THERMOECONOMIC ANALYSIS AND OPTIMIZATION OF GAS TURBINE POWER PLANT

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Abstract
A gas turbine power plant, which will be located in Jakarta, will analyzed with the aid of exergy, exergoeconomics and optimization. An exergy analysis identifies the real thermodynamics inefficiency due to irreversibility destroyed within a gas turbine power plant system. An exergoeconomics or thermodynamic analysis consists of an exergy, an economic, an exergy costing, an exergoeconomic, and an exergoeconomic optimization aims at minimizing the thermodynamic inefficiencies (exergy destruction and exergy loss) to minimize cost. The exergoeconomic analysis suggest that decreasing the exergy destruction and exergy loss due to irreversibility destroyed for the components compressor, combustion chamber, and gas turbine may lead to a reduction in electricity cost.

Keywords: Energy, Exergy, Economic, Thermoeconomic, Thermoeconomic optimization

1. INTRODUCTION

Thermoeconomics combines exergy analysis and economic principles to provides the system designer or operator with information not available through conventional energy analysis and economic evaluation, but crucial to the design and operator of a cost-effective system. Thermoeconomic can be considered as exergy-aided cost minimization. The aim of the thermoeconomic analysis is to calculate the cost of each product of the system and investigate the cost formation process in the system.

The name “Thermo-economics” made its first appearance in tribus’ MIT course note of 1960 in Evans’ doctoral of 1961. The concept was well developed in academic circles thanks to the efforts of Yehia El-Sayed, Richard Gaygioli, Tadeusz Kotas and Michael Moran in the early 80’s and of Antonio Valero and George Tsatsarinis in the late 80’es.


To evaluate and compare different thermoeconomic methodologies available in the literature, Frangopoulos, C.A., tsatsaronis, G., Valero, A. and Spakovksy, M, have proposed the CGAM (Christos frongopoulos, George Tsatsaronis, Antonio Valero, Michael R. Von Spakovksy) problem as a benchmark, with gained wide acceptance thereafter, Tsatsaronic, G., (guest editor), 1994.

The exergy analysis for power plant has been developed in department of Mechanical Engineering Hasanuddin University since 2003 in the final project of student S1 and S2, Siahaya et al (2006,2008). We conclude that exergy may be destroyed, or exergy is not converted, Bejan, A. et al (1996), Szargut, J., et al (1988), Kotas T.J., (1985).

2. A GENERAL MERTHODOLOGY FOR THE THERMOECONOMIC ANALYSIS OF GAS TURBINE POWER PLANT (MITSUBISHI TYPE M701 Da)

2.1. Description of the system

The structure of the gas turbine power plant is shown in Figure 2.1. The illustration consists of an air compressor (AC), Combustion Chamber (CC) and Gas Turbine (GT). The gas turbine power plant specification is shown in Table 1.
Table 1. Specification of Mitsubishi M701 Da.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Power</td>
<td>253 MWe</td>
</tr>
<tr>
<td>Efficiency</td>
<td>36.81%</td>
</tr>
<tr>
<td>Combustion Temperature</td>
<td>1370 °C</td>
</tr>
</tbody>
</table>

The reference conditions are defined as $T_{ref} = 298.15$ K (25 °C) and $P_{ref} = 1$ bar, the fuel for the combustion chamber is natural gas with a lower heating value (LHV) = 51000 kJ/kg.

Table 2. shows that, decision variables, parameters and dependent variables of gas turbine power plant problem.

Table 2. Decision variable and parameters of power plant

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air compressor pressure ratio ($p_1/p_2$)</td>
<td></td>
</tr>
<tr>
<td>Gas Turbine inlet temperature</td>
<td>1643 K</td>
</tr>
<tr>
<td>Isentropic Efficiency of Air Compressor</td>
<td>86 %</td>
</tr>
<tr>
<td>Isentropic Efficiency of Gas Turbine</td>
<td>86 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>253 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Power generated</td>
<td></td>
</tr>
<tr>
<td>Air compressor inlet conditions</td>
<td>25 °C, 1.013 bars</td>
</tr>
<tr>
<td>Combustion chamber pressure drop</td>
<td>5 %</td>
</tr>
</tbody>
</table>

The dependent variables the mass flow rate of the air ($\dot{m}_a$), fuel ($\dot{m}_f$) and combustion product $\dot{m}_g$ ($\dot{m}_a + \dot{m}_f$), the power required by the compressor ($W_{AC}$), the power developed by turbine, and the following pressures and temperatures: air compressor ($p_2, T_2$), combustion chamber ($p_3$), gas turbine ($p_4, T_4$).

### 2.2. Energy Analysis

The first law thermodynamic is given by the following formula:

$[\text{Energy In}] = [\text{Desired Energy Out}] + [\text{Energy Loss}]$

$[\text{Thermal Efficiency}] = \eta = [1 - \frac{\text{EnergyLoss}}{\text{EnergyIn}}]$, Energy can not be destroyed – a first law concept.

Demoting the fuel-air ratio on a molar basis as $\lambda$, the molar flow rate of the fuel, air, and combustion product are related by:

$$\frac{\dot{m}_f}{\dot{m}_a} = \lambda$$

$$\frac{\dot{m}_g}{\dot{m}_a} = 1 + \lambda$$

(1)

Where the subscripts F, P and a denote, respectively, fuel combustion product and air. For complete combustion of methane the chemical equation take the form

$$\lambda \text{CH}_4 + [0.7748 \text{N}_2 + 0.2059 \text{O}_2 + 0.003 \text{CO}_2 + 0.019 \text{H}_2\text{O}] \rightarrow [1 + \lambda] [\lambda \text{N}_2 + \lambda \text{O}_2 + \lambda \text{CO}_2 + \lambda \text{H}_2\text{O}]$$

(2)

Balancing carbon, Hydrogen, and Nitrogen, the mole fraction of the component of the combustion products:
The fuel air ratio can be obtained from an energy rate balance follows:
\[ O = Q_{CV} - W_{CV} + \dot{m}_f \bar{h}_f + \dot{m}_a \bar{h}_a - \dot{m}_p \bar{h}_p \]  
(4)

Heat loss is assumed to be 2% of the fuel lower heating value, we have:
\[ Q_{CV} = -0.02 \dot{m}_f \text{LHV} = \dot{m}_a (-0.02 \bar{X} \text{LHV}) \]  
(5)

Collecting results
\[ O = -0.02 \bar{X} \text{LHV} + h_a + \bar{X} h_f - (1+X) h_p \]  
(6)

Using ideal-gas mixture principle to determine the enthalpies of the air and combustion product, we have for \( T_3 \) 1643 K
\[ h_a = [0.7748 h_{N_2} + 0.2059 h_{O_2} + 0.003 h_{CO_2} + 0.019 h_{H_2} O_2](T_2) \]  
(7)

\[(1-\bar{X}) h_p = [0.7748 h_{N_2} + (0.2059 - 2\bar{X}) h_{O_2} + (0.003 - \bar{X}) h_{CO_2} + (0.019 + 2\bar{X}) h_{H_2} O_2](T_3) \]  
(8)

From the result of equation (3) to (10), the enthalpies of the air and combustion product, \( \bar{X} \) may be found. Evaluating enthalpy values in kJ/mol as in appendices Table C.1. Bejan at al (1996), we have \( \bar{h}_f = -74.872 \text{kJ/kmol, LHV} = 802,361 \text{kJ/kmol} \) and enthalpy \( h_{N_2} \), \( h_{O_2} \), \( h_{CO_2} \) and \( h_{H_2} O_2 \) for temperature \( T_2 \) and \( T_3 \).

From a control volume enclosing the compressor and turbine, energy rate balance take the form:
\[ O = -W_{CV} + \dot{m}_f (\bar{h}_1 - \bar{h}_2) + \dot{m}_a (\bar{h}_3 - \bar{h}_4) \]  
(9)

The term \( (\bar{h}_1 - \bar{h}_2) \) and \( (\bar{h}_3 - \bar{h}_4) \) of equation (10) are evaluated using the isentropic compressor efficiency \( (\eta_{AC}) \) and the isentropic turbine efficiency \( (\eta_{GT}) \) as follows:

\[ \eta_{AC} = \frac{\bar{h}_2 - \bar{h}_1}{h_2 - h_1} \quad \text{and} \quad \eta_{GT} = \frac{\bar{h}_3 - \bar{h}_4}{h_3 - h_4} \]  
(10)

With \( \bar{h}_1, \bar{h}_2, \bar{h}_3 \) and \( h_4 \) known, the value of mass flow rate of air \( \dot{m}_a \) can be calculated, accordingly:

\[ \dot{m}_a = \left( \frac{M_a}{(1+\bar{X})(h_3 - h_4) + (h_1 - h_2)} \right) \frac{(M_a) W_{CV}}{\eta_{AC}} \]  
(11)

The mass flow rate of the fuel is then

\[ \dot{m}_f = \bar{X} \left( \frac{\bar{M}_f}{\bar{M}_a} \right) \dot{m}_a \]  
(12)

Result of energy analysis fuel-air ratio \( (\bar{X}) \), mass flow rate of air \( \dot{m}_a \) and mass flow rate of fuel \( \dot{m}_f \) are found to be equal:

\( \bar{X} = 0.004 \text{ kg/s, } \dot{m}_a = 473.0 \text{ kg/s, } \dot{m}_f = 10.10 \text{ kg/s} \)

2.3. **Exergy Analysis**

The second law thermodynamic my be written as:

\[ [\text{Energy In}] = [\text{Desired Energy Out } ] + [\text{ Energy Loss }] \]  
(13)
Based on this equation, we defined the exergetic efficiency as follow:

$$\varepsilon = \left[1 - \frac{\text{Exergy Destruction}}{\text{Energy In}} - \frac{\text{Energy loss}}{\text{Exergy In}}\right]$$

The total exergy of a system $\dot{E}$ can be divided into four components: physical exergy $\dot{E}^{PH}$, kinetic exergy $\dot{E}^{KN}$, potential exergy $\dot{E}^{PT}$, chemical exergy $\dot{E}^{CH}$, Bejan at al (1994), Tsatsaronis at al (1994), Szargut et al (1998) and Kotas (1985):

$$\dot{E} = \dot{E}^{PH} + \dot{E}^{KN} + \dot{E}^{PT} + \dot{E}^{CH}$$

or

$$\dot{e} = e^{PH} + e^{KN} + e^{PT} + e^{CH}$$

Considering a system at rest relative to the environment ($\dot{e}^{KN} = \dot{e}^{PT} = 0$)

The physical exergy $\dot{E}^{PH}$ is given by the expression:

$$\dot{e}^{PH} = \dot{E}^{PH}/\dot{m} = (h - h_0) - T_0(s - s_o)$$

For the atmospheric conditions, chemical exergy formulation can be used:

$$e^{CH} = \sum_{K=1}^{N} X_K e^{-K} + R T_0 \sum_{K=1}^{N} X_K \ln X_K$$

An approximate formula for chemical exergy of methane is given as Tsatsaronis et al (2003)

$$\frac{e^{-CH}}{HHV} = 0.94$$

The exergy balance of each component may be given as: Bejan at al (1996)

$$\dot{E}_{FK} = \dot{E}_{PK} + \dot{E}_{LK} + \dot{E}_{DK}$$

Where $\dot{E}_{FK}$ = exergy fuel,

$\dot{E}_{PK}$ = exergy product,

$\dot{E}_{LK}$ = exergy loss,

$\dot{E}_{DK}$ = exergy destruction.

The exergy destruction $\dot{E}_{DK}$ is related to the entropy generation by

$$\dot{E}_{D} = T_0 S_{gen}$$

Equation 20. is known also as the Gouy-Stodola theorem, Bejan at al (1996) and Szarguat et al(1988). The exergetic efficiency can be written:

$$\varepsilon_K = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_L + \dot{E}_D}{\dot{E}_F}$$

Exergy destruction ratios $Y_D$ and $Y^*_D$ and the exergy loss ratio $Y_L$ may be written as

$$Y_D = \frac{\dot{E}_D}{\dot{E}_{F,tot}} , \ Y^*_D = \frac{\dot{E}_D}{\dot{E}_{D,tot}} , \ Y_L = \frac{\dot{E}_L}{\dot{E}_{F,tot}}$$

2.4. The Result of energy and exergy analysis

The results of analysis according to equation (1) to (12) and exergy analysis according to equations (13) to (22) are calculated in table 3. And table 4. According to Figure 1.
Table 3. Energy and exergy data

<table>
<thead>
<tr>
<th>state</th>
<th>Substance</th>
<th>Mass flow rate (kg/s)</th>
<th>Temp (K)</th>
<th>Pressure (bars)</th>
<th>Exergy Rate (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Air</td>
<td>473.0</td>
<td>298.15</td>
<td>1.013</td>
<td>0</td>
</tr>
<tr>
<td>2.</td>
<td>Air</td>
<td>473.0</td>
<td>688.35</td>
<td>14.182</td>
<td>180.4</td>
</tr>
<tr>
<td>3.</td>
<td>Combustion product</td>
<td>483.0</td>
<td>1643.0</td>
<td>13.473</td>
<td>607.7</td>
</tr>
<tr>
<td>4.</td>
<td>Combustion product</td>
<td>483.0</td>
<td>889.0</td>
<td>0.933</td>
<td>149.5</td>
</tr>
<tr>
<td>5.</td>
<td>Fuel</td>
<td>10.0</td>
<td>298.15</td>
<td>12.0</td>
<td>3.85</td>
</tr>
</tbody>
</table>

Using data Table 3 and Table 4, the value of exergetic efficiency ($\eta_e$) can be calculated and the value of exergetic efficiency ($\epsilon$) can be shown in Table 4.

2.5 Economic Analysis

The aim of economic analysis is to provide sufficient input to be used in thermoeconomic analysis, the following steps should be applied in this kind of economic analysis, Bejan et al (1996):

1. **Purchased equipment costs (PEC) should be estimated**: Purchase Equipment Cost (PEC) values of table (5) are calculated from the following formulations:

   \[
   \text{PEC}_{ac} = \left[ \frac{C_{11}}{C_{12} - \eta_{ac}} \right] \ln \left( \frac{p_{2}}{p_{1}} \right) \left( \frac{p_{2}}{p_{1}} \right) \tag{23} 
   \]

   \[
   \text{PEC}_{cc} = \left[ \frac{C_{21}}{C_{22} - p_{3}/p_{2}} \right] \left( \frac{p_{2}}{p_{1}} \right) \ln \left( \frac{p_{3}}{p_{4}} \right) \left( \frac{1 - \exp(C_{23} T_{3} - C_{24})}{C_{23} T_{3} - C_{24}} \right) \tag{24} 
   \]

   \[
   \text{PEC}_{\eta} = \left[ \frac{C_{31}}{C_{32} - \eta_{\eta}} \right] \ln \left( \frac{p_{3}}{p_{4}} \right) \left( \frac{1 - \exp(C_{33} T_{3} - C_{34})}{C_{33} T_{3} - C_{34}} \right) \tag{25} 
   \]

Table 5. Constant used in the equation (23) – (25).

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_{11}$ ($/\text{kg/s}$)</th>
<th>$C_{12}$ ($/\text{K}$)</th>
<th>$C_{21}$ ($/\text{kg/s}$)</th>
<th>$C_{22}$ ($/\text{K}$)</th>
<th>$C_{23}$ ($/\text{K}$)</th>
<th>$C_{24}$ ($/\text{K}$)</th>
<th>$C_{31}$ ($/\text{kg/s}$)</th>
<th>$C_{32}$ ($/\text{K}$)</th>
<th>$C_{33}$ ($/\text{K}$)</th>
<th>$C_{34}$ ($/\text{K}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor (AC)</td>
<td>71.0</td>
<td>0.9</td>
<td>46.0</td>
<td>0.995</td>
<td>0.081 (K$^1$)</td>
<td>26.4</td>
<td>479.34</td>
<td>0.92</td>
<td>0.036 (K$^1$)</td>
<td>54.4</td>
</tr>
<tr>
<td>Combustion Chamber</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine (GT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. **Year-by-year analysis should be done**: in this analysis, carrying charges and experience should be estimated for each year within the plant economic life.
3. Levelezed cost should be calculated: Cost components very significantly within the economic life of the plant. In general, carrying charges decrease while fuel and operating and maintenance cost increase with increasing year of operation. Therefore, levelized annual values for all cost component should be used to simplify thermoeconomic analysis.

Total revenue requirement, fuel and operating maintenance levelized cost can shown as:

$$TRR_L = CRF \sum_{i=1}^{n} \frac{TRR_j}{(1+i_{eff})^j}$$

Where, CRF is the capital recovery factor $i_{eff}$, effective annual-of-money and $TRR_j$ is the value of TRR in the jth capital recovery factor =

$$CRF = \frac{i_{eff}(1+i_{eff})^n}{(1+i_{eff})^n - 1}$$

A levelized fuel cost ($FC_L$) and operating maintenance cost ($OMC_L$) can be show as:

$$FC_L = FC_0 \frac{k_{FC}(1-k_{FC}^n)}{(1-k_{FC})} CRF$$

$$OMC_L = OMC_0 \frac{k_{OMC}(1-k_{OMC}^n)}{(1-k_{OMC})} CRF$$

Where $k_{FC}$ and $k_{OMC}$ is annual escalating rate for the fuel cost and operating and maintenance cost, n number of year

Therefore, the levelized carrying charge ($CC_L$) can be written as:

$$CC_L = TRR_L - FC_L - OMC_L$$

Cost rate ($\hat{Z}_K$) associated with capital investment (CI) and operating and maintenance expenses (OM) for the kth component:

$$\hat{Z}_{CI} = \frac{CCL}{\tau} \frac{PEC_K}{\sum_{K} PEC_K}$$

$$\hat{Z}_{OM} = \frac{OMCL}{\tau} \frac{PEC_K}{\sum_{K} PEC_K}$$

Table 5. Shows, the levelized total revenue requirement ($TRR_L$), annual fuel cost ($FC_L$), annual operating and maintenance cost ($OMC_L$), carrying change ($CC_L$) rates are calculated using equation (28) to (31).
Table 6. Annual levelized cost of TRR_L, FC_L, OMC_L and CC_L of Mitsubishi M701 Da

<table>
<thead>
<tr>
<th>Component</th>
<th>TRR_L</th>
<th>FC_L</th>
<th>OMC_L</th>
<th>CC_L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Revenue Requirement</td>
<td>$ 88.768 x 10^6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>$ 76.277 x 10^6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating and Maintenance Cost</td>
<td>$ 6.906 x 10^6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrying Changes</td>
<td>$ 5.585 x 10^6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Illustrates the time scale used for the calculating the annual levelized cost.

Figure 4. Illustration of time of time scales used for the year-by-year analysis and the calculation of the levelized annual cost for the case study gas turbine system.

The purchase equipment cost of the gas turbine plant component in Table 7. are calculated using equations (23), (24) and (25) and constant used in table 5.

Table 7. Purchase Equipment Cost Component.

<table>
<thead>
<tr>
<th>Component</th>
<th>PEC</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Compressor (AC)</td>
<td>PEC_{AC}</td>
<td>$ 31.056 x 10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion Chamber (CC)</td>
<td>PEC_{CC}</td>
<td>$ 12.090 x 10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine (GT)</td>
<td>PEC_{GT}</td>
<td>$ 1204.906 x 10^6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The cost rate ($\dot{Z}_K$) associated with capital investment ($\dot{Z}^{CI}$) and operating and maintenance cost ($\dot{Z}^{OH}$) is calculated with aid of carrying charges (CC_L) and the operating and maintenance cost (OMC_L) from Table 6 and Table 7 and using equations (32) and (33), thus:

$Z_{AC} = 41.627$ $/h$, $Z_{CC} = 20.84$ $/h$

$Z_{GT} = 1615.0$ $/h$

2.6. Thermoeconomic Analysis

The cost balance and auxiliary relation are formulated for each component of gas turbine power plant system. These formulations are as follows: $\dot{C}_P = \dot{C}_F + \dot{Z}_K$

Air Compressor (AC):

$\dot{\dot{C}}_1 + \dot{\dot{C}}_7 + \dot{Z}_{AC} = \dot{\dot{C}}_2$  \hspace{1cm} (34)
\hfill $\dot{\dot{C}}_1 = 0$ (assumption) \hspace{1cm} (35)

Combustion Chamber (CC): $\dot{\dot{C}}_2 + \dot{\dot{C}}_5 + \dot{Z}_{CC} = \dot{\dot{C}}_3$ \hspace{1cm} (36)

Gas Turbine (GT): $\dot{\dot{C}}_3 + \dot{Z}_{GT} = \dot{\dot{C}}_4 + \dot{\dot{C}}_6 + \dot{\dot{C}}_7$ \hspace{1cm} (37)
\( \frac{\dot{C}_4}{E_4} = \frac{\dot{C}_5}{E_5} \) (F rule), \( \frac{\dot{C}_7}{E_7} = \frac{\dot{C}_6}{E_6} \) (P rule) \hspace{1cm} (38)

Solving linear equation (34) to (38), cost formulation within the system and cost of product may be calculated. Results are tabulated below:

<table>
<thead>
<tr>
<th>Stream</th>
<th>( \dot{E} ) (MW)</th>
<th>( \dot{C} ) ($/h)</th>
<th>( C ) ($/GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>180.40</td>
<td>9081.114</td>
<td>13.986</td>
</tr>
<tr>
<td>3</td>
<td>610.40</td>
<td>19346.00</td>
<td>8.804</td>
</tr>
<tr>
<td>4</td>
<td>152.00</td>
<td>4690.0</td>
<td>8.804</td>
</tr>
<tr>
<td>5</td>
<td>522.00</td>
<td>10244.0</td>
<td>5.450</td>
</tr>
<tr>
<td>6</td>
<td>253.00</td>
<td>9039.50</td>
<td>10.139</td>
</tr>
<tr>
<td>7</td>
<td>198.13</td>
<td>7232.0</td>
<td>10.139</td>
</tr>
</tbody>
</table>

The exergy costing a cost associated with exergy stream, can be written as follow:

\[ \dot{C}_i = c_i \dot{E}_i, \dot{C}_e = c_e \dot{E}_e, \dot{C}_w = c_w \dot{E}_w, \dot{C}_q = c_q \dot{E}_q \] \hspace{1cm} (39)

Here \( c_i, c_e, c_w \) and \( c_q \) denote average cost per unit of exergy in dollar gigajoule ($/GJ), Bejan at al(1996).

The cost associated with the exergy destruction (\( \dot{C}_{DK} \)) in a component is a hidden cost, and is defined as:

\[ \dot{C}_{DK} = c_{FK} \dot{E}_{DK} (\dot{E}_{PK} \text{ fixed}) \] \hspace{1cm} (40)

\[ \dot{C}_{DK} = c_{PK} \dot{E}_{DK} (\dot{E}_{FK} \text{ fixed}) \] \hspace{1cm} (41)

The relative cost difference (\( \Gamma_k \)) is a useful for evaluating the system component, Bejan at al(1996), Tsatsaronis (2002). The relative cost difference \( \Gamma_k \) is defined by:

\[ \Gamma_k = \frac{C_{PK} (\dot{E}_{DK} + \dot{E}_{L,K}) + (Z_{KL}^{CI} + Z_{KL}^{OM})}{C_{FK} \dot{E}_{PK}} \] \hspace{1cm} (42)

Or

\[ \Gamma_k = \frac{1 - \varepsilon_k}{\varepsilon_k} + \frac{(Z_{KL}^{CI} + Z_{KL}^{OM})}{C_{FK} \dot{E}_{PK}} \] \hspace{1cm} (43)

The thermoeconomic factor \( f \) expresses the contribution of non-exergy-related cost and cost of exergy destruction, Bejan et al (1996) and Tsatsaronis (2002) is calculated from the following formulation:

\[ f_k = Z_K \] \hspace{1cm} (44)

\[ Z_K + C_{FK} (\dot{E}_{DK} + \dot{E}_{L,K}) \]

Table 9. Summarizes the thermoeconomic variable calculated for each component of the gas turbine power plant, and rank components in descending order of cost importance using the sum

\[ Z_K + C_{DK} \]
The total cost rate associated the product for the overall system \( \dot{C}_{P,tot} \) is given by Beja et al (1996)

\[
\dot{C}_{P,tot} = \dot{C}_1 + \dot{C}_s + \sum_k Z_k + \dot{Z}_{other}
\]

\[= 14,179.0 \text{ $/h}$

6. DISCUSSION

Table 8. Summarized the thermoeconomic variables for each component of the gas turbine system. According to the methodology, the component are listed in order of descending value of the sum \( Z + \dot{C}_D \), Bejan et al (1996), Tsatsaronis (1999), (2002), Siahaya et al (2006).

The combustion chamber, gas turbine and the air compressor have the highest values of the sum \( Z + \dot{C}_D \) and are, therefore, the most important components from the thermoeconomic viewpoint. The low value of the combustion chamber shows that the cost associated with the combustion chamber are almost exclusively due to exergy destruction. A part of the exergy destruction in a combustion chamber can be avoided by preheating the reactants and by reducing the heat loss and the excess air, Bejan et al (1996), Tsatsaronis (1999), (2002). By considering measure for reducing the high cost associated with the exergy destruction in the combustion chamber, two key design variables have been identified, temperature \( T_2 \) and \( T_3 \). A increase in these temperature reduces the \( Z + \dot{C}_D \) value for the combustion chamber and other components but increase their capital investment cost.

The gas turbine, which has the second highest value of the sum \( Z + \dot{C}_D \), the relatively large value of factor \( f \) suggest that the capital investment (CI) and operating and maintenance cost (OMC) dominate. The capital investment cost of the gas turbine depend on the temperature \( T_3 \), pressure \( p_2/p_1 \), and efficiency \( \eta_{GT} \). To reduce the high \( Z \) value associated with the gas turbine, we should consider a reduction of the value of at lest one of these variables.

The air compressor has the second highest thermoeconomic factor \( f \) value and the highest relative cost different \( r \) value among all the components. Thus we would expect the cost effectiveness of the entire system to improve if the \( Z \) value for the air compressor is reduced. This may be achieved by reducing the pressure ratio \( p_2/p_1 \) and or the isentropic compressor efficiency \( \eta_{AC} \), Tsatsaronis (1999) and (2002), Bejan et al (1996).

7. CONCLUSION

In this paper, gas turbine power plant system are investigate by energy, exergy and thermoeconomic analysis. General methodology of these methods are discussed. Therefore the thermoeconomic is a very powerful tool for understanding the interconnecting between thermodynamic and economic. The thermoeconomic method discussed here is a valuable tool in the optimization of complex exergy system.

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