AMBIENT AIR TEMPERATURE EFFECT ON POWER PLANT PERFORMANCE

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Abstract
The performance of the power plant strongly depends on ambient air temperature (AAT). Mass flow rate (kg/s) of air decreases in summer with increasing AAT for the same volumetric flow rate (m³/s), which results in reduced power output of turbine and increased heat rate.

This paper analyzes the effects of the AAT on various parameters of power plant viz., mass flow rate of air, fuel consumption, steam, power output of turbine, efficiency and heat rate of gas turbine, steam turbine and combined cycle plant.

The results of analysis performed are discussed for 10MW power plant. The effect of increases in ambient air temperature by 30°C, the net power output found to be decreased by 18% with 11% decrease mass flow rate of inlet air.

Keywords: Inlet air temperature, performance, combined, cycle, power plant.

1 Combined Cycle Power Plant
In a combined steam and gas turbine power plant, the loss of energy in the gas turbine exhaust is significantly reduced by utilizing its heat in a bottoming cycle; here the high temperature exhaust gas heat is utilized to raise steam for the steam turbine power plant. The combined cycle power plant combines the thermodynamic advantage of both the high temperature gas turbines and the lower temperature steam turbine power plant.

A combined cycle is a thermodynamic system comprising two or more power cycles, each using a different working fluid. Combining two independent power cycles results in higher efficiency. The gas turbine using Brayton cycle and the steam power system using Rankine cycle are two such cycles that complement each other to form efficient combined cycle. The Brayton cycle has a high source temperature and rejects heat at a temperature such that it used as energy source for the Rankine cycle in a combined cycle.

1.1 Performance of GT/CCPP
Urgent electricity demand in summer is experienced by most of the world utilities require to build power plants that generate maximum output at summer ambient temperature ratings. Due to short installation time and low installation cost, GT are often used to meet this peak demand. But the performance of GT plant is inversely proportional to the ambient temperature.

So combined cycles (CCy) based gas turbines is a competitive alternative to produce electricity power. Combined cycle is highly efficient, have low production costs and emissions, adhering to the current economic and environmental framework. However performance of GT/CCPP strongly depends on AAT. The power produced by the turbine is nearly a linear function of air mass flow rate. Ignoring the additional mass flow of the fuel, an ideal gas mass flow rate is \( m_a = \frac{PV}{RT} \). For \( P, V \) and \( R \) are constant, the mass flow rate of air is linear inverse function of temperature, i.e. \( m_a = \frac{1}{f(T)} \). Then power output will be the linear inverse function of temperature[1],

As the AAT increases during summer, the capacity of the turbine decreases and vice-versa[1]. If AAT is increases both the power output and efficiency will decrease due to decrease density of air. Again the approximate cycle efficiency, can be expressed, \( \eta = \frac{T_1}{T_2} \), where \( T_1 \) & \( T_2 \) are inlet & outlet air temperature to & from compressor respectively, it is evident that, the efficiency also decreases with increase in the compressor inlet temperature[1].

The output of a combustion turbine decreases as the ambient temperature increases due to the fact that the mass flow rate of air decreases as the air becomes less dense at higher ambient temperatures. Since the
output of GT is proportional to the airflow, the reduction in the airflow would cause a reduction in the output. In addition to that, the heat rate increases with an increase in the ambient temperature. Jolly & Nitzken[2] has stated, for simple cycle operation, every 5°C raise in the ambient temperature decreases the output by 3.2ηg[2].

The objective of this present work is thus to analysis the effect of the AAT on the combined cycle power plant.

1.2 Case Study

The combined cycle co-generation power plant has been taken for case study. The plant flow diagram of combined cycle co-generation is shown in Fig.1, which consists of gas turbine (GT), steam turbine (ST) and heat recovery steam generator (HRSG). Data regarding the specifications of plant, actual operating parameters of plant at design condition and the performance data are presented in Table 1, 2 & 3 respectively.

When other parameters held constant, the performance of CCPP are strongly depends only on AAT. Main parameters of plant influenced by AAT are as under and equations are given in appendix –I.

- Mass flow rate of air (ma) at inlet of compressor: \( m_a = \frac{P V_1}{R T_1} \), When P1, V1 & R are held constant, then ma is inversely proportional to AAT (T1).

- Outlet temperature of compressor (T2): \( T_2 = T_1 \left[ 1 + \left( \frac{r}{\eta_c} \right) \left( \frac{1}{T_1} - 1 \right) \right] \), When r, γ & ηc are held constant, then T2 is directly proportional to T1.

- Compression Work (WC): \( W_C = \frac{P V_1}{R} \cdot C_{pa} \cdot \left[ 1 + \left( \frac{r}{\eta_c} \right) \left( \frac{1}{T_1} - 1 \right) \right] \), When P1, V1, R, r, γ, Cpa & ηc are constant, Wc is independent of T1. There is no effect of T1 on the compressor work.

- Mass flow rate of fuel to GT-CC: \( m_{f1} = \frac{P V_1}{R T_1} \left( C_{pg} \cdot T_3 - C_{pa} \cdot T_1 \cdot \frac{1}{\eta_c} \left( \frac{1}{gamma} \right) \left( \frac{1}{r'} - 1 \right) \right) \), When P1, V1, R, r, γ, ηc, ηcomb, Cpa, Cpg & T3 are held constant, m_f1 is inversely proportional to T1.

- Outlet temperature of gas turbine (T4): \( T_4 = T_3 \left[ 1 - \eta_{GT} \left( 1 - \left( \frac{1}{gamma} \right) \right) \right] \), When all parameters like T3, r, γ & ηGT are constant, T4 is independent of T1.

- Gas Turbine Work (WG): \( W_{GT} = \frac{P V_1}{R T_1} \cdot C_{pg} \cdot (T_3 - T_1) \left[ 1 + \left( \frac{r}{\eta_c} \cdot C_{pg} \cdot T_3 \right) \left( \frac{1}{gamma} \right) \left( \frac{1}{r'} - 1 \right) \right] \), When P1, V1, R, r, γ, ηc, ηcomb, Cpa, Cpg, T1 & T4 are held constant, WGT is inversely proportional to T1.

- Net Power Output Gas Turbine Plant at Generator shaft: \( W_{NGT} = (W_{GT} - W_C) \cdot \eta_{gen} \), When WC, ηgen are held constant, WGT is inversely proportional to T1.
• Gas Turbine Plant Efficiency: 
\[
\eta_{GT} = \frac{C_{pg} (T_3 - T_1) \cdot \eta_{gen}}{CV \cdot \eta_{comb}} \left[ 1 + \frac{R \cdot W_{C}}{P \cdot V} \cdot \left( \frac{1}{T_3} - \frac{1}{T_1} \right) \right]^{+1}
\]

When \( P_1, V_1, R, C_{pa}, C_{pg}, \eta_{gen} \) are constant except \( T_1 \). The net power output of GT plant is inversely proportional to \( T_1 \) and energy supplied to GT plant is also inversely proportional to \( T_1 \). Therefore efficiency of GT plant is inversely proportional to \( T_1 \).

\[
\gamma, \gamma', \eta_{comb}, \eta_{GT}, \eta_{gen}, \text{ and } T_3 \text{ are constant except } T_1.
\]

\[
\text{Combined Cycle Plant Efficiency: } \eta_{CC} = \frac{W_{NGT} + W_{NST}}{m_{f_1} + m_{f_2}} \cdot CV \cdot \eta_{comb}
\]

When \( W_{NGT}, W_{NST}, m_{f_1} \) and \( m_{f_2} \) are inversely proportional to \( T_1 \). Therefore \( \eta_{CC} \) is inversely proportional to \( T_1 \).

The value of all constant parameters is used as under.

\[
\begin{align*}
P_1 & = 1.013 \times 10^5 \text{ N/m}^2, \\
V_1 & = 107.24 \text{ m}^3/\text{sec}, \\
R & = 0.287 \text{ kJ/kg K}, \\
C_{pa} & = 1.032 \text{ kJ/kg K}, \\
C_{pg} & = 1.259 \text{ kJ/kg K}, \\
CV & = 45.086 \text{ kJ/kg}, \\
h_{23} & = 3112 \text{ kJ/kg}, \\
h_{12} & = 743 \text{ kJ/kg}, \\
h_{24a} & = 2611 \text{ kJ/kg}, \\
h_{24b} & = 2992 \text{ kJ/kg}, \\
h_{24} & = 2130 \text{ kJ/kg}, \\
x' & = 0.6924, \\
y' & = 0.2556, \\
z' & = 0.052,
\end{align*}
\]
2 Results and Discussion

2.1 Effect of variation of AAT on mass flow rate of air

Parameters held constant: $P_1$, $V_1$, and $R$.

From Fig. 2, shows that as the AAT increases from 278K to 313K (5°C to 40°C), the mass flow rate of air decreases by 11%. The mass flow rate of air increases with increasing the AAT. The volumetric flow to most turbines is constant, therefore mass flow rate of air decreases with increase in AAT. This is due to the decrease in density of air.

2.2 Effect of variation of AAT on GT plant

2.2.1 Net power output of GT plant

Parameters held constant: $P_1$, $V_1$, $R$, $C_{pa}$, $C_{pg}$, $CV$, $\gamma$, $\gamma'$, $r$, $\eta_C$, $\eta_{comb}$, $\eta_{GT}$, $\eta_{gen}$, $T_3$.

From Fig. 3, depicts that as the AAT increases from 278K to 313K (5°C to 40°C), net power output of gas turbine decreases by 24%. The power consumption of compressor is directly proportional to mass flow rate of air and inlet & outlet temperature difference of compressor. It is clear from equation, $W_C = m_a \cdot c_{pa} \cdot \left( T_2 - T_1 \right)$, Watts. The temperature difference is directly proportional to $T_1$ as $(T_2 - T_1) = T_1 \cdot x$ constant term, and the mass flow rate of air is inversely proportional to $T_1$ as $m_a = PV/RT_1$. Therefore the compressor work is not dependent on $T_1$ as:

$$W_C = \frac{P_V}{R} \cdot c_{pa} \cdot \left( 1 + \left( \frac{1}{\eta_C} \right) - 1 \right) = \text{constant.}$$

Similarly power output of GT is directly proportional to inlet & outlet temperature difference of turbine and sum of mass flow rates of air & fuel. As there is no variation in inlet & outlet temperature difference of turbine, decreases the power output of GT is due to the decrease in mass flow rate of air. Since increase in AAT decreases the mass flow rate, the net power of GT decreases.

2.2.2 Efficiency of GT plant

Parameters held constant: $P_1$, $V_1$, $R$, $C_{pa}$, $C_{pg}$, $CV$, $\gamma$, $\gamma'$, $r$, $\eta_C$, $\eta_{comb}$, $\eta_{GT}$, $\eta_{gen}$, $T_3$.

Fig. 4, represent that as the AAT increases from 278K to 313K (5°C to 40°C), efficiency of gas turbine plant decreases by 9%. The efficiency of Gas Turbine is directly proportional to net power output of gas turbine and inversely proportional to energy supplied to combustion chamber of gas turbine. Power output of gas turbine is decreases with increase in AAT. Energy supply to gas turbine also decreases with increase in AAT, because the mass flow rate of air decreases and compressor outlet temperature increases. Efficiency of GT decreases with increase in AAT.

2.3 Effect of variation of AAT on ST plant

2.3.1 Mass flow rate of steam

Parameters held constant: $P_1$, $V_1$, $R$, $C_{pa}$, $C_{pg}$, $CV$, $h_{23}$, $h_{012}$, $h_{24a}$, $\gamma$, $\gamma'$, $r$, $\eta_{HRSG}$, $\eta_C$, $\eta_{comb}$, $\eta_{GT}$, $\eta_{gen}$, $T_3$, $T_5$, $T_{10}$.

From Fig. 5, shows that as the AAT increases from 278K to 313K (5°C to 40°C), mass flow rate of steam decreases by 10%. According to energy balance, heat from exhaust gases from GT and heat produced due to supplementary fuel firing are equal to heat gained by water to convert it in to steam. With increase in AAT, the mass flow rate of air decreases which results in to the decreases mass flow of exhaust gases it lead to lower amount of heat in exhaust gases. Hence, the rates of steam generation will decreases. Also, mass flow rate of extracted steam decreases with increase in AAT. Mass flow rate of steam and as well as mass flow rate of extracted steam for process heating at fixed pressure and temperature decreases with increasing AAT.

2.3.2 Net power output of ST plant

Parameters held constant: $P_1$, $V_1$, $R$, $C_{pa}$, $C_{pg}$, $CV$, $h_{23}$, $h_{012}$, $h_{24a}$, $h_{24b}$, $h_{24c}$, $\gamma$, $\gamma'$, $r$, $\eta_{HRSG}$, $\eta_{ST}$, $\eta_C$, $\eta_{comb}$, $\eta_{GT}$, $\eta_{gen}$, $T_3$, $T_5$, $T_{10}$.

From Fig. 6, it is clear that as the AAT increases from 278K to 313K (5°C to 40°C), net power output of ST plant decreases by 9%. It is known that mass flow rate of exhaust gases from GT decreases with increase in AAT, which ultimately decrease the steam generation rate. Steam turbine output is directly proportional to the mass flow rate of steam. Therefore net power output of ST decreases with increase in AAT.

2.4 Effect of variation of AAT on CC plant

2.4.1 Mass flow rate of Fuel

Parameters held constant: $P_1$, $V_1$, $R$, $C_{pa}$, $C_{pg}$, $CV$, $h_{23}$, $\gamma$, $\gamma'$, $r$, $\eta_{HRSG}$, $\eta_{ST}$, $\eta_C$, $\eta_{comb}$, $\eta_{GT}$, $\eta_{gen}$, $T_3$, $T_5$. 

From Fig. 7, it is clear that as AAT increases from 278K to 313K (5°C to 40°C), the mass flow rate of fuel consumption decreases by 18%. It is known that fuel consumption of combined cycle at particular fixed inlet temperature of GT and at fixed temperature limit of HRSG decreases with increase in AAT. At particular fixed temperature limit of HRSG, the mass flow rate of air and gases decreases with increase in AAT. Lower mass flow rate of air will result in lower fuel consumption rate required in GT and lower mass flow rate of gases will also result in the lower fuel requirement in HRSG. Also outlet temperature of compressor increases with increase in AAT, which will decrease the fuel consumption for maintaining required inlet temperature of GT. So fuel consumption decreases with increase in AAT.

2.4.2 Net power output of combined cycle
Parameters held constant: $P_1, V_1, R, C_{pa}, C_{pg}, CV, h_{112}, h_{24a}, h_{24b}, \gamma, \gamma', r, \eta_{HRSG}, \eta_{ST}, \eta_C, \eta_{comb}, \eta_{GT}, \eta_{gen}, T_3, T_a, T_10$.

The power output of GT and ST decreases with increase in AAT. Fig. 8 verifies the same and shows 18% reduction in the net power output of combined cycle in the range of AAT from 278K to 313K (5°C to 40°C).

2.4.3 Efficiency of Combined Cycle
Parameters held constant: $P_1, V_1, R, C_{pa}, C_{pg}, CV, h_{23}, h_{f12}, h_{24a}, h_{24b}, \gamma, \gamma', r, \eta_{HRSG}, \eta_{ST}, \eta_C, \eta_{comb}, \eta_{GT}, \eta_{gen}, T_3, T_a, T_10$.

From Fig. 9, shows that as the AAT increases from 278K to 313K (5°C to 40°C), the efficiency of combined cycle decreases by negligible value. It is known that efficiency of combined cycle is directly proportional to net power output of CCy and inversely proportional to sum of energy supplied to combustion chamber of GT & supplementary fuel fired to HRSG. Power output of gas turbine & steam turbine plants decreases with increase in AAT. Energy supply to GT & HRSG also decreases with increase in AAT due to the decrease in mass flow rate air and increases in compressor outlet temperature. So efficiency of combined cycle decreases with increase in AAT.

2.4.4 Heat Rate in Combined Cycle
Parameters held constant: $P_1, V_1, R, C_{pa}, C_{pg}, CV, h_{23}, h_{112}, h_{24a}, h_{24b}, \gamma, \gamma', r, \eta_{HRSG}, \eta_{ST}, \eta_C, \eta_{comb}, \eta_{GT}, \eta_{gen}, T_3, T_a, T_10$.

From Fig.10 depicts that as the AAT increases from 278K to 313K (5°C to 40°C), the heat rate of combined cycle increases by negligible value. It is known that the heat rate of combined cycle is inversely proportional to efficiency of combined cycle.

3 Tables and Figures

<table>
<thead>
<tr>
<th>Type of Cycle</th>
<th>Combined Cycle</th>
</tr>
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<tbody>
<tr>
<td>Electrical power produced by GT</td>
<td>30 MW</td>
</tr>
<tr>
<td>Electrical power produced by ST</td>
<td>20 MW</td>
</tr>
<tr>
<td>Speed of Gas Turbine</td>
<td>5100 rpm</td>
</tr>
<tr>
<td>Type of gas turbine</td>
<td>Axial flow</td>
</tr>
<tr>
<td>No. of stages in Compressor</td>
<td>17</td>
</tr>
<tr>
<td>Pressure ratio of Compressor &amp; GT</td>
<td>11.7</td>
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</table>
Table- 2 Actual Operating Parameters of Plant at Design Condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorific Value of fuels for GT-CC and supplementary CC</td>
<td>37000 kJ/m³</td>
</tr>
<tr>
<td>Density of Natural Gas</td>
<td>0.835 kg/m³</td>
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<tr>
<td>Max Net Power Output of GT Generator</td>
<td>31.640 MW</td>
</tr>
<tr>
<td>Exhaust Gas Mass Flow</td>
<td>124.11kg/s</td>
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<tr>
<td>Exhaust Gas Temperature from GT</td>
<td>560 °C</td>
</tr>
<tr>
<td>Fuel Consumption of CC-I</td>
<td>388x10⁶ kJ/hr</td>
</tr>
<tr>
<td>Exhaust gas temperature at entry of Superheater</td>
<td>788 °C</td>
</tr>
<tr>
<td>Exhaust gas temperature at leaving of CPH/Stack</td>
<td>135 °C</td>
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<tr>
<td>Steam Turbine Inlet Condition</td>
<td>37.26 bar, 355°C,125T/h</td>
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<tr>
<td>Supplementary Fuel Consumption of CC-II</td>
<td>127x10⁶ kJ/hr</td>
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<tr>
<td>Feed water flow</td>
<td>126.25T/hr</td>
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<tr>
<td>Cooling water requirement</td>
<td>4400 m³/hr</td>
</tr>
<tr>
<td>1st Steam Extraction Condition</td>
<td>13.7bar,278°C</td>
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<tr>
<td>2nd Steam Extraction Condition</td>
<td>3.4 bar,145°C</td>
</tr>
<tr>
<td>Condition of steam leaving last row of Turbine &amp; Rotor dryness fraction</td>
<td>-12ata, 49°C, 95 Ton/hr, 0.885</td>
</tr>
<tr>
<td>Inlet circulating water design temperature</td>
<td>33 °C</td>
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<tr>
<td>Outlet circulating water design Temperature</td>
<td>41.84 °C</td>
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Table- 3 Performance Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Efficiency of Compressor</td>
<td>84 %*</td>
</tr>
<tr>
<td>Efficiency of GT &amp; ST</td>
<td>85 %*</td>
</tr>
<tr>
<td>Efficiency of Combustion Chambers</td>
<td>92 %*</td>
</tr>
<tr>
<td>Efficiency of HRSG</td>
<td>86 %*</td>
</tr>
<tr>
<td>Efficiency of Generators</td>
<td>96 %*</td>
</tr>
<tr>
<td>Specific Heat of Air</td>
<td>1.032kJ/kg°K**</td>
</tr>
<tr>
<td>Specific Heat of Gases</td>
<td>1.259kJ/kg°K**</td>
</tr>
<tr>
<td>Specific Heat Ratio of Air</td>
<td>1.4***</td>
</tr>
<tr>
<td>Specific Heat Ratio of Gases</td>
<td>1.302**</td>
</tr>
</tbody>
</table>

*It assumed according to general power plant data[3].
**It found by help of Exhaust Gases Properties Table[4].
***It assumed by help of Air Properties Table[4].
Fig. 1. Simple Flow Diagram of Combined Cycle Power Plant

Fig. 2: Effect of AAT on the ma

Fig. 3: Effect of AAT on WNGT

Fig. 4: Effect of AAT on the Efficiency of GT Plant

Fig. 5: Effect of AAT on the Ms

Fig. 6: Effect of AAT on WNST

Fig. 7: Effect of AAT on the Mf
4 Conclusion

The effect of increases in AAT by 35 °C (rises of temperature from 5 °C to 40 °C), gives the following observation and conclusions:

1. 11% decrease in the mass flow rate of air is by the increased in AAT.
2. Net power output from the GT is found to be decrease by 24% and GT plant efficiency is decreased by 9%.
3. Power output from steam turbine is found to decrease by 9%. Also the mass flow rate of steam is decreased by 10%.
4. The reduction by 18% in the total fuel consumption for the CCPP is found.
5. There is decreased by negligible value in the efficiency of CCPP along with 18% decrease in net power output.
6. The heat rate of CCPP increased by negligible value.
7. Finally, there will be a decrease in plant capacity by 8 MW in summer where the average AAT is 40°C.

5 References