Quantitative analysis of energy consumption for cylinder efficiency of a Shanghai electric – siemens ultra-supercritical 660 MW steam turbine unit

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Abstract. The Shanghai Electric – Siemens ultra-supercritical 660 MW steam turbine has a large proportion in the newly produced 600 MW units in China in recent years because of its superior performance index. It has become an important development direction of 600 MW level ultra-supercritical power generation technology. Taking a N660-25/600/600 steam turbine as an example, the quantitative sensitivity analysis of energy consumption of the high-pressure cylinder, intermediate-pressure cylinder and low-pressure cylinder were carried out based on the calculation method of rated power and variable condition, the influence of each cylinder efficiency change on the heat consumption rate of steam turbine is obtained. It turns out that the efficiency of high-pressure cylinder is less sensitive to energy consumption, the efficiency of intermediate-pressure cylinder is second, and the efficiency of low-pressure cylinder is more sensitive to energy consumption. The conclusion can provide technical reference for energy conservation diagnosis and energy conservation management and evaluation on this type of steam turbine.

1. Introduction
The performance of turbine is evaluated by the efficiency of each cylinder. The steam turbines of large power stations are all designed with multi-cylinder structure, with high-pressure cylinder, intermediate-pressure cylinder and low-pressure cylinder. The efficiency of each cylinder refers to the ratio of actual enthalpy drop and ideal enthalpy drop of steam in each module. With different loads and conditions of the unit, the high-pressure cylinder efficiency changes greatly [1], intermediate-pressure cylinder efficiency changes little, and the low-pressure cylinder efficiency also changes a certain extent [2]. With the improvement of the parameters of steam and the performance of material, Shanghai electric-siemens ultra-supercritical 660 MW steam turbine has been widely recognized in the industry due to its excellent performance index. At present, the 660 MW ultra-supercritical unit, both the steam parameters and the efficiency of unit, have reached the world advanced level [3]. The most prominent feature of this type of unit is that it adopted the full-cycle steam distribution method. It adopted the high-pressure cylinder module based on small enthalpy drop, multiple series, reaction type and cylinder structure design. Compared with the nozzle steam turbine, it has higher efficiency.

Generally, the thermal performance of each cylinder of a steam turbine is obtained through the performance test of the steam turbine. The manufacturer usually only provides the correction curve of the heat consumption rate of the steam turbine, such as the initial parameters and back pressure of the
steam turbine. It does not provide the heat consumption correction curve for the change of the cylinder efficiency. When it is necessary to use the data of the influence of cylinder efficiency change on heat consumption rate or coal consumption in the daily energy conservation management of power plants, the same type of units or relevant books and literatures are used for estimation. However, there is no specific research literature on the sensitivity of energy consumption to the cylinder efficiency of Shanghai electric-siemens ultra-supercritical 660 MW unit. Therefore, the study on energy sensitivity of cylinder efficiency is of great value to the energy diagnosis of this type of turbine.

2. The energy consumption sensitivity of steam turbine unit
The production of thermal power plant involves boiler, steam turbine, condenser, heaters, pumps and fans, etc. The changes in the thermal parameters of these equipments or the performance indicators of the equipments will lead to changes in energy consumption of the unit. In the literature [4-6], the variation of thermal parameters and performance indexes of equipments on energy consumption is defined as energy sensitivity. The sensitivity of initial parameters, exhaust pressure, cylinder efficiency and the end difference of a 1000 MW unit to the heat consumption rate of steam turbine, coal consumption of power generation are studied. In literature [7], the sensitivity on the cylinder efficiency of a supercritical 600 MW unit was studied. In this paper, the variation of parameters or performance indicators on the energy consumption of unit is defined as energy consumption sensitivity. The influence of cylinder efficiency on heat consumption rate and coal consumption of Shanghai electric-siemens ultra-supercritical 660 MW steam turbine was studied. As shown in equations (1) to (4).

\[
\Delta q\bigg|_{Ax} = q\bigg|_{Ax} - q_0
\]

\[
\Delta b\bigg|_{Ax} = b\bigg|_{Ax} - b_0
\]

\[
\delta q\bigg|_{Ax} = \frac{\Delta q\bigg|_{Ax}}{q_0} \times 100
\]

\[
\delta b\bigg|_{Ax} = \frac{\Delta b\bigg|_{Ax}}{b_0} \times 100
\]

Where, \( q \) is the heat consumption rate of the steam turbine, kJ/(kW·h), \( Ax \) is the change of high-pressure cylinder, intermediate pressure cylinder or low-pressure cylinder of the steam turbine, \%; \( b \) is power generation coal consumption/power supply coal consumption g/(kW·h).

3. Constant power calculation model of steam turbine unit
The essence of sensitivity analysis on energy consumption of cylinder efficiency is to determine the influence of the changes in the cylinder efficiency on the heat consumption rate of turbine and the power generation and power supply coal consumption of unit. As many units generally adopt the operation mode of given load curve [8], the calculation method of constant power and variable condition of steam turbine [9,10] is in line with the actual situation. According to the design data provided by the steam turbine manufacturer, the relative internal efficiency of each level group of the steam turbine is calculated as the basis for the calculation of constant power. The steam pressure loss of the reheat system, the end difference of the heaters apply the design value. Assuming the flow of new steam, calculating the extraction pressure at all levels of the reheat system according to the simplified Freugel formula (5), determining the inlet pressure of the heater according to the loss of extraction pressure. The hydrophobic temperature, inlet and outlet temperature of water and enthalpy of the heater are determined according to the design values of various end differences.
According to equations (6) and (7), the relative internal efficiency of the stage group is calculated to determine the enthalpy of steam extraction at all levels of the steam turbine, i.e.

$$\eta_{(r)} = \frac{h_{i(r)} - h_{2(r)}}{\Delta H_{(r)}}$$ \hspace{1cm} (6)

$$h_{2(r)} = h_{i(r)} - \Delta H_{(r)} \eta_{(r)}$$ \hspace{1cm} (7)

Where: $h_{i(r)}$ is the inlet enthalpy of r group; $h_{2(r)}$ is the enthalpy of steam in r group; $\Delta H_{(r)}$ is the ideal enthalpy drop of the corresponding class, all units are kJ/kg.

According to the calculation results of the above variable working conditions, the quality balance and thermal balance of the steam turbine are calculated again, the flow of new main steam is obtained. When its deviation from the assumed flow is within a given range, the iterative calculation is considered to be convergent; otherwise, the iterative calculation is repeated until the iterative accuracy is satisfied. According to the results of thermal balance, the power of turbine at all levels can be calculated, according to equations (8) to (10), the shaft power of each cylinder and the power proportion of each cylinder are obtained.

$$W_H = \sum P_{H(r)}$$ \hspace{1cm} (8)

$$W_I = \sum P_{I(r)}$$ \hspace{1cm} (9)

$$W_L = \sum P_{L(r)}$$ \hspace{1cm} (10)

Where, $W_H$, $W_I$, $W_L$ are shaft power of the high-pressure cylinder, intermediate-pressure cylinder and low-pressure cylinder, kW. $\sum P_{x(r)}$ is the sum of the axial power of the corresponding stage group of each cylinder, kW. According to the heat consumption rate of steam turbine and the power proportion of high, intermediate and low-pressure cylinder under various working conditions, the influence of 1% change in the cylinder on the heat consumption rate can be calculated quantitatively.

4. The design parameters of a 660 MW ultra-supercritical steam turbine unit

This paper takes the type N660-25/600/600 unit steam turbine as the object, the flow-through part is designed with high-pressure cylinder, intermediate-pressure cylinder and low-pressure cylinder, The main steam first passes through the high-pressure cylinder, then passes through the heat again, and then enters the intermediate-pressure cylinder and the low-pressure cylinder to continue to work. The pressure drop of the reheating system is 8%, the designed exhaust pressure is 5.2 kPa. There are 8 stage heater system of the unit, the pressure loss of the first, second and third stages is 3% and the others are 5%. The design parameters of the unit under THA condition are shown in tables 1 and 2. The end difference of heaters at all levels is shown in table 3.

| Table 1. The design parameters of a ultra-supercritical 660 MW steam turbine under THA condition (a). |
|---|---|---|
| content          | unit | data |
| Main steam P     | MPa  | 25.000 |
Table 2. The design parameters of a ultra-supercritical 660 MW steam turbine under THA condition (b).

| content                                           | unit | data  |
|---------------------------------------------------|------|-------|
| Main steam T                                      | °C   | 600.0 |
| Main steam flow                                   | kg/s | 495.831 |
| High-pressure cylinder exhaust P                  | MPa  | 5.700 |
| High-pressure cylinder exhaust T                  | °C   | 363.2 |
| Reheated steam P                                  | MPa  | 5.244 |
| Reheated steam T                                  | °C   | 600.0 |
| Reheated steam flow                               | kg/s | 421.578 |
| intermediate-pressure cylinder exhaust steam P    | MPa  | 0.561 |
| intermediate-pressure cylinder exhaust steam T    | °C   | 277.3 |
| Condenser vacuum                                  | kPa  | 5.2   |
| First stage extraction P                          | MPa  | 7.484 |
| First stage extraction T                          | °C   | 401.2 |
| Secondary extraction P                            | MPa  | 5.700 |

| Secondary extraction T                            | °C   | 363.2 |
| Stage3 extraction P                               | MPa  | 2.644 |
| Stage 3 extraction T                              | °C   | 489.9 |
| Stage 4 extraction P                              | MPa  | 1.242 |
| Stage 4 extraction T                              | °C   | 379.2 |
| Stage 5 extraction P                              | MPa  | 0.561 |
| Stage 5 extraction T                              | °C   | 277.3 |
| Stage 6 extraction P                              | MPa  | 2.475 |
| Stage 6 extraction T                              | °C   | 189.0 |
| Stage 7 extraction P                              | MPa  | 0.036 |
| The dry degree of the 7 stage extraction          | °C   | x=0.9671 |
| Stage 8 extraction P                              | MPa  | 0.018 |
| The dry degree of the 8 stage extraction          | °C   | x=0.9357 |

Table 3. The design end difference of heaters at different levels in THA condition.

| Heater number | 1#   | 2#   | 3#   | 5#   |
|---------------|------|------|------|------|
| End difference of feed water °C                  | -1.7 | 0.0  | 0.0  | 2.8  |
| End difference of hydrophobic °C                 | 5.6  | 5.6  | 5.6  | 5.6  |
| Heater number                                     | 6#   | 7#   | 8#   | /    |
| End difference of feed water °C                  | 2.8  | 2.8  | 2.8  | /    |
| End difference of hydrophobic °C                 | 5.6  | 5.6  | 5.6  | /    |

5. The sensitivity analysis on energy consumption of cylinder efficiency

According to the above calculation model, the energy consumption sensitivity of cylinder efficiency under THA, 75% THA and 40% THA conditions of the unit was carried out, the influence of cylinder efficiency on heat consumption rate of steam turbine under various conditions is obtained, as is shown in table 4 and figures 1-4.

Figures 1 and 2 shows the sensitivity curve of the heat consumption rate of the steam turbine when the efficiency of the high-pressure cylinder changes, according to the change of the curve shown in the figure and the results in table 3, for every 1% reduction of the efficiency of the high-pressure cylinder,
the heat consumption rate increases to 11.04 kJ/(kW·h) to 12.80 kJ/(kW·h). Specifically, it is related to load. Under the conditions of THA, 75%THA and 40%THA, energy sensitivity gradually increases. For example, the efficiency of high-pressure cylinder decreases by 4%, and the heat consumption rate increases by 44.16 kJ/(kW·h) under THA, which increases by 0.60% compared with 51.20 kJ/(kW·h) under 40%THA, which increases by 0.65%.

Table 4. The influence of the efficiency of each cylinder of an ultra-supercritical 660 MW steam turbine on the heat consumption rate.

| content                                      | THA          | 75%THA       | 40%THA       |
|----------------------------------------------|--------------|--------------|--------------|
| High-pressure cylinder efficiency changes by 1% energy-sensitivity kJ/(kW·h) | 11.04        | 11.35        | 12.80        |
| Intermediate-pressure efficiency changes by 1% energy-sensitivity kJ/(kW·h) |              |              |              |
| Low-pressure cylinder efficiency changes by 1% energy-sensitivity kJ/(kW·h) |              |              |              |

Figure 1. The influence of high-pressure cylinder efficiency on heat consumption rate.

Figure 2. The relative influence of high-pressure cylinder efficiency on heat consumption rate.

Figure 3. The influence of intermediate-pressure cylinder efficiency on heat consumption rate.

Figure 4. The influence of low-pressure cylinder efficiency on heat consumption rate.
The sensitivity curve of energy consumption on heat consumption rate when the efficiency of intermediate-pressure cylinder changes is shown in figure 3, according to the change of the curve shown in the figure and the results in table 3, for each 1% reduction in the intermediate-pressure cylinder efficiency, the heat consumption rate increased to 21.02 kJ/(kW·h) to 22.77 kJ/(kW·h). Specifically, it is related to load. Under the conditions of THA, 75%THA and 40%THA, energy sensitivity gradually increases. The efficiency of intermediate-pressure cylinder decreases by 4%, and the heat consumption rate of turbine increases by 84.08 kJ/(kW·h) under THA condition, while increases by 91.08 kJ/(kW·h) under 40%THA condition. The energy consumption sensitivity of intermediate-pressure cylinder efficiency is much higher than that of high-pressure cylinder, which is mainly because the work done by intermediate-pressure cylinder takes a large proportion in the total shaft power of this type of turbine. Local of supercritical 600 MW units in the past, in which the exhaust steam pressure of the intermediate-pressure cylinder is mostly in the 4th extraction location, while that of Shanghai electric-Siemens 660 MW and 1000 MW ultra-supercritical steam turbine is in the 5th extraction location. The design concept that the boundary point between the intermediate and low-pressure cylinder move backward is adopted effectively increases the work ratio of intermediate-pressure cylinder. Because the efficiency of the intermediate-pressure cylinder is the highest in the whole through-flow part, the work ratio of the steam turbine is increased in the intermediate-pressure module with the highest efficiency, which is also a reason for the superior economic index of this type of unit. The sensitivity curve on the heat consumption rate, when the efficiency of the low-pressure cylinder changes, is shown in figure 4. According to the change of the curve and the results in table 2, for every 1% reduction in low-pressure cylinder efficiency, the heat consumption rate increases to 23.42 kJ/(kW·h) to 24.68 kJ/(kW·h). Specifically, it is related to load. Under the conditions of THA, 75%THA and 40%THA, energy sensitivity gradually increases. The efficiency of the low-pressure cylinder decreased by 4%, and the heat consumption rate of the steam turbine increased by 93.68 kJ/(kW·h) under THA condition, and by 98.72 kJ/(kW·h) under 40%THA condition. The sensitivity of the low-pressure cylinder efficiency is the sensitive in the whole turbine, also because the work ratio of low-pressure cylinder takes the largest proportion in the total power of the turbine.

6. Performance diagnosis based on energy consumption sensitivity
The performance diagnosis of the steam turbine is the basis of energy conservation evaluation and management, energy consumption benchmarking and energy conservation transformation of generating set. For example, literature [11] proposed a thermal economy diagnosis method for steam turbines based on the improved equivalent heat drop method. Literature [12] is put forward based on the theory of multi-factor coupling variable condition of steam turbine energy-saving diagnosis method, in addition to the circulation of researchers have proposed using function method, matrix method [13] and other method is applied to performance diagnosis of the steam turbine, the calculation process of the above method is complex and the operability is limited in practical engineering application. The author thinks that the most accurate and practical method of performance diagnosis is still thermal performance test. For example, literature [14-16] is based on the thermal performance test data of the steam turbine for performance diagnosis, which is the most appropriate method for the actual operation of the unit and has good engineering practicability. A 660 MW ultra-supercritical unit was put into operation in 2014. Table 5 shows the design values of high, intermediate and low-pressure cylinder efficiency and the test results before maintenance.

It can be seen from table 5 that the efficiency of the high, intermediate and low-pressure cylinder of the unit is 2.29, 2.41 and 1.04 percentage points lower than the design value under the full opening of the high-pressure damper respectively. According to the results in table 4, it can be seen that the heat consumption rate affected by the deviation of the design value of high, intermediate and low-pressure cylinder is 25.28, 50.66 and 24.36 kJ/(kW·h) respectively, and the total heat consumption rate of the three cylinders is 100.30 kJ/(kW·h). The efficiency of high-pressure cylinder under 495 MW load is 3.21 percentage points lower than that under 660 MW condition, mainly because the throttle loss of
high-pressure damper under partial opening degree. Therefore, during the operation of this type of unit, it is necessary to keep the high-voltage running at a large opening as far as possible.

**Table 5.** The test values of each cylinder efficiency of an ultra-supercritical 660 MW steam turbine.

| content                  | Design value | The test results 660 MW(2VWO) | The test results 495 MW |
|--------------------------|--------------|--------------------------------|------------------------|
| GV1 opening %            | /            | 99.95%                         | 35.95                  |
| GV2 opening %            | /            | 99.28%                         | 35.60                  |
| High-pressure cylinder efficiency % | 91.14        | 88.85                          | 85.64                  |
| Intermediate -cylinder efficiency % | 93.75        | 91.34                          | 90.72                  |
| Low-pressure cylinder efficiency % | 92.80        | 91.76                          | 91.08                  |

7. Conclusions
This paper takes a Shanghai electric-siemens ultra-supercritical 660 MW steam turbine as the object to study the energy consumption sensitivity. The influence of the cylinder efficiency on the heat consumption rate is obtained by using the method of constant power and variable conditions of steam turbine. An example is given to illustrate the performance diagnosis method of turbine based on energy consumption sensitivity. The purpose is to provide technical reference for energy management and evaluation of this type of unit. The main conclusions of this paper are as follows:

For this type of ultra-supercritical 660 MW steam turbine, the heat consumption rate increases by 11.04 kJ/(kW·h) to 12.80 kJ/(kW·h) under different load conditions for every 1 percentage point reduction in the efficiency of the high-pressure cylinder. In the case of THA, 75% THA and 40% THA, energy consumption sensitivity gradually increased.

The energy consumption sensitivity of intermediate-pressure cylinder is higher than the high-pressure cylinder, for every one percentage point reduction in the intermediate-pressure cylinder efficiency, the heat consumption rate under different load conditions increased to 21.02 kJ/(kW·h) to 22.77 kJ/(kW·h). The intermediate-pressure cylinder efficiency is the highest in the whole three-cylinder efficiency, and the work ratio is increased in the intermediate-pressure module with the highest efficiency, which is also a reason for the superior economic index of this type of unit.

For every 1% reduction in the efficiency of the low-pressure cylinder, the heat consumption rate increases to 23.42 kJ/(kW·h) to 24.68 kJ/(kW·h) under different load conditions. The energy consumption sensitivity is the sensitive in the entire pass-through section of Shanghai electric-siemens ultra-supercritical 660 MW steam turbine. Therefore, we should focus on the operation of the low-pressure cylinder in the actual operation of the unit.

Acknowledgments
This research was financially supported by Huadian Electric Power Science Research Institute Co. LTD.

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