Exergy Analysis of Afam IV Gas Turbine Power Plant.

B.M Ogunedo and V.I Okoro
Department of Mechanical Engineering, Imo State University, Owerri, Nigeria.

ABSTRACT

In this study an exergy analysis of 75 MW gas turbine is carried out. Exergy analysis based on second law was applied to the gas cycle and individual components through an off design point modeling approach. The analysis shows that the highest exergy destruction occurs in the combustion chamber (CC), and the gas turbine is significantly affected by the ambient temperature; increase in temperature leads to decrease in GT power output. The compressor has the largest exergy efficiency of 99% as compared to the other components (combustion chamber – 76%, Turbine – 95%). The highest destruction in exergy was recorded in the combustion chamber. As a result of this destruction, 2.23kJ of energy is lost in every 1MW output of power produced by the plant.

Keywords
Exergy, Irreversibility, Efficiency, Turbine, Combustion, Compressor.

Table 1. Technical data of GT18 gas turbine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temperature, T_a (K)</td>
<td>301.48</td>
</tr>
<tr>
<td>Compressor Outlet Temperature, T_2 (K)</td>
<td>595.82</td>
</tr>
<tr>
<td>Turbine inlet Temperature, T_1 (K)</td>
<td>1192.82</td>
</tr>
<tr>
<td>Turbine outlet Temperature, T_4 (K)</td>
<td>723.75</td>
</tr>
<tr>
<td>Temperature of exhaust gas, T_exh (K)</td>
<td>664.65</td>
</tr>
<tr>
<td>Compressor inlet Pressure, P_1 (bar)</td>
<td>1.013</td>
</tr>
<tr>
<td>Compressor outlet Pressure, P_2 (bar)</td>
<td>9.80</td>
</tr>
<tr>
<td>Pressure Ratio</td>
<td>9.67</td>
</tr>
<tr>
<td>Mass flow rate of fuel (kg/s)</td>
<td>6.40</td>
</tr>
<tr>
<td>Inlet mass flow rate of air (kg/s)</td>
<td>359.00</td>
</tr>
<tr>
<td>Power Output (MW)</td>
<td>58.00</td>
</tr>
<tr>
<td>LHV of fuel(kJ/kg)</td>
<td>48948.30</td>
</tr>
<tr>
<td>Pressure drop in combustion chamber</td>
<td>3%</td>
</tr>
</tbody>
</table>

The exergy analysis formulation in this study is developed using the methodology established by [1]-[5]. The exergy balance for a thermal system as stated by [1] is expressed as:
\[
\psi_W = \sum_{k=1}^{n} \left(1 - \frac{T_k}{T_f}\right) Q_k + \sum_{k=1}^{p} \left[(\ln \psi)_i - (\ln \psi)_o\right] - T_o S_{gen}
\]

(1)

Where:

\[\Sigma_{k=1}^{n} \left(1 - \frac{T_k}{T_f}\right) Q_k\] represents the exergy summation supplied through heat transfer.

\[\Sigma_{k=1}^{p} \left[(\ln \psi)_i - (\ln \psi)_o\right]\] represents the exergy summation of the working fluid.

\[T_o S_{gen}\] represents the irreversibility in the system.

\[\psi_W\] represents the useful work done on/ by the system.

**Exergy Analysis on Air Compressor**

Since there is no heat transfer, and work is done on the compressor by the turbine, equation 1 becomes

\[-W_{ac} = \sum_{k=1}^{p} \left[(\ln \psi)_i - (\ln \psi)_o\right] - T_o S_{gen}
\]

(2)

The exergy of air at inlet and outlet conditions can be quantified with the expression given by [2]

\[(\ln \psi)_{in} = (\ln \psi)_{out} - (h_a - T_o S_a)
\]

(3)

Where: \(h\) and \(S\) are the enthalpy and entropy of air at their corresponding inlet and outlet pressure and temperature conditions, and \(T_o\) is the ambient temperature.

[3] established the expression for the exergy loss (irreversibility/Anergy) in the system as:

\[I_{ac} = T_o S_{gen} = \dot{m}_a (h_a - T_o S_a)\]

(4)

\[S_2 - S_1 = C_{pa} \ln \frac{T_2}{T_1} - R_a \ln \frac{P_2}{P_1}\]

(5)

Where:

\[R_a = C_{pa} (\gamma_a - 1)\]

\[(S_2 - S_1)\] represents entropy change between compressor exit and inlet conditions.

\[\gamma_a\]: Specific heat ratio of air = 1.4

**Exergy Analysis on Combustion Chamber**

Exergy balance on the combustion chamber is carried out considering the figure 3.

At equilibrium,

\[\dot{m}_a \psi_a + \dot{m}_f \psi_f = \dot{m}_g \psi_g + I_c\]

(6)

Where: \(\psi_a, \psi_f, \psi_g\) are exergy of air, fuel, and products respectively.

\[\dot{m}_a \psi_a = (\ln \psi)_a = -498832.44 kJ\]

Expression for the exergy of fuel can be deduced from the methodology used by [2].

\[\dot{m}_f \psi_f = \dot{m}_f (h_f - T_o S_f)\]

(8)

Exergy destruction is expressed as:

\[I_{de} = T_o S_{gen} = \dot{m}_f (h_f - T_o S_f) - Q_{ce} \frac{T_o}{T_{ave}}\]

(9)

Where:

\[Q_{ce} = C_{pg} (T_3 - T_2)\]

\[T_{ave} = \frac{T_3 + T_2}{2}\]

**Exergy Analysis on Turbine.**

Considering the exergy flow diagram in figure 4, at equilibrium, exergy flow into the turbine equals exergy flow out of the turbine. Hence,

\[\dot{m}_g \psi_g = \dot{W}_u + \dot{m}_exh \psi_{exh} + I_{turb}\]

(10)

[3] expressed the relationship between the mass flow rate of fuel and gaseous product to be:

\[\dot{m}_f = \dot{F} \times m_g\]

(11)

Where \(F\) represents flow of fuel and \(m_g\) is 401.57 kg/s.

\[C_{pg}\]: specific heat of gaseous products \(= 1.148 \text{kJ/kgK}\).

Hence, \(F = 0.016, \dot{m}_g = 401.57 \text{ kg/s}\)

Substituting values into equation 13, \(\dot{m}_g \psi_g = 182781.01 kJ\).

Similarly,

\[\dot{m}_exh \psi_{exh} = \dot{m}_f \left[C_{pg} (T_4 - T_{exh}) - T_o C_{pg} \ln \frac{T_4}{T_{exh}} - R_g \ln \frac{P_3}{P_2}\right]\]

(13)

\[\frac{P_4}{P_3} = \frac{1}{\left[\frac{T_4}{T_{exh}}\right]^{\gamma_g - 1}} = 0.883 R = 0.2848\]

Where:

\[\dot{m}_a \psi_a = \dot{m}_f \psi_f = \dot{m}_g \psi_g\]

\[\dot{m}_exh \psi_{exh}\]

\[\dot{m}_f \psi_f\]

\[\dot{I}_c\]

\[\dot{W}_u\]

\[\dot{m}_g \psi_g\]

\[\dot{m}_exh \psi_{exh}\]

\[\dot{m}_f \psi_f\]

\[\dot{I}_c\]

\[\dot{W}_u\]

Figure 3. Exergy flow balance on combustion chamber.

**Results**

**Results on Compressor analysis.**

Substituting values for \(\dot{m}_a, T_o, and [S_2 - S_1]\) into equation 4, we get that:

\[I_{ac} = 60.59 kJ\]

At inlet condition, \(P=9.8 \text{ bar}; T=301.48 \text{K}\). From tables, the values for enthalpy and entropy of air is:

\[h = 301.95 \text{kJ/kg}; S = 6.875 \text{kJ/kgK}\]. Substituting into equation 3, \(\dot{m}_a \psi_a = -602790.16 kJ\).

At outlet condition, \(P=9.8 \text{ bar}; T=595.82 \text{K}\). From tables, the values for enthalpy and entropy of air is:

\[h = 603.34 \text{kJ/kg}; S = 6.916 \text{kJ/kgK}\]. Substituting into equation 3, \(\dot{m}_a \psi_a = -498832.44 kJ\)
Substituting values of \((\overline{\dot{m}} \overline{\psi})_0, (\overline{\dot{m}} \overline{\psi})_i,\) and \(I_{ac}\) into equation 2,
\[
\dot{W}_{ac} = 104018.32 \text{kJ/s}
\]
Therefore:
\[
\text{exergy added} = (\overline{\dot{m}} \overline{\psi})_0 - (\overline{\dot{m}} \overline{\psi})_i = -498832.44 - (-602790.16) = 103957.72 \text{kJ}
\]
Utilized exergy (Availability) = Exergy added – Exergy loss = 103897.13kJ
Exergetic efficiency of the compressor can be expressed as:
\[
\eta_{ac} = 1 - \frac{I_{at}}{\dot{W}} = 1 - \frac{60.59}{104018} = 0.99
\]
or
\[
\eta_{ac} = \frac{\text{utilized exergy}}{\text{exergy added}} = 0.99
\]

Results on Combustion Chamber.
From Methane tables; at 9.8 bar and 595.82K, \(h_f = 805.398 \text{kJ/kg} \) and \(S_f = 0.6569 \text{kJ/kgK} \).
Substituting values of \(m_f, h_f, T_o, \) and \(S_f\) into equation 8,
\[
\eta_{tf} = 3943.12k\text{J}
\]
Since there is a pressure drop of 3% in the combustion chamber, \(P_3 = 9.506 \text{ bar}.\) Substituting values of \(m_f, T_o, [S_3 - S_2], Q_{ec} \) and \(T_{ave}\) into equation 9;

The exergy destroyed, \(I_{cc} = 120340.12 \text{kJ}\)
Therefore:
\[
\text{Exergy added} = \overline{m}_f \overline{\psi}_f - \overline{m}_a \overline{\psi}_a = 3943.12k\text{J} - (-498832.44k\text{J}) = 502775.56k\text{J}
\]
Utilized exergy (Availability) = exergy added – exergy destroyed = 382435.44kJ
Exergetic efficiency of the combustion chamber can be expressed as:
\[
\eta_{cc} = 1 - \frac{I_{cc}}{\text{Exergy added}} = 1 - \frac{120340.12}{502775.56} = 0.76 \text{ or } \eta_{cc} = 0.97
\]

Results on Turbine Analysis
Substituting values of \(n_{ex}, C_{fg}, T_4, T_{exh}, T_o, R_g, \) and \(P_3\) into equation 14, 
\[
\overline{\dot{m}}_{exh} \overline{\psi}_{exh} = 11830.10k\text{J}
\]
Substituting values of \(n_g \overline{\dot{m}}_g \overline{\psi}_g, \dot{W}_c, \dot{W}_u, \) and \(n_{exh} \overline{\dot{m}}_{exh} \overline{\psi}_{exh}\) into equation 10, Exergy loss, \(I_{turb} = 8932.58k\text{J}\)
Therefore:
\[
\text{Exergy added} = \overline{m}_g \overline{\psi}_g - \overline{m}_{exh} \overline{\psi}_{exh} = 182831.01k\text{J} - 11830.10k\text{J} = 170950.90k\text{J}
\]
Utilized Exergy (Availability) = \(\dot{W}_{turb} = \dot{W}_c + \dot{W}_u = 162018.32k\text{J}\)
The exergetic efficiency of the turbine is expressed below.
\[
\eta_{turb} = 1 - \frac{I_{turb}}{\text{Exergy added}} = 1 - \frac{8932.58}{170950.90} = 0.95
\]
or
\[
\eta_{turb} = \frac{\text{utilized exergy}}{\text{exergy added}} = 0.95
\]
From figure 4, the exergetic efficiency can also be expressed as:
\[
\eta_{turb} = \frac{\text{output exergy}}{\text{input exergy}} = \frac{\overline{\dot{m}}_{exh} \overline{\psi}_{exh} + \dot{W}_c + \dot{W}_u}{\overline{m}_g \overline{\psi}_g} = 0.95
\]
Total irreversibility of the system is given as:
\[
I_{Total} = I_{ac} + I_{cc} + I_{turb}
\]
\[
I_{Total} = 129333.29k\text{J}
\]

Exergetic performance coefficient of the power plant gives the amount of exergy lost per unit power output, and it is expressed as;
\[
\xi = \frac{\dot{W}_{net}}{\dot{W}_{net}} = 2.23k\text{J/MW}
\]
This means that 2.23k\text{J of energy is lost in every 1MW output of power produced.}
Exergetic efficiency of the power plant is expressed as;
\[
\Psi = \frac{\text{total availability across the subsystems}}{\text{total added exergy across the subsystems}} = 0.834
\]

-or-
\[
\Psi = 1 - \frac{\text{total irreversibility in the system}}{\text{total added exergy across the subsystems}} = 0.834
\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Exergy Added (kJ)</th>
<th>Exergy Utilized (kJ)</th>
<th>Exergy Destroyed (kJ)</th>
<th>Exergetic Efficiency</th>
<th>Percentage Exergy Destroyed (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor</td>
<td>103957.72</td>
<td>103897.13</td>
<td>60.59</td>
<td>0.99</td>
<td>0.058</td>
</tr>
<tr>
<td>Combustion Chamber</td>
<td>502775.56</td>
<td>382435.44</td>
<td>120340.12</td>
<td>0.76</td>
<td>23.94</td>
</tr>
<tr>
<td>Turbine</td>
<td>170950.90</td>
<td>162018.32</td>
<td>8932.58</td>
<td>0.95</td>
<td>5.23</td>
</tr>
</tbody>
</table>

Discussion
Air Compressor
From the analysis, we observe that the exergy destroyed is only 0.058% of the total exergy added to the system due to the change in exergy between air inlet and outlet conditions. This means that the air compressor is effective since it utilizes 99.9% of the supplied exergy. Exergy is least added and destroyed in the air compressor. This could be as a result of the temperature gradient across it which doesn’t favour higher generation of entropy when compared to other components in the system.

Combustion Chamber.
The exergy study carried out on the combustion chamber shows that there is a significant increase in the loss of exergy when compared to that of the compressor.

Figure 5.0. Exergetic efficiency Vs System components.

Figure 6.0. Exergy added, Exergy Utilized, and Exergy destroyed across subsystems.
Due to a larger departure in the exit and inlet temperatures, the exergy added was seen to be higher than its value in the air compressor which also led to an increase in the irreversibility recorded. The destroyed exergy is 23.94% of the supplied exergy leading to a lower value in the exergetic efficiency.

**Turbine**

The turbine recorded an exergetic efficiency of 95%, indicating that the irreversibility/exergy destruction is lower than that of the combustion chamber.

The plant exergetic efficiency connotes the real performance of the system. From the analysis carried out, this was found to be 83.4%. This means that only 16.6% of energy is destroyed within the system. From this, we can see that irreversibility which is dependent on entropy generation is also dependent on the prevailing temperature within the system. The higher the temperature, the higher the entropy generated, and subsequently, the irreversibility increases. This explains why the irreversibility is highest in the combustion chamber, followed by the turbine while in the air compressor where there is no heat addition/exhaustion the irreversibility is quite low when compared to other sub systems.

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**References**


