Research on Valve Characteristics and Economic Operation of Ultra-Supercritical Steam Turbine with Throttle Steam Distribution Mode

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Abstract: High pressure governing valve is modelled by elliptic equations, and verified through the comparison with the literature data. Then a 660MW ultra-supercritical steam turbine with throttle steam distribution mode is modelled to explore the efficiency of HP cylinder and the unit's economic under different loads with different operation strategies. Analysis shows that the valve opening is an important factor that impacts the heat rate and the valve in 30%-40% opening should be recommended for operation. According to the requirements of grid frequency adjustment, the proposed operation strategies can improve the units' economic performance and enhance the ability of deep peak regulation.

1. Introduction

China electric power enters the period of oversupply, the average annual load and utilization hours of the unit decreasing year by year. Large thermal power units are responsible for balancing electricity consumption and supply. It means they have to improve the depth peak load cycling and quick load change capability, which has adverse effects on the unit operation [1-4].

A lot of researches have been carried out at home and abroad around the flexibility of thermal power units. In terms of the sliding pressure operation unit, the domestic research is relatively rare. With the gradual production of such units, it becomes more and more important to do research on the safe and economic operation under wide range load rate and the flexibility of the unit.

The operation of throttle steam distribution steam turbine depends on the hp governing valve. In order to achieve the governing valve characteristics, establishing a simplified model that meets both theory and engineering precision is necessary.

In this paper it was found that the valve characteristics could not be directly expressed by elliptic formula, but they have something in common. If the relationship between the critical pressure ratio, opening and critical flow of the valve is known, it can be applied to engineering in combination with the elliptic formula. Then with the analysis of the units’ operating characteristics, a wide-range load rate operation scheme was proposed, through which the throttling loss of high pressure can be controlled within a certain range on the premise of meeting the frequency regulation of power network to improve the efficiency.
2. The establishment of governing valve model

Governing valve can be regarded as a convergent-divergent nozzle with variable throat area. The critical pressure ratio and critical flow rate of valve vary with the opening degree, so the discharge is determined by valve opening and pressure ratio. The throat can be treated as a diffusing pipe, converting the velocity head of the fluid into the pressure head to reduce the throttling loss of governing valve.

The study on the nozzle is mainly to research the relationship between pressure ratio and the discharge. When the adiabatic exponent $\kappa$ and the discharge coefficient $\mu_n$ are constant, the relationship between the steam flow through the nozzle and the pressure ratio can be expressed as follows.

\[ \varepsilon > \varepsilon_n \quad G = \mu_n A_n \sqrt{\frac{p_2}{u_0^*}} \sqrt{\frac{k}{2k-1} \left( \varepsilon^n_k - \varepsilon_k \right)} \]  

\[ \varepsilon < \varepsilon_n \quad G = G_c = 0.6473 A_n \sqrt{\frac{p_2}{u_0}} \]  

\[ \varepsilon_n = \frac{p_2}{p_0} \]  

For each given lift $L$ or opening $V$ of valve, there are:

\[ \beta = \frac{G}{G_{\text{max}}} \]  

For convergent-divergent nozzle, the curve segment where $\varepsilon > \varepsilon_n$ amounts to the 1/4 segment of the ellipse, so the elliptic equation can be used to establish the model of governing valve:

\[ \left( \frac{\varepsilon - \varepsilon_c}{1 - \varepsilon_c} \right)^2 + \left( \frac{\beta}{\beta_c} \right)^2 = 1 \]  

Where, $V$ is the valve’s opening degree, %; $\varepsilon_c$ is the critical pressure ratio, $\beta$ is the discharge ratio, and they change with the valve opening; $G_{\text{max}}$ is the maximum critical flow of the valve, kg/s; $\beta_c$ is the ratio of the critical flow to the maximum critical flow.

3. Verification of the model

In order to verify the accuracy of the model, make comparison between the experimental data in the literature [5] and the values calculated by the formula (5). The results are shown in figure 1. The experimental values basically fall on or near the simulation curve, and they are generally in consistence. The average relative errors between them are within 3.42%, so the model is accurate and reliable.
4. Application of the model

Thermal efficiency is used to evaluate the economic performance, the expression is equation (6). Since the sliding pressure unit has no governing stage, the flow efficiency $\eta_{ri}$ is considered to be constant, so the unit efficiency is affected by the cycle efficiency $\eta_t$ and the throttling efficiency $\eta_{th}$.

$$\eta = \eta_t \eta_{th} \eta_{ri}$$  (6)

Where, $\eta$ is the thermal efficiency of the unit; $\eta_t$, $\eta_{th}$ and $\eta_{ri}$ are the cycle efficiency, throttling efficiency and relative internal efficiency of the unit respectively.

A 660WM ultra-supercritical steam turbine unit was taken as the research object. Changing the main steam pressure and opening of governing valve, the influence of different steam distribution methods on the performance of the unit is observed. The relationship between heat consumption and load of the unit under throttling operation with different valve opening is shown in figure 2. Among all the operating modes, the unit has the lowest heat consumption and the highest economic efficiency in the sliding pressure operation, which is consistent with the results of the sliding pressure operation test in literature[6]. In this steam distribution mode, the governing valve is fully open, leaving no adjustment margin, and the main steam parameters are completely dependent on the boiler’s fuel and feed water flow, causing large thermal inertia and delay in the load adjustment. On the contrary, under
throttling operation, the governing valve has a large margin and the unit has great flexibility and peaking capability. Therefore, it can adapt to the power grid frequency modulation, but the heat consumption is the most, which is uneconomical.

With the same valve opening, the lower the load, the higher the heat consumption. Keeping the same valve opening, the throttling efficiency $\eta_{th}$ is constant. The main steam parameters in low load condition are small, the cycle efficiency $\eta_t$ of the unit is low, and the relative internal efficiency is considered to be constant. According to equation (6), the lower the load, the higher the efficiency of the sliding pressure operation, which means the difference in heat consumption with the pure throttling operation is greater.

Under different main steam pressures, opening of the governing valve is reduced for throttling operation. The relationship between the heat consumption and the load of the unit is shown in figure 3. If the main steam pressure is constant, there is a parabola relationship between the heat consumption and the load of the unit. The heat consumption increasing with the decrease of the load, and at low load, the heat consumption increases more obviously. Since the main steam pressure is constant, the cycle efficiency $\eta_t$ of the unit remains unchanged, the throttling efficiency $\eta_{th}$ is lowered due to the increase of the throttling loss causing by throttling operation. Then the thermal efficiency is lowered, and the heat consumption is increased.

![Figure 3. Relationship between heat consumption and load of the unit under different main steam pressure](image)

When the unit is under off-design operation, especially the low load operation, the governing valve has a large throttling loss, which leads to a drop in the hp cylinder’s efficiency and is not conducive to the economic operation of the unit. Figure 4 shows the variation of cylinder efficiency with the opening of governing valve. As the opening of the valve is reduced, the throttling loss increases and the efficiency of the hp cylinder decreases exponentially. When the opening changes from 100% to 45%, the inlet steam loss increases from 2% to 5.8% slowly. As the opening reduces to 23%, the hp cylinder efficiency changes from 88% to 74.5%, where the increase of throttling effect is very obvious. For every 1% increase in inlet steam loss of hp cylinder, the efficiency of it will be reduced by about 0.5%.
Large units involve in peaking generation, so the economic operation of the unit will only be considered in case of meeting the need of frequency modulation. A power grid frequency modulation assessment requires variable load speed of 660 MW unit more than 9.9 MW/min. The ultra-supercritical boiler is a once-through boiler with high response speed. Under the premise of without considering the parameters such as coal quality, the turbine should retain the margin for the power grid frequency modulation. The variable load rate of the power grid frequency modulation is a fixed value, as the load is decreased, more adjustment margin is required, that is, the opening of valve must be gradually reduced.

Table 1. Adjustment margin of hp governing valve under different loads

| Load | minimum adjustment margin (required by the power grid) | Adjustment margin (recommended operating scheme) |
|------|--------------------------------------------------------|--------------------------------------------------|
| MW   | %                                                     | %                                                |
| 660  | 0.15                                                  | 0                                                |
| 600  | 1.60                                                  | 4.13                                             |
| 540  | 1.80                                                  | 5.63                                             |
| 480  | 2.00                                                  | 7.24                                             |
| 420  | 2.30                                                  | 8.46                                             |
| 360  | 2.70                                                  | 9.88                                             |
| 300  | 3.30                                                  | 11.31                                            |
| 240  | 4.10                                                  | 13.94                                            |

According to above requirements, the adjustment margins required under different loads are calculated and listed in the second column of table 1. This paper suggests that the valve opening varies between 30% and 45% under variable operation. When the opening is reduced from 100% to 45%, the hp cylinder efficiency is only reduced by about 2.5%. The maximum difference in heat consumption compared with the pure sliding pressure operation is 13.42kJ/kWh, and the valve still has a margin of 3.9%. It is reasonable to sacrifice the small economic benefits for the controllability of the valve to ensure the safe operation of the unit. Therefore, it is recommended to control the upper limit of the valve opening around 45% on off-design operation.

It is also recommended that the lower limit of the valve opening is controlled around 30% under
variable operation. Since the opening is reduced from 45% to 30%, the efficiency of the hp cylinder is decreased by about 5.5%, that is, every 1% decrease in the opening, the efficiency of the hp cylinder is decreased by 0.37%. Compared with the valve opening of 45%, the average heat consumption is about 25kJ/kWh, and the economic loss is within the acceptable limits, and the lower the load, the smaller the difference in heat consumption between the two opening. If the opening is continually reduced to 23%, the efficiency of the hp cylinder will drop sharply. 1% decrease in the valve opening will lead to 1.3% decrease in the efficiency of the hp cylinder, then the heat consumption will increase. Therefore, the governing valve should be opened to more than 30%. 30% opening of valve corresponds to a load margin about 10%, which can meet the power frequency modulation requirements under low loads. Based on the analysis, the operation control strategy of this kind of unit when the load varies from 660MW to 240MW is given. The detailed scheme and parameters are listed in table 2.

Table 2. Recommended operation control strategies and parameters

| Load (MW) | Main steam pressure (Mpa) | Main steam temperature (°C) | Main steam flow (t/h) | Valve opening (%) | Efficiency of HP cylinder (%) | Heat consumption (kJ/kWh) | Difference of heat consumption with sliding pressure (kJ/kWh) | Difference of heat consumption with throttling (kJ/kWh) |
|-----------|-------------------------|-----------------------------|----------------------|------------------|-----------------------------|--------------------------|-------------------------------------------------------------|-----------------------------------------------------|
| 660       | 24.99                   | 600                         | 1915.58              | 100.0            | 91.03                       | 7388.51                  | 0                                                            | 0                                                  |
| 600       | 23.1                    | 600                         | 1672.79              | 43.45            | 87.64                       | 7466.76                  | 15.42                                                        | -28.24                                             |
| 540       | 21.2                    | 600                         | 1497.62              | 38.9             | 86.54                       | 7543.55                  | 17.81                                                        | -52.73                                             |
| 480       | 19.2                    | 600                         | 1325.36              | 36.5             | 85.60                       | 7623.45                  | 22.39                                                        | -79.40                                             |
| 420       | 17.1                    | 600                         | 1155.92              | 34.17            | 84.85                       | 7710.35                  | 22.91                                                        | -11.21                                             |
| 360       | 15.1                    | 600                         | 989.65               | 31.77            | 83.69                       | 7808.15                  | 25.43                                                        | -140.93                                            |
| 300       | 13                      | 600                         | 825.22               | 29.92            | 82.58                       | 7923.95                  | 27.49                                                        | -171.79                                            |
| 240       | 10.8                    | 600                         | 662.37               | 28.36            | 81.46                       | 8068.51                  | 26.57                                                        | -210.97                                            |

It can be seen from table 2 that with the use of the recommended operation scheme, the heat consumption is only 15~28kJ/kWh larger than the sliding pressure operation during the load reduction of the unit. The heat consumption difference can be ignored under off-design operation. This scheme has a far smaller heat consumption than throttling operation, which can expand the running scope of the unit and improve the ability of depth peak load cycling. In terms of safety, it can be seen from the third column of Table 2 under this scheme, the regulated margin which corresponds to recommended valve opening is larger than the minimum regulated margin required by power grid, which can meet the requirements of power frequency modulation.

5. Conclusion

(1) The calculation model of governing valve for ultra-supercritical steam turbine with throttle steam distribution mode is established. Through the comparison with experimental data in documents, it is proved to be accurate and reliable.

(2) When the opening of the valve is above 45%, the efficiency of the high-pressure cylinder changes mildly but the controllability of the valve is low; when the opening is below 30%, the efficiency of the high-pressure cylinder decreases linearly, and the economic efficiency of the unit is poor. It is recommended that the unit's opening should be in the range of 30%-45% under variable operating conditions.

(3) The heat consumption of the unit increases with the decrease of the load and the opening of the high pressure governing valve. The proposed operation scheme meets the requirements of the power grid frequency modulation and also improves the economics of the unit. It has practical guiding significance for the operation control strategy of the same type units in China.
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