# Performance Analysis of Ccgt Power Cylce at Varying A/F Ratio and Pressure Ratio

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***Abstract: A combined cycle is a synergistic combination of two or more power cycles operating at different temperatures running independently. Normally the cycles are classified as a 'topping' and a 'bottoming' cycle. Most of the heat is supplied in the topping cycle and the produced waste heat is utilized in a cycle at a lower temperature which is referred as bottoming cycle. Presently, the gas steam combined cycle is widely accepted, where 'waste energy' is utilized for generation of steam. The performance of combined cycle depends upon number of parameters like TIT, component efficiencies, turbine exhaust temperature, degree of supplementary firing and condition of steam generation. Our work is to optimize the thermal efficiency of combined cycle by reheating & intercooling without supplementary firing and reheating & intercooling with supplementary firing for a given set of parameters like temperature, pressure ratio and a/f ratio The research work has been further validated by using MAT lab coding.***

***Keywords: Combined Cycle, optimization, Steam turbine, Gas turbine, efficiency, supplementary heating, intercooling, a/f ratio, pressure ratio.***

## 1. INTRODUCTION

The introduction of combined cycle had opened new avenues in the field of power generation. The gas turbines that were initially used in peak load power generation and emergency conditions could be used in base load power generation. Combined cycle is a synergistic combination of gas cycle and power cycle. Thus performance of combined cycle depends upon the performance of gas cycle and steam cycle. So in order to achieve this objective the parameters that affect the performance of gas turbine (maximum temperature, component efficiency, a/f ratio and pressure ratio) the limitations that restrict the performance of gas turbine (space, cost and metallurgical limitations) were determined .One of the major limitations of gas cycle is the unavailability of materials that could withstand high temperature. So, gas turbines are provided with high a/f ratio to maintain the temperature of turbine blades. Due to this turbine exhaust have high amount of unused oxygen in which additional fuel can be burnt. Thus concept of supplementary heating comes into picture. S.De et al (1) and P.K Nag had done energy analysis of various components at different degree of supplementary heating. . They found that the most favorable benefit of supplementary heating is for a low temperature ratio only and for higher temperature ratio gain in work output is at an expense of overall efficiency of the plant. .G.CARRY et al (2) in 1985 published a technical paper. In this technical paper the effect of steam cycle regeneration on combined cycle was discussed. In this paper they mentioned that higher the number of extraction the lower the relative efficiency gain. They also found out that efficiency could rise for low turbine pressure ratio and for small regeneration degree. And regeneration degree causes an increase in efficiency when it is small enough .O. BOLLAND (3) had published a technical paper on comparative evaluation of advanced combined cycle alternatives.

In this technical paper he chooses a modem dual pressure combined cycle as reference. He has considered several alternatives to improve the efficiency. These comprises dual pressure reheat cycle, the triple pressure reheat cycle, the triple pressure reheat cycle, triple pressure cycle, the dual pressure supercritical cycle and the triple pressure supercritical reheat cycle. He found out that triple pressure supercritical reheat cycle gives largest increase in efficiency as compared to dual pressure sub-critical steam cycle. In 1980 IG RICE (4) published a technical paper on combined reheat gas turbine/steam turbine cycle. In this paper the effect of pressure ratio and firing temperature are seen on power output, thermal efficiency turbine exit temperature. According to this paper the reheat cycle gas turbine efficiency is degraded slightly over the simple cycle for equal firing temperature and the reheat cycle gas turbine output is increased significantly. In this paper it is observed that combined cycle incorporating the reheat gas turbine offers significant cycle efficiency improvement for equal firing temperatures. In his technical paper I.G RICE mentioned that as the pressure ratio is increased the compressor discharge temperature $t_2$ also increase. However gas generator exit temperature decreases with increase in pressure ratio. In our analysis we also get similar results. I.G RICE in his technical paper also emphasize on the role of pressure ratio on specific power output and thermal efficiency. It is observed that as the pressure ratio for compression increases the specific work output for gas turbine increases whereas this lead to lower work output in steam turbine we also get similar results in our technical paper.This technical paper lay the foundation for our analysis however in our analysis the firing temperature was not constant and its value depends upon pressure ratio. Another major difference is that in our analysis the mass of fuel burnt in the combustion chamber is constant. Where as in I.G RICE technical paper the mass of fuel burnt in the combustion chamber is not constant. In our analysis we observe the effect of cooling and reheating on the performance of gas turbine. For this the work of M.A. Da Cunha et al (5) was of immense help. In his technical paper the concept of inter cooling and reheat for gas turbines are assessed in a systematic way and the effect of position of inter-cooling and reheating on gas turbine performance was discussed.. In our analysis we discuss the optimized efficiency of the combined cycle with given sets of constraints and variables. The results so obtained give the optimized value of efficiency at which machines should be run for maximum utilization. The gas turbines have lower efficiencies and steam turbines are more efficient but here we are using exhaust gases for the steam generation in steam cycle so steam cycle will have lower efficiencies compared to gas turbine cycle. The optimized result will give the maximum efficiency of the combined cycle which defines the running conditions of both the gas turbine and steam turbine cycles. In 2012 Thamir K. Ibrahim 2(6) published a technical paper on Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine In the present work; a parametric thermodynamic analysis of a combined-cycle gas turbine is undertaken. The effect of operating parameters, including peak pressure ratio, gas turbine peak temperature ratio, isentropic compressor and efficiency and air fuel ratio, on the overall plant performance is investigated.. . In the present analysis, specific work output and thermal efficiency of combined cycle is determined at different a/f ratio and pressure ratio. In the present paper the pressure ratio has been taken in the in range of 4-40 and a/f ratio in the range of 50-130. It is observed that specific work output and thermal efficiency improve at lower a/f ratio and higher-pressure ratio.

## 2. THERMODYNAMIC MODELING OF COMBINED CYCLE

In the present analysis of combined cycle we have seen the effect of various parameters like a/f ratio), pressure ratio on specific work output and thermal efficiency. We also analysis the effect of reheat, supplementary heating and condition of steam generation i.e. pressure and temperature on specific work output and thermal efficiency.

To analyze the present study the methodology adopted are

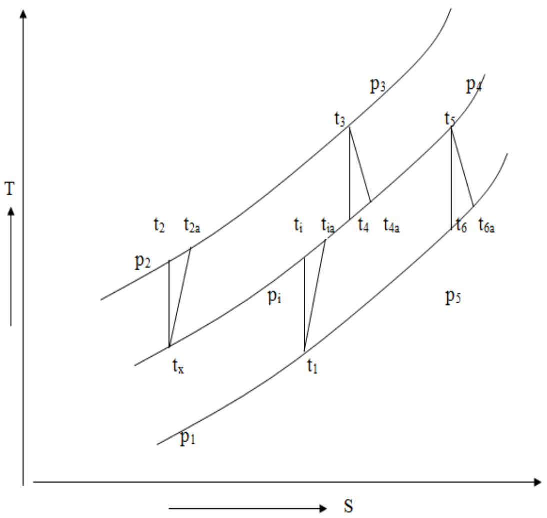
First we calculate work net 1, work net2 and efficiency 1, efficiency2 at different a/f ratio and pressure ratio for

a) With reheat, inter-cooling without supplementary firing
b) Without reheat, inter-cooling with supplementary firing

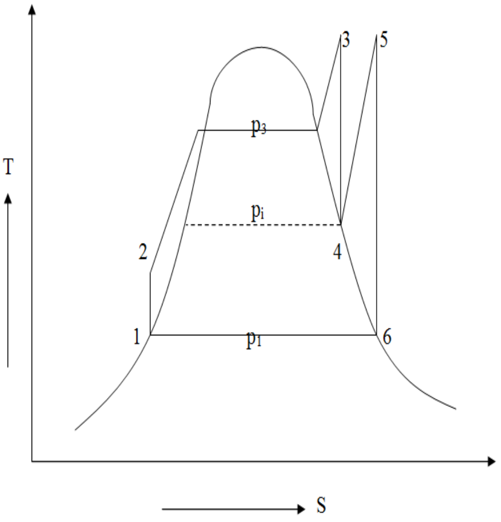
Once the exhaust gas has temperature higher than the temperature needed for steam generation, the steam cycle would contribute.

Thus we can calculate work3 and efficiency3. Here,
work 3 = work net 1 + work net 2

efficiency 3 = efficiency 1 + efficiency 2



**Gas Turbine Cycle (Brayton Cycle) without Supplementary heating with Reheat and with Inter-cooling.**



**Rankine Cycle without Supplementary heating with Reheat and with Inter-cooling.**

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|---|---|
| Analysis of gas turbine cycle<br>With reheat with inter cooling<br>$\frac{t_i}{t_1} = \left(\frac{p_i}{p_1}\right)^{\gamma-1/\gamma}$<br>where $\frac{\gamma-1}{\gamma} = 0.2857$<br>Also, $p_i = \text{sqrt}(p_1 \times p_2)$, where Sqrt = Square Root<br>Now,<br>$\frac{t_i - t_1}{t_{ia} - t_1} = \eta_c$<br>$t_{ia} = \frac{t_i - t_1}{\eta_c} + t_1$<br>Now, similarly<br>$t_{2a} = \frac{t_2 - t_x}{\quad} + t_x$ | Analysis of steam Cycle<br>With reheat without supplementary heating<br>Mass of steam generated by utilization of waste energy.<br>Work (steam) = $m_s \times (h3-h2)$<br>Now to calculate '$m_s$'<br>$m_s = \frac{(m_f + m_a) \times C_{pg} \times (t_8 - t_9)}{(h3 - h2)}$<br>Also,<br>work net 2 = $\frac{(\text{work } 2)}{(m_f + m_a)}$<br>*Efficiency 2* = $\frac{(\text{work } 2)}{m_f \times L.C.V + (m_f + m_a) \times C_{pg} \times (t_5 - t_{4a})}$<br>With supplementary heating with reheat with inter cooling<br>To calculate mass of steam<br>$m_s(h_1 - h_{f3}) =$<br>$Z \times (m_f + m_a) \times C_{pg} \times (t_8 - t_9) + Z_a \times m_f \times L.C.V$ |

$\eta_c$

Here, for perfect inter-cooling, $t_x = t_1$

$$\text{So} \quad t_{2a} = \frac{t_2 - t_1}{\eta_c} + t_1$$

Now, to calculate $t_3$

$$m_f \times L.C.V = (m_f + m_a) \times C_{pg} \times (t_3 - t_{2a})$$

$$m_a = 1 \times a/f$$

$$t_3 = \frac{m_f \times L.C.V}{(m_f + m_a) \times C_{pg}} + t_{2a}$$

$$\frac{t_3}{t_4} = \left(\frac{p_3}{p_4}\right) 0.2857$$

and $p_4 = \text{sqrt}\ (p_3 \times p_5)$

$$t_4 = \frac{t_3}{(p_3 / p_5)\ 0.2857}$$

and $t_5 = t_3$

$$t_6 = \frac{t_5}{(p_4 / p_5)\ 0.2857}$$

$$\eta_t = \frac{t_5 - t_{6a}}{t_5 - t_6}, \quad t_{6a} = t_5 - \eta_t (t_5 - t_6)$$

Here,

$w_t = (m_f + m_a) \times C_{pg} \times (t_3 - t_{4a} + t_5 - t_{6a})$

and

$w_c = m_a \times C_{pa} \times (t_{2a} - tx + t_{ia} - t_1)$

Now,

$$\text{Thermal Efficiency} = \frac{\text{Work 1}}{m_f \times L.C.V + (m_f + m_a) \times C_{pg} \times (t_5 - t_{4a})}$$

With supplementary heating with reheat with inter cooling

We have,

$w_t = Z \times (m_f + m_a) \times C_{pg} \times (t_3 - t_{4a} + t_5 - t_{6a})$

Here $Z_a = 1 - Z$,

Where Z is supplementary fuel fired.

$$m_s = \frac{Z \times (m_f + m_a) \times C_{pg} \times (t_8 - t_9) + Z_a \times m_f \times L.C.V}{(h3 - h2)}$$

$$\text{work net2} = \frac{\text{work2}}{(m_f + m_a)}$$

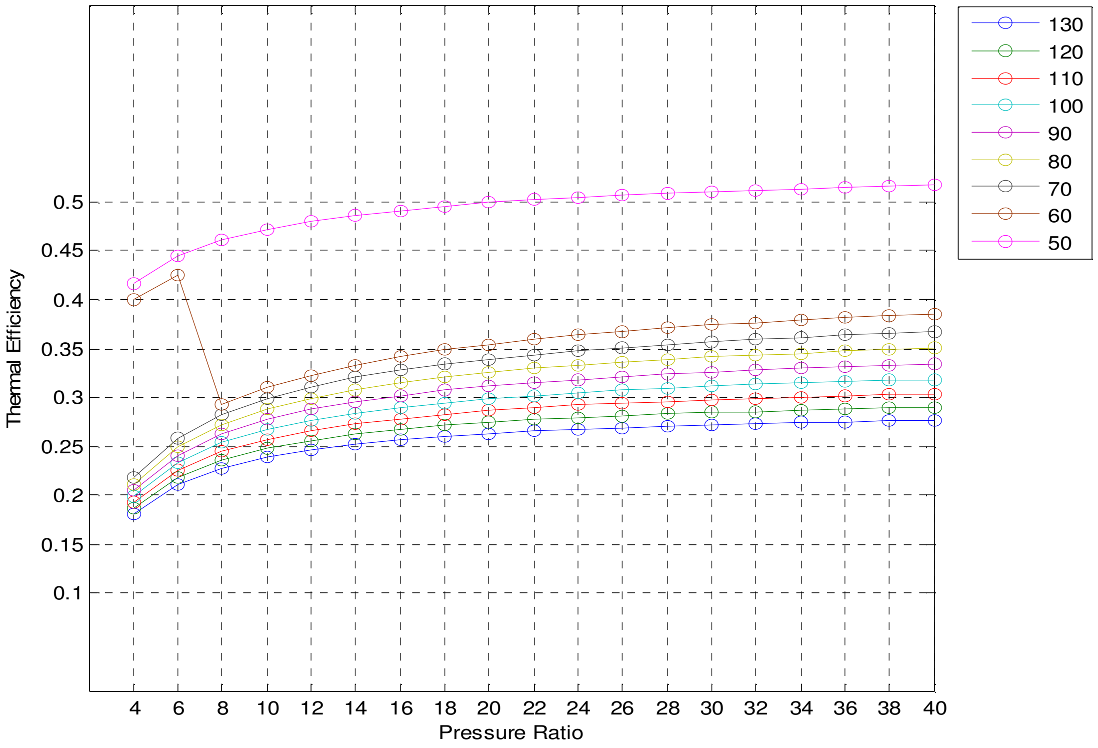
Here,

$$\text{Efficiency 2} = \frac{\text{work2}}{m_f \times L.C.V + (m_f + m_a) \times C_{pg} \times (t_5 - t_{4a})}$$

## 3. ANALYSIS THROUGH MATLAB CODING

### *3.1 – ANALYSIS OF COMBINED CYCLE WITH REHEAT WITH INTERCOOLING WITHOUT SUPPLEMENTARY HEATING.*

***Graph 1: Thermal Efficiency v/s Pressure Ratio at Different A/F Ratio with Reheat without Supplementary Heating When Steam is generated at 20 bar 540$^0$C***



***Refer to Graph 1***

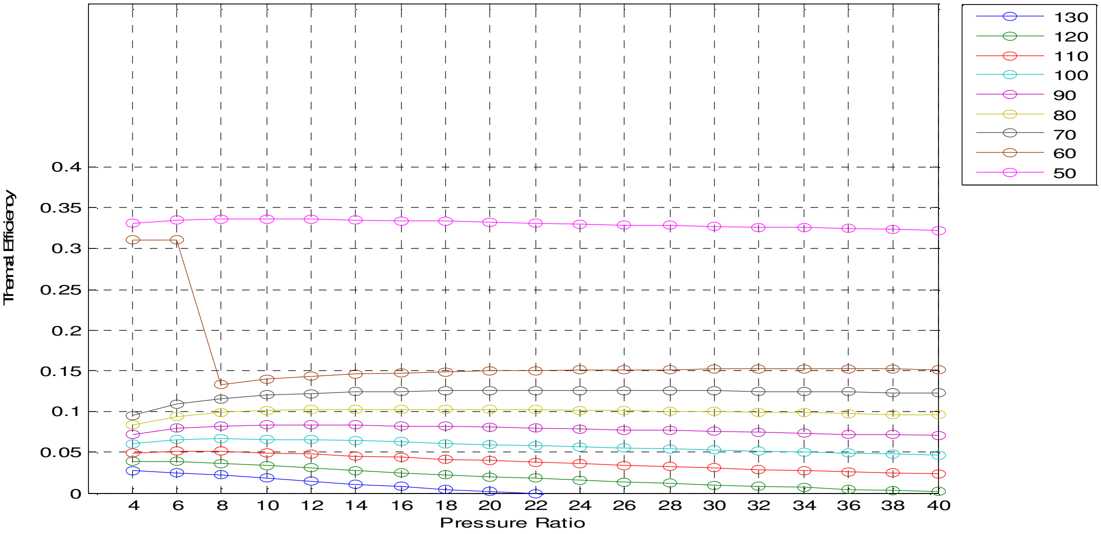
***The Optimized Value of Efficiency at Air/Fuel Ratio 50.00 and Pressure Ratio 40.00 = 0.517***

1) It is seen that from A/F 130 to A/F 70 the turbine exit temperature i.e. t8 is less than 540$^0$ C i.e. ( the condition of Steam) generated so steam cycle does not contribute and, Efficiency = Efficiency 1.
2) Steam cycle became effective at A/F ratio of 60 and lower.
   Here Efficiency = Efficiency 1 + Efficiency
3) At A/F ratio of 60 Efficiency 3 initially increase up to pressure ratio of 6 bar then there is sudden drop in these parameters and these parameters again rises from pressure 8 onwards.
4) The optimized value of Efficiency 3 is at A/F ratio 50 and pressure ratio 40.

### *3.2 – ANALYSIS OF COMBINED CYCLE WITH REHEAT WITH INTERCOOLING WITH SUPPLEMENTARY HEATING.*

Graph 2: Thermal Efficiency v/s Pressure Ratio at Different A/F Ratio with

Reheat with Supplementary Heating When Steam is generated at 20 bar $540^0$C



**Refer to Graph 2**

***The Optimized Value of Efficiency at Air/Fuel Ratio 50.00 and Pressure Ratio 10.00 = 0.336***

1) At a particular pressure ratio the Efficiency 3 increases with lowering of A/F ratio.

2) The steam cycle became effective for A/F ratio 60 or lower.

3) At A/F ratio of 60 Efficiency 3 first increases from pressure ratio of 4 bar then in the range of 6-8 bars these parameters decrease sharply. From pressure ratio 8 onward these parameters continuously increase with pressure.

4) The optimized value of Efficiency 3 is at A/F ratio 50 and pressure ratio 10.

## 4. CONCLUSION

Turbine exit temperature goes on decreasing as pressure ratio increase keeping A/F ratio constant because turbine maximum temperature does increase with pressure ratio but this effect is marginalized by the increase of expansion ratio owing to higher pressure ratio. At a particular pressure ratio if a higher A/F ratio is optimized then turbine maximum temperature goes on decreasing as the mass of fuel is constant and at higher A/F ratio the heat released due to combustion of same mass of fuel is used for raising the temperature of higher quantity of flue gas resulting in low temperature of turbine inlet temperature. In the gas turbine cycle the efficiency first increase and then decrees with increasing in pressure ratio when steam is generated at, 20 bar $540^0$C with reheat. A steam cycle does not effective at higher A/F ratio. Generally steam cycle is effective at A/F ratio 110 and less than it. Efficiency of steam cycle is decreases as pressure ratio increases when steam is generated at 20 bar $540^0$C, with or without reheating and with or without supplementary heating. In combined cycle for A/F 130 to A/F 70 the turbine exit temperature is less than $540^0$ C i.e. ( the condition of Steam generated )so steam cycle does not contribute and, Efficiency = Efficiency 1.Steam cycle became effective at A/F ratio of 60 and lower. Here Efficiency = Efficiency 1 + Efficiency 2.At a particular pressure ratio the efficiency of combined cycle is increases with lowering of A/F fuel ratio.

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