Analysis of the stage group efficiency of steam turbine based on the unified model for coal-fired power unit

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Abstract. During actual operation of the unit, the group efficiency inevitably deviates from the design value and influences the unit heat consumption rate. This paper conduct a series of turbine stage efficiency analysis of the influence of unit energy consumption based on the basic equations for economic analysis, combined with the variable condition of steam turbine model. 1000 MW unit produced by DFSTW as the research object, this paper calculates the load of several groups of different stage group efficiency, and the amount of change of the unit coal consumption. Summarizing, this paper analyses the stage group efficiency influence on the power supply coal consumption rate of the unit, and the variation of stage group efficiency influence on the unit energy consumption with the load change. The results can provide great reference for the operation optimization of thermal power unit.

1. Introduction

The efficiency of the steam turbine cylinder is the main indicator that reflects the performance of the cylinder. It is measured as an important monitoring parameter in the steam turbine thermal performance test and the unit operation process. When the efficiency of the steam turbine cylinder changes, it is often necessary to further calculate the change in the energy consumption of the unit. In addition, in order to evaluate the economics and safety of the technical transformation, the transformation of the steam turbine also needs to determine the impact of the efficiency of the steam turbine cylinders and stage group on the energy consumption of the unit. Economic analysis of thermal system based on the unified model of thermal power unit [1,2] proposed by Professor Yan Shunlin in North China Electric Power University (NCEPU). Combined with the calculation of the variable working condition of steam turbine, the efficiency of the turbine unit is change. Analysis of the impact on energy consumption is necessary. Taking the DF 1000 MW unit as the research object, calculate the energy consumption of the unit when the efficiency of the turbine is changed under different working conditions. The order of the influence of the efficiency of each group on the coal consumption of the unit and the variation of the efficiency of the cylinder group into the random group load are obtained, which has great guiding significance for the operation optimization of the 1000 MW thermal power unit.

2. Methods and analysis

The following are unified physical model and equations for the effect of stage group efficiency on energy consumption.
2.1. Unified physical model

Based on the energy balance equation and the mass balance equation, the following unified physical model of the thermal power unit is established as shown in figure 1.

![Figure 1: The unified model for coal-fired power unit.](image)

Where $h_{ii}$ is the exhaust steam of the i-th small steam turbine; $h_i$ is the outlet working volume of the i+1th small boiler; $Q_{ii}$ is the auxiliary steam-water heat algebra of the i-th small boiler; $D_i$ is the i-th name of the steam turbine; $D_{0}$ is the working fluid flow in the i-th small boiler; $D_0$ is the steam flow involved in the work in the i-th small steam turbine. $G_i$ is the sum of the water flow of the control unit in the i-th stage; $h_{i1}$ enters and exits the enthalpy of the i-th control body; $Q_{j}$ is the nominal heating amount entering the i-th control; $h_{ji}$ j-th extraction and the i-th control body shackles. Unless otherwise specified, “small steam turbine” and “small boiler” refer to the model of small steam turbine and small boiler in the unified model.

2.2. Group efficiency equation

In the unified model of the thermal power unit, the relative internal efficiency of each small steam turbine is the efficiency of the steam turbine stage. The relative internal efficiency of any small steam turbine is:

$$\eta_i = \frac{h_{i1} - h_{i2}}{\Delta h_{ii}}$$  \hspace{1cm} (1)

In the formula: $h_{i1}$, $h_{i2}$, $\Delta h_{ii}$ respectively, the steam enthalpy in and out value and the ideal ratio enthalpy of the small steam turbine under the reference condition, kJ·kg⁻¹.

2.3. Steam and water distribution equation

Using the first law of thermodynamics to establish the energy balance equation, the following general Steam and water distribution equations are obtained [2]:

$$...$$
Each of the equations, such as the $i$-th equation, indicates that the sum of the heat release from the $i$-th heater and the auxiliary energy enters and exits of the $i$-th heater is equal to enthalpy rise of the feed water or condensate in the $i$-th heater. Among them: when $i<j$, $\alpha_{ij}$ takes 0; when $i=j$, $\alpha_{ij}$ is the unit of steam exotherm; when $i>j$, $\alpha_{ij}$ is the unit of hydrophobic heat release, and $\tau$ is unit of condensate or feed water enthalpy rise.

The solution of the steam extraction amount is:

$$D_i = \frac{\tau G_i - Q_i - \sum_{j=1}^{i-1} a_{ij} D_j}{a_{ii}}$$  \hspace{1cm} (3)

2.4. Cycle heat absorption equation

The cycle heat absorption means the heat absorbed by the working fluid from the generalized boiler during the entire cycle of the unit, namely:

$$Q = \sum_{i=4}^{n+1} D_{bi} (h_{i-1} - h_{i-1,i-1}) + \sum_{i=1}^{n+1} Q_{bi}$$ \hspace{1cm} (4)

2.5. Steam turbine internal power equation

The internal work is the sum of the internal work done in each small steam turbine in the cycle, namely:

$$N = \sum_{i=1}^{n+1} D_{bi} (h_{i-1} - h_{i})$$ \hspace{1cm} (5)

2.6. Influence of relative internal efficiency change of small steam turbine on energy consumption

When the efficiency of the steam turbine stage $\eta_i$ changes, $\eta_{i1}$, $\eta_{i2}$, $\eta_{i3}$, etc., and then, $\eta'_{i1}$, $\eta'_{i2}$, $\eta'_{i3}$, etc., the coal consumption rate of the power supply $b_i$ also changes accordingly, from $b_i$ to $b'_i$, the amount of change is $\Delta b_i$. Taylor series expansion form:

$$\Delta b_i \approx \frac{\partial b_i}{\partial \eta_i} \cdot \Delta \eta_i + \frac{\partial b_i}{\partial \eta_2} \cdot \Delta \eta_2 + \frac{\partial b_i}{\partial \eta_3} \cdot \Delta \eta_3 + \ldots$$ \hspace{1cm} (6)

3. Results

The following is the analysis of influence of efficiency of each turbine stage on unit energy consumption.

Take the N1000-25.0/600/600 steam turbine produced by DongFang Steam Turbine as the research object, the thermal power unit unified model was used to calculate the efficiency change under 70% THA, 50% THA, 40% THA and THA sliding conditions. The impact on the energy consumption of the unit is calculated [3].

3.1. 1000 MW ultra-supercritical unit parameters

The N1000-25.0/600/600 steam turbine produced by DongFang Steam Turbine is a four-cylinder steam and condensing steam turbine. The boiler efficiency is 93%, the pipeline efficiency is 99%, the

$$\sum_{\substack{j=1 \atop i \neq j}}^{n} a_{ij} D_j + Q_i = \tau_i G_i \hspace{1cm} (i=1 \sim n)$$  \hspace{1cm} (2)
steam feed pump efficiency is 83%, the small steam turbine efficiency is 81%; the 1~3 section extraction steam pressure loss is 3%, and the 4~8 section extraction steam pressure loss is 5%; The operating parameters of the working conditions are shown in table 1, and the design values of the heater termina differences are shown in table 2.

### Table 1. Benchmark operation parameters of 1000 MW unit.

| Name                        | 40% THA | 50% THA | 70% THA | THA  |
|-----------------------------|--------|--------|--------|------|
| Power/MW                    | 400    | 500    | 700    | 1000 |
| Main steam pressure/MPa     | 11.1   | 13.6   | 19.1   | 25   |
| Main steam temperature/°C   | 600    | 600    | 600    | 600  |
| Main steam flow/t/h         | 1047.8 | 1289.8 | 1833.6 | 2733.4 |
| Reheat steam pressure/MPa   | 1.71   | 2.11   | 2.95   | 4.25 |
| Reheat steam temperature/°C | 585    | 600    | 600    | 600  |
| Back pressure/kPa           | 4.5/5.7| 4.5/5.7| 4.5/5.7| 4.5/5.7 |
| Factory electricity rate/%  | 5.9    | 5.77   | 5.5    | 5.03 |

### Table 2. Heater terminal difference design values of 1000 MW unit.

| Name | #1 | #2 | #3 | #5 | #6 | #7 | #8 |
|------|----|----|----|----|----|----|----|
| Upper| -1.7 | 0  | 0  | 2.8| 2.8| 2.8| 2.8|
| Lower| 5.6 | 5.6| 5.6| 5.6| 5.6| 5.6| 5.6|

3.2. Influence of efficiency changes of various groups on unit energy consumption [4]

Under different benchmark conditions, the efficiency of each group is reduced by 1%, and the influence of the efficiency of the single-stage group on the coal consumption rate of the unit is obtained. The calculation results are shown in figure 2:

![Figure 2. Group efficiency increased by 1% contrast effect on the coal consumption of unit.](image)

It can be seen that the efficiency of each group is reduced, the coal consumption rate of the unit is increased, but the increase range is quite different; the efficiency change of the high-pressure cylinder and the low-pressure cylinder has a strong influence on the energy efficiency of the unit [5], and the efficiency of the medium-pressure cylinder group changes to the unit. The energy efficiency effect is weaker; the group 1 has a large impact on coal consumption rate; The efficiency change in the 7~9
group becomes stronger and stronger on the unit's energy efficiency [6]. Group 9 is located at the end of the expansion process line, so it has the strongest impact on energy consumption.

3.3. Influence of efficiency in each cylinder stage group on unit energy consumption under different working conditions

In order to compare the effect of the efficiency of each cylinder in the different working conditions on the coal consumption rate of the unit, the author changed the efficiency of all the groups in the same cylinder to the same amplitude and the change of the coal consumption rate of the computer group under different working conditions.

Figures 3~5 shows the synchronous change of the efficiency of the high-pressure cylinder (HP), medium-pressure cylinder (IP) and low-pressure cylinder (LP) under 40% THA, 50% THA, 70% THA, THA and other conditions. The influence line of the rate; figure 6 shows the energy consumption analysis of the efficiency increase in each cylinder group.

As can be seen from figures 3 to 5, the energy consumption of the power unit is linear with the change in efficiency. The energy consumption of the low-pressure group is the largest. Under the THA condition, the efficiency of the group is increased by 1% in the 7~9, and the coal consumption rate of the unit is reduced by 1.106 g\(\text{kw}\cdot\text{h}^{-1}\). The energy consumption of the high-pressure cylinder group
is the second. Under the THA condition, the efficiency of the group 1–2 in HP is increased by 1%, the coal consumption rate of the unit is reduced by about 0.452 \( \text{g(kw·h)}^{-1} \), and the energy consumption of the medium-pressure cylinder group is the smallest. Under the THA condition, the efficiency of the group 3–6 in IP is increased by 1%, and the coal consumption rate of the unit is reduced by about 0.331 \( \text{g(kw·h)}^{-1} \).

4. Discussion
The stage group efficiency influences the efficiency of the turbine cylinder, then influence on the coal consumption rate of the unit, and the variation of stage group efficiency influence on the unit energy consumption with the load change [7].

The unit load is reduced, the influence of the high and low pressure cylinder stage efficiency on the unit energy consumption is gradually increased, and the influence of the medium pressure cylinder stage efficiency on the unit energy consumption is gradually reduced; The impact of the efficiency of the high-pressure cylinder group on the energy consumption of the unit changes rapidly at low load; The impact of the efficiency of the medium-pressure cylinder group on the energy consumption of the unit changes rapidly at high load. The influence of the efficiency of the low-pressure cylinder group on the energy consumption of the unit is decreasing.

DF N1000-25.0/600/600 steam turbine, the low pressure cylinder has the largest power, the high pressure cylinder is the second, the medium-pressure cylinder is the smallest, and the low pressure cylinder is located at the end of the unit. The LP stage group has the highest energy consumption and high pressure. The HP stage group is the second, and the MP stage group is the smallest.

5. Conclusions
When we analyze the influence of turbine efficiency change on the energy consumption of the power unit, the method based on the thermal power unit unified model analysis can be used to obtain 40% THA, 50% THA, 70% THA, and THA conditions. The change law of coal consumption rate of the unit when the efficiency of the group changes.

The influence of the efficiency of the group on the coal consumption rate of the unit is linear with the change of efficiency; the efficiency of the group is reduced, and the coal consumption rate of the unit is increased; the efficiency change of the high-pressure cylinder and the low-pressure cylinder group has a strong influence on the energy efficiency of the unit, and the medium-pressure cylinder The efficiency of the group is less affected by the energy efficiency of the unit. Therefore, in the operation, we should focus on the efficiency of the cascade in the low-pressure cylinder and the high-pressure cylinder, and optimize the operation of the main steam pressure and the cold-end system to improve the economic operation of the unit.

Although the influence of parameter fluctuation on the unit energy consumption is more complicated in the actual operation of the unit, the analysis model of the influence of each cylinder stage group on the coal consumption rate of the unit can be used as the efficiency of each unit.

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