A Thermo-Economic Analysis Method for Combined Cycle Power Plants under Flexible Operation Modes

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Abstract

Gas steam combined cycle power plants have been playing an important role in peak shaving of a power grid. The increasingly complexity of power demand and power supply structure puts forward higher requirements for flexible operation, which is characterized by frequent load changes and start-stop operation. Under such circumstances, obtaining an optimal operation strategy becomes essential for profitability of combine cycle power plants. In this paper, a thermodynamic model comprising key functional modules of a combined cycle power plant and its overall cycle process are presented. An economic analysis method based on heat consumption rate is proposed. The proposed model is applied in a combined cycle power plant in China, and quantitative impacts of flexible operation on maintenance cost are discussed. Results show that the model can reflect the thermal economy of the power plant under variable environmental conditions. The economic analysis shows that there are significant economic differences between different flexible operation cases.

Keywords: Combined Cycle Power Plant, Thermo-Economic Analysis, Flexible Operation

1. Introduction

Gas steam combined cycle (GTCC) power plants perceives the advantages of high cycle efficiency and clean emissions. Also, due to its feature of very short-time start-up and load-change operations, GTCC have been playing an important role in peak shaving and demand respond of electricity grid. Recently, the availability of renewable energy and complex power demand have placed greater requirements on grid stability. Accordingly, GTCC faces a more arduous task of peak shaving and flexible operation. The economy of GTCC is highly sensitive to fuel cost, also frequent load changes will affect the service life of components, determining maintenance and replacement costs. It is essential to establish a thermo-economic analysis method applicable to GTCC under flexible operation modes.

Many studies have been done using different analysis methods to investigate the cost and economy of GTCC. Based on exergy analysis, the thermal economics model and cost equation of GTCC are established, and the exergy cost of each component of the system is calculated (Li et al., 2015). Considering the multiple benefits of the economy and environment, multi-objective optimization was carried out using three objective functions, concerned with exergy efficiency, total cost rate and CO₂ emission (Avval et al., 2011). Moreover, intelligent search techniques such as genetic algorithm was applied to find the
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Pareto Frontier of exergy efficiency and total cost rate of GTCC, and best values of design parameters were presented (Ahmadi et al., 2011). However, the existing research mainly focus on GTCC operating under design mode and aim at finding the best design values of cycle parameters. There are few studies focused on economy of an established GTCC under different flexible operation modes. Also the analysis of operation and maintenance cost related to drastic load changes is still lacking. In response to these research gaps, this paper proposes a thermal-economic analysis method, which is based on a thermal dynamic GTCC model. In terms of fuel cost, this paper calculates fuel consumptions under various operating conditions with different power output and environmental conditions. In terms of maintenance cost, this paper quantitatively describes the impact of start-stop and load-change operations by investigating equivalent operation hours. Moreover, a GTCC power plant in China is taken as a case study to verify the applicability of the method.

2. Methodology

2.1. Thermal dynamic model of GTCC

Figure 1 illustrates a gas steam combined cycle with a non-additionally heat recover steam generator (HRSG). In this study, thermo-dynamic models of gas turbine, steam turbine and HRSG are established, and parameters of gas and steam function as connections among each component model.

A typical gas turbine consists of a compressor, a combustor and a turbine. For compressor, parameters that characterizes its performance under off-mode operation are relative reduced pressure ratio $\pi_C$ and relative reduced efficiency $\eta_C$, which are affected by relative reduced flow rate $M_{\text{red}}$ and relative reduced speed $n_C$. Empirical formula as Eq. (1) - Eq.(5), can be constructed based on compressor characteristic diagrams (Zhang et al., 2011). The two empirical parameters $p$ and $m$ can be obtained from Figure 2 and Figure 3.

$$\pi_C = c_1 \cdot M_{\text{red}}^2 + c_2 \cdot M_{\text{red}} + c_3$$  \hspace{1cm} (1)

$$\eta_C = [1 - c_4(1 - \pi_C)^2] \cdot \left( \frac{n_{\text{red}}}{M_{\text{red}}} \right) \cdot \left[ 2 - \left( \frac{n_C}{M_{\text{red}}} \right) \right]$$  \hspace{1cm} (2)

$$c_1 = \frac{n_C}{p(1 - \frac{m}{n_C}) + n_C(n_C - m)^2}$$  \hspace{1cm} (3)
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\[ c_2 = \frac{(p - 2mn_c^2)}{p \left(1 - \frac{m}{n_c}\right) + n_c(n_c - m)^2} \]  
(4)

\[ c_3 = \frac{- \left(2mn_c - m^2n_c^3\right)}{p \left(1 - \frac{m}{n_c}\right) + n_c(n_c - m)^2} \]  
(5)

The gas temperature at combustor outlet follows the energy balance equation Eq.(6). For turbine, the mathematical relationship between pressure and flow can be quantified by Flugel formula Eq.(7). Net power output of gas turbine is shown in Eq.(8).

\[
m_{fuel} \cdot \left[c_{p,fuel} \cdot (T_{fuel} - T_{ref}) + LHV\right] + m_{air} \cdot c_{p,air} \cdot (T_2 - T_{ref}) = m_t \cdot c_t \cdot (T_3 - T_{ref}) \]  
(6)

\[
\frac{M_t}{(M_t)_0} = \frac{p_3^2 - p_4^2}{(p_3^2 - p_4^2)_0} \cdot \frac{(T_3)_0}{T_3} 
\]  
(7)

\[
P_{GT} = M_{air} \cdot c_{p,air} \cdot (T_2 - T_1) + M_t \cdot c_t \cdot (T_a - T_3) 
\]  
(8)

The steam turbine in GTCC usually operates under sliding pressure mode. The characteristics of it under off-mode operation also follow Flugel formula Eq.(7). Variables in the formula represent the state of superheated steam.

2.2. Operation and maintenance cost related to start-stop operation and load change

This study applied equivalent operating hours (EOH) to describe the life expenditure of gas turbine. And there exists a threshold of EOH for maintenance and replacement of parts. Start-stop operation and load change can be expressed quantitatively by adding additional EOH. Eq.(9) shows the calculation of EOH, where AOH represents actual stable operating hours. And A represents a correction coefficient, which shows the amount of actual stable operating hours equivalent to a normal Start-stop operation. The value of A is determined by the ratio of the thermal stress applied to the high-temperature components during start-stop operation to the thermal stress during stable operation. The influence of load change is essentially similar to start-stop operation, so we can use Eq.(10) to describe the equivalent number of Start-stop during a period of time comprising j Start-stop operation and n load-change operation. LC is a correction
coefficient indicating the amount of equivalent number of start-stop operation of a single load-change operation. Fig 4 shows the value of $LC$ as a function of percentage change in load and rate of load change, which is suggested by Mao (2010).

$$E_{OH} = (AOH + A \times E) \times F$$  \hspace{1cm} (9)

$$E = j + \sum_{i=1}^{n} (LC)_i$$  \hspace{1cm} (10)

![Figure 4 Value of LC as a function of percentage change in load and rate of load change](image)

3. Case study

A GTCC power plant in China is chosen to carry out case study using the method proposed. The power plant consists of a 9E gas turbine, a non-additionally HRSG and a steam turbine. Values of operation parameters under design mode are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameters of gas turbine</th>
<th>Value</th>
<th>Unit</th>
<th>Parameters of steam turbine</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>power output</td>
<td>125.9</td>
<td>MW</td>
<td>power output</td>
<td>61.61</td>
<td>MW</td>
</tr>
<tr>
<td>speed</td>
<td>3000</td>
<td>rpm</td>
<td>HP steam pressure</td>
<td>62</td>
<td>bar</td>
</tr>
<tr>
<td>pressure ratio</td>
<td>12.3</td>
<td>-</td>
<td>HP steam temperature</td>
<td>519</td>
<td>ºC</td>
</tr>
<tr>
<td>air/fuel inlet temperature</td>
<td>15</td>
<td>ºC</td>
<td>HP steam flow rate</td>
<td>51.56</td>
<td>kg/s</td>
</tr>
<tr>
<td>air/fuel inlet pressure</td>
<td>1.013</td>
<td>bar</td>
<td>LP steam pressure</td>
<td>6.5</td>
<td>bar</td>
</tr>
<tr>
<td>mass flow of air</td>
<td>402.8</td>
<td>kg/s</td>
<td>LP steam temperature</td>
<td>259</td>
<td>ºC</td>
</tr>
<tr>
<td>mass flow of fuel</td>
<td>8.3</td>
<td>kg/s</td>
<td>LP steam flow rate</td>
<td>8.72</td>
<td>kg/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>back pressure</td>
<td>0.07</td>
<td>bar</td>
</tr>
</tbody>
</table>

3.1. Gas turbine simulation

This study takes power output, environment pressure and environment temperature as the input to figure out the fuel consumption. Then we select 1400 sets of measurement data for simulation, and the result is shown as Fig 5. Average relative error of simulation is 1.7%, and it demonstrate the accuracy of the model.

3.2. Steam turbine simulation

The HRSG produces high-pressure steam and low-pressure steam simultaneously. The high-pressure steam enters steam turbine at inlet directly, whilst the low-pressure steam enters at the middle of steam turbine and expands at remaining stages. Therefore, this study divides the steam turbine into high-pressure section and low-pressure section.
Simulation of the model is carried out with 2000 sets of operating data. Fig 6 shows the results and average relative error of simulation is 0.8%.

3.3. Operation and maintenance cost calculation

This study designs three scenarios with different load curve, as is shown in Fig 7. The most important factors that distinguish the three scenarios are the number and severity of start-stop operations and load changes. Scenario A reproduces the actual load curve of a given day of the GTCC power plant in China. The gas turbine starts and stops daily for the purpose of peak shaving. Scenario B shows that the gas turbine only starts and stops once a week, and the rest of the time it operates at continuous constant load. Scenario C indicates frequent start-stop operation and load change. The time range is one week and the output range of gas turbine under stable operation is between 80MW and 125.9MW. The AOH of the three scenarios are controlled as 95.08h, and the power generation is controlled as 11.1GW·h.

Table 2 displays the results of calculation. Compared to Scenario A, a constant-load operation strategy like scenario B will extend the service life of components to 2.06 times. However, frequent load change like scenario C will shorten the service life by 0.6%.
In general, the EOH threshold of components such as combustion chamber flame tube is 24,000h (Mao et al., 2010). This study supposes that a single maintenance and replacement cost is 26,000 EUR and the interest rate is 15%. Compared to scenario A, a constant-load operation strategy like scenario B can save 24.75% of the replacement and maintenance cost, whilst frequent load change like scenario C will increase 0.3% of the replacement and maintenance cost.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>EOH (h)</th>
<th>Number of start-stop operations</th>
<th>Number of load-change operations</th>
<th>Service Life (a)</th>
<th>Discounted maintenance and replacement cost (EUR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>238.93</td>
<td>7</td>
<td>14</td>
<td>1.93</td>
<td>19,853</td>
</tr>
<tr>
<td>Scenario B</td>
<td>116</td>
<td>1</td>
<td>0</td>
<td>3.97</td>
<td>14,928</td>
</tr>
<tr>
<td>Scenario C</td>
<td>240.47</td>
<td>7</td>
<td>70</td>
<td>1.91</td>
<td>19,909</td>
</tr>
</tbody>
</table>

4. Conclusions

A thermo-economy analysis method based on thermo-dynamic GTCC model is proposed in this paper. Off-mode modeling is carried out for key components such as gas turbine and steam turbine. The simulation results indicate that average relative error of thermo-dynamic gas turbine model is 1.7%, and the average relative error of steam turbine model is 0.8%. This paper also applies equivalent running hours to quantify the cost of start-stop and load-change operations. Three scenarios with different load curves are studied. Results show that there are significant economic differences between different flexible operation scenarios. These differences are reflected in the huge difference in service life of equipment, which affects the maintenance and replacement costs.

Acknowledgement

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References


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