Research on the Influence of Thermal Performance of Steam Turbine on Energy Loss and Heat Rate

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Abstract. A steam turbine as research object in this paper, and the thermodynamic calculation program of steam turbine and thermal system was programmed, and the influence of thermal performance change of flow passage component on the heat rate was analyzed. The results show that the efficiency of the unit is linear with the heat rate; the greater the power of the unit, the closer to the exhaust end, then the influence of unit efficiency change on heat rate is also greater. The effect of the turbine efficiency change on the heat rate was analyzed in this paper based on the heat rate change relation model; the calculation results were basically consistent with the thermal calculation, it shows that this mathematical model has high calculation accuracy and it is properly applied into engineering calculation.

1. Introduction
As the electricity demand continues to increase in our country, the supply of electrical coal is becoming increasingly tense, moreover, the situation of environmental protection and carbon emission reduction continues to develop, which force thermal power plant to tap energy-saving potential, improve the economics and reliability of the unit, reduce costs and improve competition. This puts higher requirements on the transformation of flow passage component of steam turbine and thermal economy diagnostic technology of steam turbine. In the transformation of flow passage component of steam turbine flow or thermal economy diagnosis of steam turbine, it is often necessary to determine the relative internal efficiency or unit efficiency change of a cylinder of a steam turbine to cause a change in the heat rate, in order to predict the thermal economic benefits of the transformation of flow passage component or determine the cause and location of the increase in heat rate during operation. Therefore, it is increasingly important to study the influence of the performance change of the flow passage component of steam turbine on the heat rate.

Based on the off-design condition theory of thermal system, this paper analyzes and calculates the influence of change of unit efficiency and cylinder efficiency on the heat rate of the one 600MW steam turbine, and the results are checked by a simplified mathematical model of the relationship between the efficiency change and the heat rate of the steam turbine cylinders. The conclusions drawn in this paper can be applied to the transformation of the flow passage component of steam turbine or thermal economic diagnosis of steam turbine; it provides a theoretical basis for more accurately predicting the energy loss and heat rate of steam turbine.
2. Research Object

The steam turbine in this paper is the N600-24.2/566/566 steam turbine produced by Westinghouse Technology of the United States, which is a reaction, supercritical, single-shaft; three-cylinder, four-exhaust, and one intermediate reheat condensing steam turbine. The steam distribution ways of the steam turbine is nozzle regulation, and the steam from the regulating valve passes through four steam guiding tubes (two in the upper part of the cylinder and two in the lower part) and enters the middle of the high and medium pressure cylinders, and then flows into the four nozzle chambers. The feed water regenerative system is three high-pressure heaters, one deaerator and four low-pressure heaters, deaerators are hybrid, others are surface heaters, and hydrophobic is flowing automatically. The rated feed water temperature is 274.4 °C, and the feed water pump is driven by a small steam turbine. The flow passage component of the unit has 48 stages, including high pressure cylinder I+11, medium pressure cylinder 8 and low pressure cylinder 2x2x7, the other stages are reaction type except the regulation stage is reaction. The blade height of final stage of low pressure cylinder is 905 mm, and the rated average back pressure is 0.00588 MPa. The unit division and the power of each stage unit under rated working condition and 75% working condition are shown in the Table.1. According to the unit type and the extraction arrangement, the steam turbine is divided into units, the specific distribution scheme and the rated working condition and the partial power of the steam turbine under the 75% working condition are shown in Table 1.

| cylinder                      | unit number | unit position          | unit power of rated working condition(MW) | unit power of 75% working conditions(MW) |
|-------------------------------|-------------|------------------------|------------------------------------------|----------------------------------------|
| high pressure cylinder        | 1           | regulating stage       | 35.2                                     | 35.9                                   |
|                               | 2           | regulating stage: No.1 extraction opening | 123.5                                    | 88.0                                   |
|                               | 3           | No.1 extraction port- No.2 extraction opening | 37                                       | 26.5                                   |
| intermediate pressure cylinder| 4           | intermediate pressure cylinder admission - No.3 extraction opening | 86.8                                     | 65.4                                   |
|                               | 5           | No.3 extraction opening- No.4 extraction opening | 71.9                                     | 52.9                                   |
| low pressure cylinder         | 6           | low pressure cylinder inlet- No.5 extraction opening | 69.1                                     | 52.9                                   |
|                               | 7           | No.5 extraction opening- No.6 extraction opening | 78.7                                     | 60.2                                   |
|                               | 8           | No.6 extraction opening- No.7 extraction opening | 37.4                                     | 28.4                                   |
|                               | 9           | No.7 extraction opening- No.8 extraction opening | 25.6                                     | 19.9                                   |
|                               | 10          | No.8 extraction opening- low pressure cylinder inlet | 35.6                                     | 20.9                                   |

3. Thermal Calculation of Off-design Condition

3.1. Thermal calculation program

At present, there are many methods for calculating the thermal capacity of off-design condition of steam turbine. Among them, the construction of mathematical model is one of the important methods for conducting off-design condition analysis, but due to the complexity of the steam turbine thermal system and the strong coupling of the components, many assumptions must be made in mathematical modeling, this will cause the calculation accuracy of the model to decrease, and sometimes the calculation errors
of the model can even affect the true value; or because the model is complicated, it is not easy to be calculated and applied in practice, it is not as convenient to directly calculate the thermal calculation of the off-design condition of the steam turbine and the thermal system. Today, computer technology is developed and can be iteratively calculated by common software to achieve higher precision. Based on the theory of off-design condition theory of steam turbine, this paper uses Excel to make the thermal calculation program of steam turbine and off-design condition of thermal system to solve it iteratively, and analyzes the influence of steam turbine stage efficiency change on cylinder efficiency and heat rate. When the characteristics of the steam turbine change, the mass and energy balance of the entire turbine and thermal system will be redistributed, to this end, the steam turbine and the thermal system before and after off-design condition must be simplified.

![Flow chart of working condition of steam turbine](image.jpg)

**Fig.1** Flow chart of working condition of steam turbine

Under the condition that the flow of steam is determined, assuming the steam extraction amount of No 1-8 heaters and the small turbine pumps, the steam flow of each unit of the turbine flow passage component can be calculated and compared with the design condition, the Freughier's formula can be
used to obtain pressures in various units. Since the pressure loss coefficient of each unit is known, the pressure in each heater can be determined, and the saturation temperature under each heater pressure can be obtained, thereby obtaining the water temperature of each inlet and outlet of the heater; the temperature of flow passage component of the steam turbine can be determined. The above calculations obtain the parameters of the thermal system after off-design condition, which will generate a new set of steam extraction. Therefore, iterative calculation is needed according to the newly obtained set of steam extraction amount until the error between adjacent two iterations is less than 0.001%. The calculation process is shown in Fig.1.

3.2. Calculation results and analysis
In order to verify the correctness of the off-design condition of calculation procedure of the steam turbine introduced above, the program was used to calculate the unit design conditions. The N600-24.2/566/566 steam turbines, whose designed heat rate is 7587 kJ/(kg.K) under rated conditions, and the calculated value of program is 7585.1kJ/(kg.K). It can be seen from the above calculation that the calculation program has high precision and can be used to calculate the thermal power of the turbine under off-design condition. The rated condition and 75% working condition of N600-24.2/566/566 steam turbine are calculated in detail with the off-design condition thermal calculation program. The influence of the efficiency change of the flow passage unit on the heat rate of the unit is shown in Table.2 and Table.3, according to the data in the table, the relationship between the efficiency change of the unit and the heat rate is shown in Fig. 2 and Fig. 3.

Table 2. The influence of efficiency change of N600-24.2/566/566 steam turbine on heat rate (rated condition)

| unit efficiency reduction (%) | 1    | 2    | 3    | 5    | 7    |
|------------------------------|------|------|------|------|------|
| high pressure cylinder       |      |      |      |      |      |
| 1                            | 0.033| 0.066| 0.099| 0.165| 0.232|
| 2                            | 0.110| 0.221| 0.332| 0.555| 0.780|
| 3                            | 0.036| 0.071| 0.107| 0.178| 0.250|
| intermediate pressure cylinder|    |      |      |      |      |
| 4                            | 0.072| 0.144| 0.215| 0.359| 0.502|
| 5                            | 0.067| 0.134| 0.200| 0.334| 0.467|
| low pressure cylinder        |      |      |      |      |      |
| 6                            | 0.076| 0.151| 0.227| 0.378| 0.529|
| 7                            | 0.111| 0.222| 0.333| 0.554| 0.775|
| 8                            | 0.058| 0.116| 0.174| 0.290| 0.406|
| 9                            | 0.056| 0.113| 0.170| 0.283| 0.397|
| 10                           | 0.071| 0.142| 0.214| 0.357| 0.500|

Table 3. The influence of efficiency change of N600-24.2/566/566 steam turbine on heat rate (75% working condition)

| unit efficiency reduction (%) | 1    | 2    | 3    | 5    | 7    |
|------------------------------|------|------|------|------|------|
| high pressure cylinder       |      |      |      |      |      |
| 1                            | 0.035| 0.07 | 0.105| 0.175| 0.245|
| 2                            | 0.117| 0.234| 0.352| 0.589| 0.828|
| 3                            | 0.036| 0.073| 0.11 | 0.183| 0.256|
| intermediate pressure cylinder|    |      |      |      |      |
| 4                            | 0.08 | 0.16 | 0.239| 0.398| 0.558|
| 5                            | 0.072| 0.145| 0.217| 0.362| 0.507|
| low pressure cylinder        |      |      |      |      |      |
| 6                            | 0.078| 0.157| 0.235| 0.392| 0.549|
| 7                            | 0.115| 0.229| 0.344| 0.572| 0.8  |
| 8                            | 0.059| 0.119| 0.179| 0.298| 0.418|
| 9                            | 0.058| 0.115| 0.173| 0.288| 0.404|
| 10                           | 0.073| 0.146| 0.219| 0.366| 0.511|
According to Table 2, Table 3 and Fig. 2 and Fig. 3, the efficiency change of each unit is linear with heat rate change; the efficiency of the unit 2 and 7 has the greatest influence on the heat rate, and efficiency change of unit 1 and unit 3 has the least impact on heat rate. In the same cylinder, the greater the power of the unit takes on, the greater the impact of the efficiency change of the unit on the heat rate. Under the condition of the same power, the closer to the exhaust end, the greater effect the efficiency change of the unit on the heat rate, this is because the reheat coefficient of the unit near the exhaust end is low, after the efficiency of these unit is reduced, there are no units and extractions to weaken their influence; the last two units in the low pressure cylinder are small or not due to reheating, the impact of efficiency change on the heat rate is much higher than other units with a large enthalpy drop. Therefore, in the monitoring and reconstruction of steam turbines, more attention should be paid to the high-power unit, especially the low pressure cylinder unit, it is important to ensure that these units work at high efficiency to increase the output of the unit and reduce the heat rate.
4. Conclusion

In this paper, the influence of the unit efficiency change or cylinder efficiency change of a 600MW steam turbine on the heat rate was analyzed; and the simplified mathematical model of the relationship between the efficiency change of the steam turbine cylinders and the heat rate was verified, the following conclusion was drawn: the efficiency change of each unit is linear with the change amount of heat rate, in the same cylinder, the greater the power of the group, the greater the impact of the efficiency change of the unit on the heat rate. Under the condition of same power, the closer to the exhaust end, the greater the influence of the efficiency change of the unit on the heat rate; the effect of the last two units in low-pressure cylinders on the heat rate is much higher than that of the other units.

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