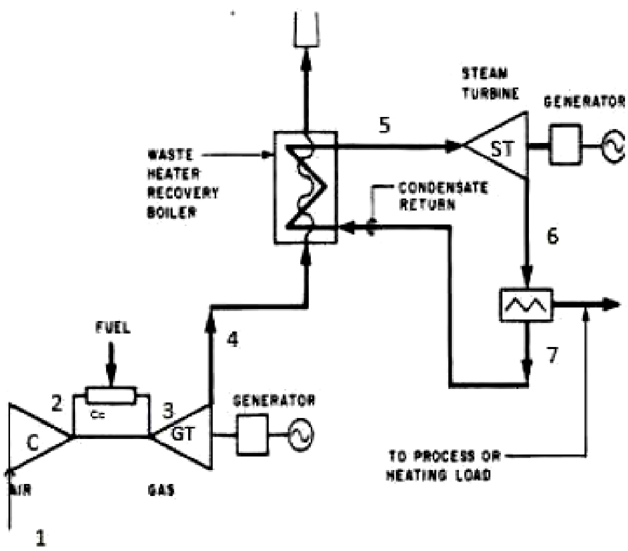

Figure-1. Schematic diagram of combined cycle power plant.

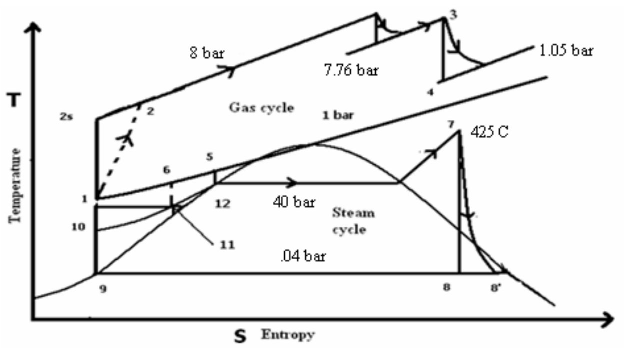

Figure-2. Temperature-entropy diagram of combined cycle power plant.

Effect of operating variables

The variables that affect the overall efficiency of the combined cycle power plant are listed below.

Inlet temperature of air to the compressor $= T_1 K$, $298\ K$

Inlet pressure of the air to the compressor $= p_1$ bar, 1 bar

Pressure Ratio of the compressor $(p_2/p_1) = r_p$, 8

Efficiency of the compressor $= \eta_c$, 0.88

Pressure drop in the combustion chamber = 3 %

Maximum gas temperature at inlet to the gas turbine = $T_3 K$

Efficiency of gas turbine $= \eta_{gt}$, 0.88

Inlet pressure of steam in steam turbine = p_7 bar, 40 bar

Inlet Temperature of steam in steam turbine = $T_7 K$, 698K

Efficiency of Steam Turbine = η_{st}, 0.82

Condenser pressure = p_8 bar, 0.04 bar

Steam Flow Rate = $m_s \frac{Kg}{S}$, $29.235\ \frac{Kg}{S}$

Feed water temperature to the HRSG = T_{11}, 170.4 °C

Pressure drop of gas in the HRSG = 5KPa

Calorific value of fuel = $44.43 \frac{MJ}{kg}$

Specific heat of air = $1.006 \frac{KJ}{kgK}$

Specific heat of gas = $1.33 \frac{KJ}{kgK}$

Specific heat ratio of air = 1.4

Thermodynamic analysis

Considering gas turbine plant:

Process 1 -2 $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma\eta_c}}$

Putting $\gamma = 1.4$ and $\frac{P_2}{P_1} = r_p$ Compression Ratio

$$T_2 = T_1 \left[r_p^{\frac{0.2857}{\eta_c}}\right] \quad (1)$$

Considering

Combustor Process 2-3: Pressure drop = $0.03 \times p_2$

$p_3 = 0.97\ p_2$

Let the flow rate of combustion gas be 1kg /s and that of fuel f kg /s so flow of air = (1-f) kg/s

Therefore,

$$f \times CV = 1 \times C_{pg} (T_3 - T_1) - (1-f)\, C_{pa} (T_2 - T_1)$$

After solving it $f = \frac{1.148T_3 - 1.006T_3 - 0.142T_1}{(44430 - 1.066(T_2 - T_1))}$

Now

Air fuel ratio $\frac{1-f}{f} = \frac{44430 + 1.148\,(T_1 - T_2)}{1.148T_3 - 1.006T_2 - 0.142T_1}$ (2)

Considering process 3-4

$$p_4 = 1 + 0.05 = 1.05 \text{ bar}$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{(\gamma-1)x^{\eta_{gt}}/\gamma}$$

$$T_4 = \frac{T_3}{\left((0.9238 r_p)^{0.2498\eta_{gt}}\right)}$$

(p_1=1 bar)

Considering HRSG (Heat recovery Steam Generator)

Let the pinch point difference $T_5 - T_{12} = \Delta t$

Now from energy balance equation

$$m_g \times C_{pg} \times (T_4 - T_5) = m_s (h_7 - h_{12})$$

VOL. 5, NO. 12, DECEMBER 2010 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

$$m_s = m_g \times 1.148\frac{T_4 - T_5}{h_7 - h_{12}}$$

$$m_s = 1.148\left(\frac{\frac{T_3}{(0.9238r_p)^{0.2498\eta_{gt}}} - (\Delta t + t_{12})}{h_7 - h_{12}}\right)$$

Power output of steam turbine

$$P_{st} = m_s(h_7 - h_8)\eta_{st}$$

Now mass flow rate of Gas Turbine

$$m_g = \frac{m_s \times (h_7 - h_{12})(0.9238r_p)^{0.2498\eta_{gt}}}{1} .148\left(T_3 - (\Delta t + T_1)(0.9238r_p)^{0.2498\eta_{gt}}\right)$$

Air flow rate entering the compressor

$$m_a = (1 - f) \times m_g$$

$$= \frac{44430 + 1.148\,T_1 - 1.148T_3}{44430 - 1.006(T_2 - T_1)}$$

Power output from the gas turbine

$$P_{gt} = m_g \times 1.148 \times (T_3 - T_4) - m_a \times 1.006(T_2 - T_1)$$

Total power output = $P_{st} + P_{gt}$

$$= m_s(h_7 - h_8)\eta_{st} + m_g \times 1.148(T_3 - T_4) - m_a \times 1.006(T_2 -$$

(3)

Overall efficiency

$$\eta_o = \frac{P_{st} + P_{gt}}{f \times m_g \times 44430} \quad (4)$$

After putting the value of f, P_{st}, P_{gt}, and m_g in (4) one gets the overall efficiency of combined cycle power plant.

RESULTS

1. Effect of air inlet temperature of compressor on the overall efficiency

With the help of equation (4) we see the effect of different variables on the overall efficiencies.

We considered the variables air inlet temperature in the compressor, by substituting the values of all variables except air inlet temperature T_1 we get the equation.

$$\eta_o = \frac{7162537641 - 11691522.72T_1 - 307.97{T_1}^2}{198424.38 \times (44430 - 0.97T_1)} \quad (5)$$

Table-1

T_1 (K)	283	286	288	293	298	303	308	313	318	323
η_o (%)	43.7	43.33	43.03	42.35	41.68	41.01	40.33	39.66	38.99	38.33

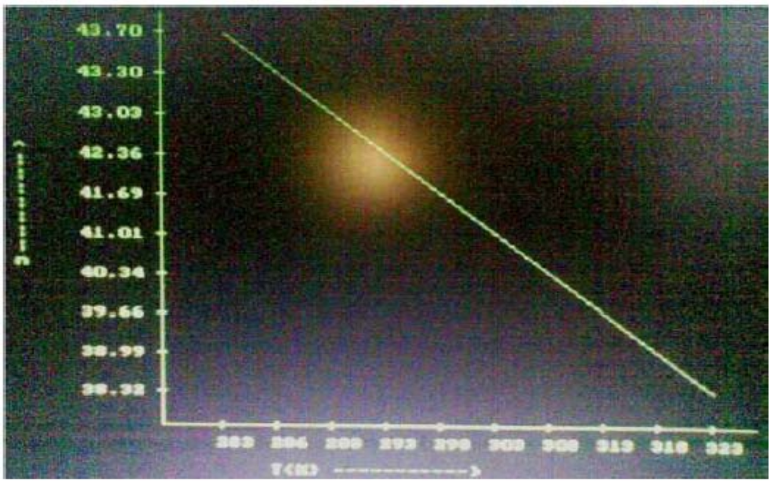

Figure-3. Effect of Air inlet temperature of compressor on overall efficiency.

2. Effect of gas turbine inlet temperature

We considered the variables gas turbine inlet temperature T_3, similarly by putting the values of all variables except gas turbine inlet temperature T_3 we get the equation.

$$\eta_o = \frac{47926.12T_3 - 37095557.65}{(1.148T_3 - 631.83) \times 64299.1} \quad (6)$$

 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-2

T_3(K)	1173	1198	1223	1248	12 73	1323	1373	1673	1773	1873
η_o (%)	41.60	42.51	43.33	44.11	44.89	46.13	47.27	51.99	53.05	53.95

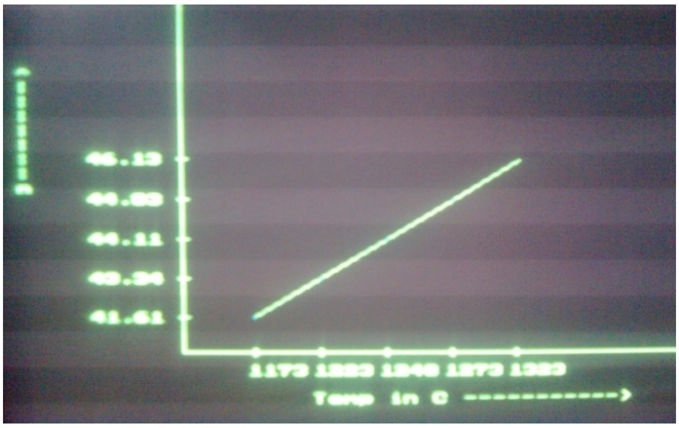

Figure-4. Effect of gas turbine inlet temperature on overall efficiency.

3. Effect of pinch point

The temperature difference between the exhaust temperature of toping cycle and inlet temperature of bottoming cycle is called pinch point, which is generally in the range of 15 C° to 30 C°. Here difference between $T_5 - T_{11}$ is the pinch point which is normally kept 15 to 30 °C.

By substituting the value of all variables in equation 4 except pinch point we get the following equation.

$$\eta_o = 0.4374951 - 0.000721\Delta t \quad (7)$$

Table-3

Δt(^{0}C)	5	10	15	20	25	30
η_o (%)	43.38	43.02	42.66	42.30	41.94	41.58

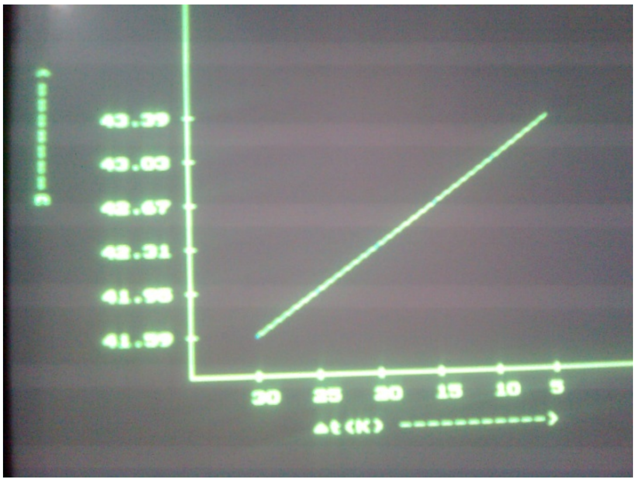

Figure-5. Effect of pinch point on overall thermal efficiency.

4. Effect of inlet temperature and pressure of steam turbine on overall efficiency of combined cycle

By substituting the value of all variables in equation (4) except enthalpy of inlet steam in the turbine we get the following equation.

$$\eta_o = 0.27055 + 0.2641\frac{(h_7 - h_8)}{h_7 - 1087.31} \quad (8)$$

Table-4

Pressure (bar)	35	40	45	50	55	60	60
Temperature (^{o}C)	400	425	450	475	500	525	540
Efficiency ηo (%)	41.42	41.66	41.84	42.03	42.19	42.34	42.35

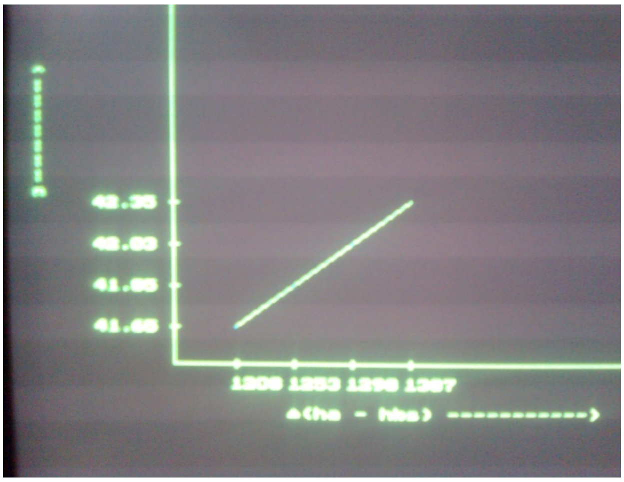

Figure-6. Effect of Inlet temperature and pressure of steam turbine on overall efficiency of combined cycle.

CONCLUSIONS

a) From equation 5 and graph we can conclude that if air temperature increases the overall efficiency of the combined cycle plant decreases. Because

- Increasing the air temperature reduces the density of air, and there by reduces the air mass flow drawn in.
- The power consumed by the compressor increases in proportion to the inlet temperature without their being a corresponding increase in the output from the turbine.
- In combined cycle plant as a function of air temperature with ambient conditions remaining otherwise unchanged. As its shows, an increasing in air temperature even has a slightly positive effect on the efficiency of the combined cycle power plant, since the increase temperature in the gas turbine exhaust raises the efficiency of steam process enough to more than compensate for the reduce efficiency of the gas turbine unit.

b) As we increase the inlet temperature of the gas turbine the overall efficiency of combined cycle power plant increases. Because gas turbine efficiency and steam process efficiency increases.

c) It is clear from the graph as we decrease the pinch point the overall efficiency of combined cycle plant increases. This is an important parameter, by reducing the pinch point the rate of energy utilization in the HRSG can be influenced within certain limits. How ever the surface of the heat exchanger increases exponentially which quickly sets in limit for the utilization rate.

d) The Table and graph shows the steam temperature and pressure increases the efficiency will increase. But in combined cycle plant, a high live steam pressure does not necessarily mean a high efficiency. A higher pressure does indeed bring an increase efficiency of the water steam cycle due to the greater enthalpy gradient in the turbine. The rate of waste heat energy utilization in the exhaust gases however drops off sharply. The overall efficiency of the steam process is the product of the rate of energy utilization and the efficiency of the water steam cycle. There is an optimum at approx 30bar.

REFERENCES

[1] Combined cycle gas and steam Turbine power plant by Rolf Kehlhofer.

[2] Advance gas turbine cycle by J.H. Horlock F.R. Eng, F.R.s. CFE.

[3] Power plant engineering by P.K. Nag (TMH).

[4] Combined cycle power plant by Jane hagerstrom, GSA publications.

[5] Proceedings of ASME Turbo Expo. 2003. Power of Land, Sea, and Air June 16-19, Atlanta, Georgia, USA.

[6] 1999. Int. J. Applied Thermodynamics, ISSN 1301-9724. 2(3): 97-114, September.

[7] Department di Energetica, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy.

[8] The Modelica Association , Modelica2006, September 4th-5th.

[9] Combined cycle repowering more attractive than ever (104-106) by L.M. Pruce, Power March.79.

[10]1971. Wrgi gasification process for combine cycle power generation (230-39) by Loeffler and Vierrath IJPRVD, July-Aug 1988 Kirparti, S.P. and M.M Nagiv Combined Helium Steam cycle for Nuclear Power Plant, Mechanical Engineering. 93(8): 14, Aug.

[11]Bilgen E. 2000. Exergetic and engineering analysis of gas turbine based co generation system energy. 25: 1215-1229.

[12]Gas turbine Engineering Handbook by Meherwan p. Boyce.