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Calculation Method of Influence of Relative Efficiency Change of Steam Turbine Cylinder on Heat Loss

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Abstract. Based on the equivalent heat drop theory, the calculation method of the influence of the relative internal efficiency change of steam turbine cylinder on heat loss is proposed. The numerical results show that the method can more accurately evaluate the effect of efficiency change of each cylinder on heat loss, and provides a theoretical basis for the thermal economic diagnosis of steam turbine.

1. Introduction

Most of the units in the province have been in service for more than ten years, and the thermal performance of the unit is objectively decreasing. In the routine thermal test work, we often see a big gap between the unit test heat consumption and the design heat consumption. Needless to say, the relative internal efficiency of the turbine cylinder body has a significant impact on the unit heat consumption. When the amount of change in the relative internal efficiency of a certain cylinder of a steam turbine is known, how to accurately calculate the amount of change in the heat rate is a common concern.

Based on the equivalent heat drop theory, the calculation and analysis method of the influence of cylinder efficiency change on heat loss is proposed. The calculation accuracy of this method is higher than that of the previous simplified calculation model, which reduces the error in the analysis and diagnosis of steam turbine thermal economy.

2. Theoretical Analysis

According to the steam turbine principle, for the intermediate reheat unit, when the relative internal efficiency of the steam turbine high pressure cylinder changes, the heat absorption of the cold re-steam in the reheater will be changed, which results in a change in the ideal cycle thermal efficiency of the steam turbine. Usually the reheat steam temperature is controlled by the boiler. If the reheat steam temperature is assumed to remain the same, the relative internal efficiency change of the high pressure cylinder has no effect on the relative internal efficiency of the medium and low pressure cylinders, and also has no effect on the ideal heat drop and reheating of the entire steam turbine. When the relative internal efficiency of the medium pressure cylinder changes, it is bound to change the steam inlet parameters of the low pressure cylinder, so the curve of the low pressure cylinder expansion process

will change accordingly. It can be seen that the efficiency change of the single cylinder of the steam turbine is not an isolated thermal process [1].

At the same time, for a steam turbine with regenerative extraction, when the relative internal efficiency of the cylinder body changes, the post-stage parameters of each pressure level will change. If it is assumed that the resistance coefficients of the corresponding heater extraction pipes are basically unchanged, the corresponding steam side saturation pressure and the corresponding saturated water enthalpy of each heater also change. In the case where the main steam parameter is constant, the heat absorption of the steam in the superheater is changed, so that the ideal cycle thermal efficiency of the steam turbine changes. Thus, a single cylinder efficiency change is a complex thermal process involving other cylinders and coupling with the respective regenerative systems to which they are connected.

At present, although there are many literatures discussing this issue, different literatures often give different calculation methods. Especially for the intermediate reheat steam turbine, when the relative internal efficiency of the high pressure cylinder changes, how to calculate the amount of change in the heat rate caused by the high pressure cylinder has different calculation models. Among them, the more prominent one is the literature [2]: the calculation model of the effect of the efficiency change of each cylinder on the heat consumption is given by the thermodynamic method, which fully considers the ideal cycle thermal efficiency and steam turbine of the intermediate reheat steam turbine with regenerative extraction. Its calculation accuracy is higher than other mathematical models in the literature [3], literature [4], literature [5], etc., and is closer to the detailed calculation of the variable working conditions [6], but the theoretical analysis and calculation process of the calculation model is complicated, which is not convenient for engineering application and on-site thermal test work.
Therefore, based on the equivalent heat drop theory, a relatively simple calculation method is derived. In order to verify whether the calculation is accurate, the calculation result of the method is compared with the calculation result of the literature 1.

3. Solution idea
According to the definition of relative internal efficiency, for the rated inlet steam parameters, the turbine cylinder efficiency drop is numerically reflected in the increase of exhaust steam.

There are many reasons for the relative internal efficiency change of the turbine cylinder body. For example, fouling, clogging, corrosion, and damage to the moving blade can cause the cylinder efficiency to decrease. Leakage of the tip of the blade between the upper and lower groups will also cause the lower inlet enthalpy to increase, and it is also one of the factors that cause the cylinder efficiency to drop.

Therefore, the proposition that the cylinder efficiency change affects the heat consumption can be transformed into the problem of the regenerative extraction steam leakage between the different energy levels of the single cylinder. In this way, on the one hand, it can subtly avoid the influence of the temperature change of the high-pressure cylinder exhaust steam on the heat absorption of the reheater, the influence of the change of the efficiency of the medium-pressure cylinder on the expansion process of the low-pressure cylinder, and the mutual change between the cylinder efficiency and the regenerative system. On the other hand, the equivalent heat drop theory can be used to accurately calculate the influence of the regenerative extraction steam leakage between different energy levels on the heat loss, and then the effect of the cylinder efficiency change on the heat consumption.

In order to illustrate the problem, this article takes the 200MW group as an example and lists the detailed calculation process for peer review.

4. Specific calculation methods and examples

4.1. Raw materials

The equivalent heat loss calculation raw data was taken from the manufacturer's "N210-130/535/535 steam turbine thermal characteristics" (69.000.ISM-1) [7].

Table 1. Raw materials.

Item	H_j	η_j	α_j	τ_j	q_j	γ_j
1	231.74	0.091676	0.043260	149.24	2527.81	
2	415.56	0.162259	0.035086	121.00	2561.08	201.63
3	475.27	0.193840	0.022387	68.47	2451.88	75.71
4	580.78	0.232650	0.017288	83.91	2496.35	
5	695.91	0.265566	0.018547	83.05	2620.48	190.78
6	810.00	0.312203	0.039229	121.74	2594.45	36.1
7	958.00	0.431471	0.063671	150.60	2220.3	228.92
8	960.16	0.458899	0.048008	108.16	2092.32	

$H=1203.0 kJ.kg^{-1}$，$Q=2803.30 kJ.kg^{-1}$，$\sigma=497.32 kJ.kg^{-1}$，

$\alpha_H=0.825478$，$\alpha_{zr}=0.869519$，$\alpha_{nn}=0.67403$，$\eta_i=0.429142$

$\eta_H=84.54\%$，$\eta_M=89.34\%$，$\eta_L=83.42\%$（η_H, η_M, η_L respectively indicate the relative internal efficiency of the high pressure cylinder, medium pressure cylinder and low pressure cylinder design）

4.2. Calculation steps

According to the relative internal efficiency calculation formula, the exhaust enthalpy change amount Δh after the cylinder efficiency change 1% is calculated by inversely designing the cylinder efficiency. Next, referring to the data of the rated flow condition in the manufacturer's thermal calculation book, the leakage steam fraction α required for the upper stage to cause the extraction Δh of the lower stage is obtained. Then, using the equivalent heat drop theory, the rate of change $\delta\eta$ of the device efficiency caused by the leakage of the α-fraction of the regenerative extraction between different energy levels is obtained, and then the rate of change δH of the heat loss of the unit is obtained.

4.3. Calculation of relative internal efficiency change of high pressure cylinder

The steam inlet parameters of the high-pressure cylinder are determined by the boiler and remain unchanged. Therefore, when the relative internal efficiency of the high-pressure cylinder changes, only the corresponding high-pressure cylinder exhaust steam parameters change.

It is assumed that the relative internal efficiency drop of the high-pressure cylinder is caused by an abnormal leakage of a section of extraction steam to the second-stage extraction.

From the relative internal efficiency calculation formula, the high-pressure cylinder exhaust steam enthalpy rise $\Delta hH=4.645 kJ/kg$ when the relative internal efficiency change $\Delta\eta H=1\%$ of the high-pressure cylinder is reversed, and the required leakage fraction $\alpha1-2 =0.043521$ is calculated from the enthalpy rise value.

$\Delta H_H = \alpha_1-2 \times （h_1+\sigma-h_n-（h_1-h_2）\times\eta_2-h_2-\sigma+h_n）=-2.497535$

$\Delta Q_H = \sigma \times \alpha_1-2 \times （h_1-h_2）/q_2=0.983974$

$\delta\eta_H =（\Delta H_H-\Delta Q_H\eta_i）/(H+\Delta H_H)=-0.002426$

$\delta H_H = \delta\eta_H = -0.002426$

It can be seen from the above calculation that the high-pressure cylinder exhaust steam enthalpy rise Δh_H caused by the decrease of cylinder efficiency is used as the first-stage extraction enthalpy value is higher than the second-stage extraction enthalpy value in the equivalent heat drop theory. The heat part is completely utilized by the No. 2 high-pressure heater. Therefore, in the calculation, the change of the heat absorption σ of the reheater caused by the increase of the exhaust steam temperature of the high pressure cylinder is avoided; At the same time, the variation of the second section of steam extraction caused by the first section of the extraction steam enthalpy value is higher than the second section of the extraction steam enthalpy value, and the variation ΔQ_H of the boiler heat absorption amount is calculated.

In order to verify the accuracy of the proposed calculation method, the relevant data in the literature [1] is compared as follows:

Table 2. Comparison of calculation results.

Relative internal efficiency change of high pressure cylinder $\Delta\eta$(%)	relative loss rate of heat rate				
	Detailed calculation [6]	This article	Literature [2]	Literature [3]、[4]	Literature [5]
-0.138	0.0302	0.0335	0.0229	0.0225	0.0448
-0.088	0.0189	0.0213	0.0146	0.0143	0.0286
-0.038	0.0080	0.0092	0.0063	0.0062	0.0123
0.000	0.0000	0.0000	0.0000	0.0000	0.0000
0.012	-0.0025	-0.0029	-0.0020	-0.0020	-0.0039
0.062	-0.0127	-0.0150	-0.0103	-0.0101	-0.0201

It can be seen from the comparison that when the relative internal efficiency change $\Delta\eta_H$ of the high-pressure cylinder is within the range of -13.80%~+6.2% relative to the design value η_H, the accuracy of the relative internal efficiency change of the high-pressure cylinder calculated in this paper is higher than that of other calculation methods.

4.4. Calculation of relative internal efficiency of medium pressure cylinder

It is assumed that the efficiency drop in the medium pressure cylinder is caused by the abnormal leakage of the fifth stage extraction steam to the sixth stage. The intermediate cylinder desuperheating enthalpy rise Δh_M=6.318kJ/kg when the relative internal efficiency change 1% is reversed by the relative internal efficiency calculation formula, and the corresponding leakage fraction is calculated as α_{5-6}=0.041564 from the enthalpy value.

$\triangle H_M＝\alpha_{5-6}\times（h_5－h_n－（h_5\text{-}h_6）\times\eta_6\text{-}h_6 +h_n）=-4.026944$

$\triangle Q_M=0$

$\triangle\eta_M＝\triangle H_M/H=-0.003347$

$\delta H_M＝\delta\eta_M＝-0.003347$

In the past, in the analysis of the relative internal efficiency change of the medium pressure cylinder, the change of the medium pressure cylinder efficiency change to the low pressure cylinder was neglected, so that the calculated influence of the medium pressure cylinder on the heat consumption was higher than the actual value; Sometimes, simply treating the medium and low pressure cylinders as one cylinder, it is difficult to separately identify the impact of the medium and low pressure cylinder changes on the heat consumption. In the calculation of this paper, the equivalent heat drop theory is used to convert the benefits of the medium pressure cylinder exhaust to the low pressure cylinder into the benefit of the No. 6 low pressure heater, which not only cleverly avoids the problem of re-determining the low-pressure cylinder expansion process line when the medium-pressure cylinder efficiency changes, but also considers the mutual coupling of the medium-low pressure cylinders. Therefore, the method improves the calculation accuracy.

4.5. Calculation of relative internal efficiency change of low pressure cylinder

It is assumed that the efficiency drop in the low-pressure cylinder is caused by the abnormal leakage of the eighth-stage extraction steam to the low-pressure cylinder. The low pressure cylinder exhaust steam enthalpy rise $\triangle h_L$=6.253kJ/kg when the relative internal efficiency change 1% is reversed by the relative internal efficiency calculation formula, and the corresponding leakage fraction is calculated as α_{8-n} =0.018614 from the enthalpy rise value.

$\triangle H_L＝\alpha_{8-n}\times（h_8－h_n）=-4.31371$

$\triangle Q_L=0$

$\delta\eta_L＝\triangle H_L/H=-0.003586$

$\delta H_L＝\delta\eta_L＝-0.003586$

4.6. Qualitative and quantitative analysis

For 200 MW Unit, the single cylinder working ratio of the high pressure cylinder, the medium pressure cylinder and the low pressure cylinder is 0.312:0.381:0.307. It seems that the effect of the relative internal efficiency change of the medium pressure cylinder on the heat consumption seems to be greater than the influence of the relative internal efficiency change of the high pressure cylinder, and the effect of the relative internal efficiency change of the high pressure cylinder and the low pressure cylinder should be approximately the same. However, the decrease in the efficiency of the high-pressure cylinder leads to an increase in the exhaust steam temperature of the high-pressure cylinder, which invisibly reduces the heat absorption $\triangle h_H$ of the cold re-steam in the boiler reheater; The decrease in efficiency of the medium-pressure cylinder leads to an increase in the inlet steam temperature of the low-pressure cylinder, part of the $\triangle h_M$ will be converted into useful work by the low-pressure cylinder due to the reheating effect of the steam turbine stage.The effect of the relative internal efficiency changes on the heat loss of the unit has its advantages and disadvantages. The increase in exhaust steam enthalpy caused by the decrease in efficiency in the low-pressure cylinder can only be converted into cold source loss, which cannot be utilized at all.

It can be seen from the calculation results in this paper that the effect of the relative heat loss of the low-pressure cylinder is the most prominent among the three cylinders when the relative internal efficiency is decreased by 1%;the medium-pressure cylinder is slightly smaller, and the high-pressure cylinder has the least influence on the heat consumption. This trend is basically consistent with theoretical qualitative analysis.

5. Conclusion

Based on the theory of equivalent heat drop, a new calculation method for calculating the influence of the relative internal efficiency of each cylinder on the relative internal efficiency and heat rate of the entire turbine is derived. By comparing with the detailed calculation results, it is proved that the accuracy of the proposed model is higher than other calculation models. It provides a theoretical basis for more accurate assessment of the economic efficiency of cylinder efficiency.

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