Economic Analysis of Power Plants Under Different Loads Based on Structural Theory

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Abstract. The economy analysis of coal-fired power plants is usually based on traditional thermal balance method, which only considers the thermodynamic factors but ignores the economic factors such as cost. In this paper, to have a more comprehensive and accurate evaluation on the production performance and economical efficiency of thermal systems, the cost analysis method based on the Structural Theory of Thermoeconomic is applied to a 300MW thermal power generating unit in Yunnan province. The thermoeconomic model and the exergetic cost model for the plant based on the Fuel—Product concept have been defined to quantify the productive interaction between different devices. By calculating the thermoeconomic cost of four typical different working conditions and analyzing the distributions and change rules of generating cost, the Structural Theory of Thermoeconomic is proved scientific and useful and offers a set of feasible and reliable analysis method for the performance analyses and improvement of power plants.

1. Introduction
Thermal economics developed on the basis of exergy analysis, focusing on economic activities based on thermodynamic analysis. Exergy analysis method takes account of both "quantity" and "quality" of energy, which can reflect the essence of the loss of ability, and it is more accurate and objective than the thermal equilibrium method based on the first law of thermodynamics. Besides of this, thermal economics also considers the cost of energy, based on thermodynamics and economics [1], [2]. In recent years, due to the difference between peak-valley electricity load increases, thermal power plants in China often run under low load conditions [3], [4]. In order to improve the operating economy under the low load of the unit, this paper uses the structural theory of thermal economics to analyze the operating economy of a 300MW unit in Yunnan under rated working conditions of different load. In this paper, the exergy cost and thermal economics cost of each component under different working conditions are calculated, and the economic operation suggestions under the low load is put forward.

2. Structural Theory And Data
The structural theory is created by the Spanish scholar A. Valero et al. The basic idea is to divide the energy system into multiple subsystems. The sub-systems communicate the simulated element behavior through some mass flow and energy flow to obtain a series of mathematical equations of characteristic equations. Since thermal economics calculations are based on analysis, this section also introduces the concept of exergy analysis [5]-[7].
2.1. A. Fuel-Product

The concept (Fuel-Product) is used to define the functions that describe each device, where "fuel" (F) is the flow required to obtain the product, and "Product" (P) refers to the flow of production as a subsystem. In addition to the two components of the condenser and the generator, the other components in the system consume two fuels: the negative entropy (FS) generated by the resource (FB) and the condenser. The specific definitions can refer to reference 6.

2.2. B. Drawing of Physical Structure Sketch and Productive Structure Sketch

The physical structure sketch of this paper is based on the system thermal balance sketch. According to the required degree of integration, the system will be divided into 24 components, and the physical structure sketch will be drawn in accordance with the relationship between the components. The productive structure sketch is based on the fuel-product definition after the completion of the physical structure drawing, using the interaction between the production elements. The physical structure sketch of this paper is shown in Fig. 1, and the productive structure sketch is shown in Fig. 2.

2.3. C. Indicators of Exergy Analysis

1) Loss of exergy: The actual process is irreversible, accompanied by a decline in exergy quality, and the total amount of exergy decreases, which is unavoidable. The part that is dissipated during the transfer process is called exergy loss. The formula can be expressed as: FB=P+I, where: I is the loss of the device; FB is the fuel of the input device and P is the product output of the product.
2) Exergy efficiency: it is the ratio of the resulting product to the fuel used to obtain the fuel, and is expressed by $\eta$. The expression is $\eta = \frac{P}{FB}$.

3) Exergy loss factor: it is the ratio of the loss of exergy ($I_i$) in a device to the total exergy fuel input to the system. It is expressed as: $\lambda_i = \frac{I_i}{\sum F}$.

2.4. D. Exergy Cost Modeling

The cost equation of the system expresses the resource $B_0$ consumed by the system as a function of each stream $B_i$, the internal parameter set of each component, and the system's final product can be gotten, that is:

$$B_0 = B_0(B_i, x, \omega) \quad i = 1, \ldots, m$$  \hspace{1cm} (1)

The establishment of the cost equation usually uses the differential chain rule to derive the derivation of the cost equation and the characteristic equation. When the consumption of any flow resource in the system changes, the chain differential rule is used to derive the derivative of (1), and then we have the formula as below:

$$\frac{\partial B_0}{\partial B_i} = k_{0,i}^* \quad i = 1, \ldots, e$$  \hspace{1cm} (2)

$$\frac{\partial B_0}{\partial B_i} = \sum_{j=i}^{m} \frac{\partial B_0}{\partial B_j} \frac{\partial g_j}{\partial B_i} \quad i = e + 1, \ldots, m$$ \hspace{1cm} (3)

The equation can be expressed as unit exergy consumption and technical product coefficient:

$$k_{p,i}^* = k_{0,i} + \sum_{j=1}^{n} k_{ij} k_{p,j}^* \quad i = 1, \ldots, n$$ \hspace{1cm} (4)

It can be seen from equation (4) that the unit cost per unit of flow is a function of the unit consumption of each component in the production structure. If the characteristic equation of each process element is known, then by solving this we can get the unit exergy cost.

2.5. E. Thermal Economics Modeling

The thermal economic model is a mathematical expression of the system production structure diagram. Each input stream $B_i$ is taken as the mathematical function of the output stream $B_j$, considering the whole product structure process and a series of internal parameters $X_i$, the characteristic equation can be established as follows: [8]-[11]

$$B_i = g_i(x_i, B_j)$$ \hspace{1cm} (5)

By using the Euler and fuel-product definitions of the first-order homogeneous equation, the above equation can be converted to the following linear equation:

$$P_i = B_{i0} + \sum_{j=1}^{n} k_{ij} p_j \quad i = 0, 1, \ldots, n$$ \hspace{1cm} (6)

where: $B_{i0}$ is the product of the i-th component as the total product of the system output to the environment; $k_{ij}=\frac{\partial g_i}{\partial B_j} \frac{B_{ij}}{p_j}$ stands for the technical product coefficient [6], to express the proportion of the i-th component in order to obtain the j-th unit of the unit product.
In the end, the thermal economics costs of the product include the cost of non-energy costs and the cost of non-energy costs, which are economic dimensions, $10^6$ yuan / kJ, and the cost of non-energy costs is calculated as:

$$cp = kB_n c_{FBn}^* + kS_n c_{FSn}^* + kZ_n$$  \( (7) \)

where $kZ_n$ is the product investment costs for the unit ($10^6$ yuan / kJ). $c_{FBn}^*$ and $c_{FSn}^*$ is the cost of unit fuel thermal economics and unit negative entropy costs, the specific calculation method can refer to the literature [6].

3. Example And Result Analysis

Taking a 300MW thermal power unit in Yunnan as the research object, the structural theory is used to calculate the exergy cost and unit thermal economic cost of each unit at 100%, 50%, 40% and 30% THA condition. According to the changes of the cost, suggestions are proposed to improve the economic efficiency of the unit.

Table 1 below shows the values of unit exergy cost for each component in the four different operating conditions.

| Component | 100% THA | 50% THA | 40% THA | 30% THA |
|-----------|----------|---------|---------|---------|
| GJ1       | 2.26     | 2.41    | 2.48    | 2.58    |
| GJ2       | 2.29     | 2.45    | 2.51    | 2.62    |
| GJ3       | 2.39     | 2.55    | 2.62    | 2.74    |
| DTR       | 2.49     | 2.68    | 2.75    | 2.87    |
| DJ1       | 2.50     | 2.72    | 2.81    | 2.95    |
| DJ2       | 2.43     | 2.64    | 2.73    | 2.87    |
| DJ3       | 2.74     | 3.09    | 3.25    | 3.49    |
| DJ4       | 3.14     | 3.06    | 2.99    | 2.94    |
| BSH       | 2.02     | 2.14    | 2.19    | 2.28    |
| RH        | 1.99     | 2.05    | 2.07    | 2.13    |
| HP1       | 2.31     | 2.50    | 2.56    | 2.66    |
| HP 2      | 2.22     | 2.35    | 2.41    | 2.50    |
| IP 1      | 2.21     | 2.34    | 2.28    | 2.51    |
| IP 2      | 2.17     | 2.31    | 2.37    | 2.45    |
| IP 3      | 2.23     | 2.36    | 2.41    | 2.50    |
| LP 1      | 2.25     | 2.43    | 2.46    | 2.57    |
| LP 2      | 2.24     | 2.33    | 2.44    | 2.54    |
| LP 3      | 2.43     | 2.53    | 2.60    | 2.68    |
| LP 4      | 2.72     | 2.81    | 2.63    | 3.69    |
| BFPT      | 2.57     | 2.80    | 2.94    | 3.08    |
| CND       | 0.09     | 0.10    | 0.10    | 0.10    |
| CP        | 12.95    | 14.69   | 15.74   | 17.35   |
| FWP       | 3.56     | 4.86    | 5.75    | 6.65    |
| GEN       | 2.31     | 2.45    | 2.48    | 2.62    |

The changes of the thermal economics cost for each component was shown in the histogram below.
From the table and chart above, the following conclusions can be drawn:

1) As the load decreases, the unit's loss coefficient and cost are significantly changed, and the total exergy loss and cost are increased.

2) As the load decreases, the thermoeconomics cost of each component is increased and the loss share of each component calculated by the thermoeconomics analysis is different from the results by previous heat balance method.

3) After the change of the load, the change trend of the exergy cost for each unit is different. The cost of the second and third high pressure cylinder and low pressure cylinder increase obviously increased with the decrease of the load. Therefore, we should focus on its economy when the power plants are running under low load.

4) Based on thermal economics, the place which has the larger exergy loss coefficient, have larger energy saving potential, and the boiler in the thermal system has the largest potential.

4. Conclusion

Through the calculation and analysis of the 300MW unit studied in this paper, it is found that there are still some problems in the design of the unit, and the conclusions can be draw:

1) The load has a great impact on the economy of the unit. When the unit load is less than 100%, with the decrease of the load, the unit's exergy loss and thermoeconomics cost increase, the efficiency and economy of the unit are reduced, so the unit should be run at the load as high as possible, but less than 100%.

2) It is more scientific to evaluate the performance of the unit equipment by and thermal economics than the traditional thermal equilibrium method.

This is because the analysis of thermal economics does not only take into account the quantity of energy, but also the quality of the energy, so that it can evaluate the production performance of each component in the system more scientifically.

3) When the 300MW unit is operated at a lower load, it should be noted that the relevant parameters and efficiency of the second and third parts of the high and low pressure cylinder, which reflects its internal irreversible resource loss is of great amount. So it has a greater energy-saving potential. In order to improve the economy, to reduce its exergy loss and its extraction steam pressure loss is necessary.

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