Analysis on thermal characteristics of high back pressure heating retrofit for large-scale steam turbine units

Cheng Dong-tao, Ma Ting-shan, Zeng Li-fei, Ning Zhe, Wang Yan

Xi’an Thermal Power Research Institute Co., LTD., Xi’an 710054, China

Abstract: High back pressure heating with large-scale steam turbine units boasts preponderant heating capacity and preferable integrated utilization of energy while suffering high operation and maintenance cost and low operation flexibility. First, the high back pressure heating retrofit technology is introduced. Then, a model to analyze off-design performance of turbine and condenser for a 350MW heating unit was established using EBSILON software, by which quantitative calculation was performed of the influence of the key factors, so as to attain thermal characteristics of high back pressure heating. Finally, the paper was ended with multivariate analysis of the key factors in a combination of the theoretical analysis, the calculation results and the actual operating environment of the 350MW heating unit, in a bid to outline a change range of each factor. It thereby provided reference for selection of key parameters, feasibility analysis and operation economic analysis in high back pressure heating retrofit.

1. Foreword

Urban expansion, heating area enlargement, and pressure on wintertime haze control and heating boiler shut-down in Northern China raise a pressing need of escalating heating capacity for power/heat cogeneration units. With strengths in improving heating capacity and recycling cold source losses\(^2\) of large-scale steam turbine units, the high back-pressure heating technology\(^1\) has been suited to some heating units in recent years. However, existing technical literature by a group of scientific research institutes and power engineers only places emphasis on retrofit content and energy-saving outcomes of such retrofit projects. Among them, literature\(^4\) was an application analysis of the double-low-pressure rotor exchange technology in high-back-pressure heating retrofit; literature\(^5,6\) focused on theoretical analysis and experimental research on what the retrofit led to the thermodynamic performance indexes; and in literature\(^7\), applicability of return water temperature in the heating network to high back pressure heating was analyzed.

While becoming increasingly sophisticated, the high back pressure heating technology may disable some retrofitted units from operating for a long time or from being high powered. This is the consequence of deficient analysis on thermal characteristics of the retrofitted units in project approachment, especially on the influence of key factors such as heating load, circulating water flow, and return water temperature on the thermal characteristics\(^8\). In this paper, following analysis on thermal performance of the high back pressure heating unit, a model was established with EBSILON \(^9\) software to calculate the off-design characteristics of turbine \(^{10}\) and condenser \(^{11}\). By the calculation model, investigation was made of what qualitative and quantitative influences key factors including heating load, circulating water flow and return water temperature exerted on heating-generation load and steam exhaust pressure of low-pressure cylinder, offering guidance for the selection of key parameters and feasibility analysis of high back pressure retrofit, and providing analysis and calculation basis for the operation economy of retrofitted units\(^12\).
2. High back pressure heating retrofit

The unit is retrofitted with the high back-pressure heating technique to pump circulating water of the heating network instead of original circulating cooling water into the condenser at the same time that it pressurizes the low-pressure cylinder of the steam turbine when it exhausts steam, making the condenser the primary heating network heater. Thus, condenser water absorbs heat as it circulates and then flows into the heater of the original heating network where it continues heat absorption until it is heated to the required temperature before supplying heat. See Figure 1 for the schematic diagram of high back pressure heating system.

![Figure 1 Schematic diagram of high back pressure heating system](image)

The steam heat exhausted by the low-pressure cylinder of the steam turbine that runs at a high back pressure is used for external heating, which does generate cold source loss while improving the heating capacity and integrated utilization of energy. Such a manoeuvre could cut both ways.

For wet cooling units retrofitted with a high back pressure heating system, their original low-pressure rotors fail to fit unit operation and generally have alternatives during the heating season or sometimes work with a last two-stage blade retrofit. Both schemes involve retrofit for low-pressure rotor, condenser, circulating water lines in the heating network, condensate polishing system, small steam turbine of a feed pump (if any) and open water system, with high retrofit cost. It is generally necessary to stop running the unit before operation mode shift, with high maintenance charge. Specially, if the unit turns to operating at a high back pressure in the heating season, it will remain in this mode and be based on heat load throughout this time bucket, with low operating flexibility.

For air cooling units[13,14], their low pressure rotors, considering the high steam exhaust pressure of the low-pressure cylinder, basically dispense with the need for a retrofit but are outfitted with an independent condenser, which generates a high cost. Mode switch does not require downtime, with low operation and maintenance cost. Nevertheless, when running on high back pressure, air cooling units often need isolating in part or all columns. Besides, their complicated operations and susceptibility to anti-freeze measures in an air-cooling island lead to a decrease in economic efficiency and operation flexibility.

Despite the ups, the high back pressure heating method also has its downs, such as high operation-maintenance cost and low operational flexibility. Thus, if this technique is applied to heating units, its heating advantages should be given full play, which, however fails in some retrofitted units, causing steam exhaust pressure out of control, and small heating load demand and consequent downfall of generating capacity.

3. EBSILON modeling, analysis and calculation

A model was developed using EBSILON software to systematically analyze thermodynamic performance of steam turbine and condenser in a 350MW high back-pressure cascade heating unit for off-design operating conditions. The analysis covered how heating load distribution, heating load value, return water temperature and circulating water flow affected the thermal performance of the unit. The
flow passage components of steam turbine under off-design conditions were calculated by Friuli Greig formula\cite{15} while the calculation for the condenser based itself on condenser performance test standards.

3.1. EBSILON modeling
The model was established as described above and as shown in Figure 2. By this basic model, analysis was made of how heating load distribution and load value were involved in thermal performance calculation for the high back pressure heating unit under different main steam flow conditions. Then, the calculation for the condenser under off-design conditions was performed to determine the adaptability of heating load, water return temperature and circulating water flow to exhaust pressure of the low-pressure cylinder.

Since factors often interact with each other directly or indirectly, the following analysis of an individual factor was premised on keeping other factors unchanged, in order to clarify the influence degree and law of the individual factor on the thermal performance of the retrofitted unit, leaving integrated exploration on all factors for subsequent work.

![Figure 2 Model of high back pressure heating unit](image)

3.2. Heating load distribution
Following the theoretical analysis on key factors and their influences was the analysis and calculation of the influence of heating load distribution on the thermal performance of the unit with rated main steam flow, as shown in Table 1.

| Project                      | Unit            | Case 1  | Case 2  | Case 3  | Case 4  | Case 5  |
|------------------------------|-----------------|---------|---------|---------|---------|---------|
| Main steam flow              | t/h             | 1079.6  | 1079.6  | 1079.6  | 1079.6  | 1079.6  |
| Exhaust pressure             | kPa             | 45.0    | 45.0    | 45.0    | 45.0    | 45.0    |
| Extraction heating flow      | t/h             | 100.0   | 200.0   | 300.0   | 400.0   | 500.0   |
| Intake of low pressure cylinder | t/h           | 603.4   | 495.4   | 386.3   | 275.6   | 163.2   |
| Extraction heating load      | MW              | 74.9    | 149.8   | 224.8   | 299.7   | 374.6   |
| Heating load of condenser    | MW              | 399.7   | 339.6   | 278.7   | 216.7   | 153.1   |
| Total heating load           | MW              | 474.6   | 489.5   | 503.5   | 516.4   | 527.7   |
| Generation load              | MW              | 311.3   | 297.2   | 284.0   | 271.9   | 261.4   |
| Heat consumption for power generation | KJ/(kW·h) | 3678.4  | 3672.6  | 3665.6  | 3657.9  | 3649.5  |
| Coal equivalent calculation  | g/(kW·h)        | 136.3   | 136.1   | 135.8   | 135.6   | 135.2   |
Table 1 and Figure 3 illustrated that, for the high-back-pressure heating units under the same main steam flow condition, the larger the extraction heating flow and load, the smaller the heating load of condenser, alongside larger total heating load and smaller generation load, only producing a small deviation in coal equivalent calculation under various off-design operating conditions.

A prevalent method of heat rate transformation coefficient that attributes cogeneration gain only to heat supply was introduced for coal equivalent calculation in this study. Since electricity quality always outperforms heating quality in actual production, high back pressure units should minimize the heating load of extraction steam while maximizing that of the condenser in heating load distribution. Such distribution is designed to achieve rational utilization of energy and accords with the basic principle of cascade energy utilization.

The theoretical-analysis-based modeling arrived at the law by which heating load distribution (with extraction heating flow at 100t/h-500t/h) acted on the thermal performance of the unit. In actual unit operation, extraction heating flow is adjusted to a limited extent so as to keep the exhaust pressure and intake flow of low-pressure cylinder as well as water supply temperature in the heating network within the required range. Therefore, the following was to work out the allowable range of condenser heating load through the analysis of factors behind the return water temperature and circulating water flow. Then the adjustment range of extraction heating load under different main steam flow conditions was defined.

### 3.3. Heating load

The theoretical analysis of key factors and their impacts concluded that heating load capacity of the high back pressure unit mainly depended on the main steam flow. Given the maximum extraction heating load and the minimum condenser heating load (the low-pressure cylinder remained the minimum steam intake flow of 224t/h), the heating load and generation load were calculated under different main steam flow conditions, as shown in Table 2, while Figure 4 revealed the relation curves of heating load, generating load and main steam flow.

| Table 2 Heating load and generation load under different main steam flow conditions |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Project                         | Unit            | 100% THA        | 75% THA         | 50% THA         |
| Main steam flow                 | t/h             | 1079.6          | 809.7           | 539.8           |
| Exhaust pressure                | kPa             | 45.0            | 45.0            | 45.0            |
| Intake of low pressure cylinder | t/h             | 224.0           | 224.0           | 224.0           |
| Extraction heating flow         | t/h             | 446.1           | 316.8           | 167.9           |
| Extraction heating load         | MW              | 334.2           | 242.7           | 132.8           |
| Heating load of condenser       | MW              | 187.6           | 171.5           | 163.6           |
| Total heating load              | MW              | 521.9           | 414.3           | 296.4           |
| Power generation load           | MW              | 266.8           | 203.5           | 136.2           |
Figure 4 Relation between heating load, generating load and main steam flow

It can be seen from Table 2 and Figure 4 that, with the rated main steam flow between 50% and 100% and the low-pressure cylinder at the minimum intake flow of 224 t/h, the unit had the heating load spanning from 296.4MW to 521.9MW, corresponding to generation load from 136.2MW to 266.8MW. Besides, different main steam flow conditions led to approximate coal consumption in power generation.

At high back pressure, the unit basically operated in a heat-load-based mode. By heating load distribution analysis, the heating load and generation load could be adjusted when main steam flow was given. Adjustment in the extraction heating flow caused an according change in the intake flow of the low-pressure cylinder. In the actual operation, the maximum allowable intake flow of the low-pressure cylinder could be calculated via the influence analysis of the water return temperature and circulating water flow, while the exhaust pressure and the water supply temperature were kept within the required range. Often the intake flow and heating load distribution are subject to narrow adjustment space. The heating load and generating load values obtained by modeling with the designed minimum intake flow of the low-pressure cylinder were those of the high back pressure heating unit under different main steam flow conditions, which can be used to investigate the heating and generating characteristics.

The retrofit scheme and operation mode analysis should give sufficient consideration to the adaptability of heating and generation load parameters to the actual heating demand, lest the high back pressure heating unit cannot operate normally or operate at low generation load for a long time as a result of too little heating demand. It would thereby reduce overall power generation and operation efficiency.

3.4 Temperature of circulating water

It was concluded from the theoretical analysis that the key to analyze the effects of circulating water temperature was to explore how exhaust pressure of the low-pressure cylinder changed at different return water temperatures, if the condenser run with the minimum heating load (minimum intake flow of low-pressure cylinder) and circulating water flow was given. On the premise that the exhaust pressure was within the limit range, to increase distribution ratio of the condenser heating load may be considered.

The 350MV steam turbine was designed with the minimum intake flow of the low pressure cylinder to be 224 t/h and the corresponding heat load of condenser to approximate 188MV. The selected power plant is equipped with two units of the same type, where the circulating water flow was set as the maximum 12000 t/h value according to the original design. The exhaust pressure of the low-pressure cylinder at different return water temperatures was figured out as shown in Table 3, with the relationship between exhaust pressure and return water temperature in Figure 5.

| Project       | Unit | T1   | T2   | T3   | T4   | T5   |
|---------------|------|------|------|------|------|------|
| Intake of LP  | t/h  | 224.0| 224.0| 224.0| 224.0| 224.0|
In Table 3 and Figure 5, given the heating load of condenser and the circulating water flow, the low-pressure cylinder operated under increasingly higher exhaust pressure as the circulating water temperature went up. The wet cooling unit was usually retrofitted with the low-pressure cylinder at 45kPa when it exhausted steam and circulating water return in temperatures below 65°C whereas the air cooling unit was remade with the exhaust pressure of 35kPa and circulating water return lower than 59°C.

Notably, the return water temperature limits for the wet cooling unit and the air cooling unit were evaluated from the above analysis by presetting the heating load for the condenser and circulating water flow of the heating network. Calculation could be performed to get new turn water temperature limits according to changes in condenser heating load and circulating water flow, providing a basis for regulating heating load distribution and the heating load of the condenser.

### 3.5. Circulating water flow

It was concluded from the theoretical analysis that the key to analyze the effects of circulating water flow was to explore how exhaust pressure figures for the low-pressure cylinder changed at different return water flow values, when the condenser run with the minimum heating load (minimum intake flow of low-pressure cylinder) and circulating water temperature was given. On the premise that the exhaust pressure was within the limit range, to increase distribution ratio of the condenser heating load may be considered.

The 350MV steam turbine was designed with the minimum intake flow of the low pressure cylinder to be 224 t/h and the corresponding heat load of the condenser to approximate 188MV. Given the circulating water return at 60°C, the low-pressure cylinder had its exhaust pressure calculated under different circulating water flow rates as shown in Table 4, leading the relation between the exhaust pressure and the circulating water flow to Figure 6.

### Table 4 Calculation results of exhaust pressure under different circulating water flow rates

| Project                        | Unit | flow 1 | flow 2 | flow 3 | flow 4 | Flow 5 |
|-------------------------------|------|--------|--------|--------|--------|--------|
| Intake of low pressure cylinder | t/h  | 224.0  | 224.0  | 224.0  | 224.0  | 224.0  |
| Heating load of condenser     | MV   | 188    | 188    | 188    | 188    | 188    |
| Circulating water flow        | t/h  | 8000   | 10000  | 12000  | 14000  | 16000  |
| Circulating water temperature | °C   | 60.0   | 60.0   | 60.0   | 60.0   | 60.0   |
| Outlet temperature of condenser | °C  | 79.9   | 75.9   | 73.3   | 71.4   | 70.0   |
| Exhaust pressure of low pressure cylinder | kPa  | 48.3   | 41.2   | 37.0   | 34.2   | 32.3   |
In Table 4 and Figure 6, given the heating load and the circulating water temperature, the low-pressure cylinder operated at increasingly lower exhaust pressure as the circulating water flow got bigger. The wet cooling unit was usually retrofitted with the low-pressure cylinder at 45kPa when it exhausted steam and water return of the heating network at above 8900t/h whereas the air cooling unit was remade with the exhaust pressure of 35kPa and circulating water return of greater than 13100t/h.

Notably, the circulating water flow limits for the wet cooling unit and the air cooling unit were evaluated from the above analysis by presetting the heating load for the condenser and return water temperature of the heating network. Calculation could be performed to get new turn water flow limits using changes in heating load and water return, providing a basis for regulating heating load distribution and the heating load of the condenser.

4. Comprehensive analysis
While the above analysis on an individual factor was conducted with other factors given, factors actually influence each other and have their respective change space. Theoretically, thermal performance of the high back pressure heating unit was in multivariate analysis synthesizing the influence and possible variation range of each key factor as well as the actual production situation, so as to narrow the analysis scope.

The thermal performance analysis was almost all about the adaptability of the low-pressure cylinder in terms of exhaust pressure and characteristics of the heating-generation load. Analysis-based recommendations below followed a combination of the theoretical analysis and modeling & calculation with the actual operating environment.

4.1. Adaptability of exhaust pressure
To study the adaptability of exhaust pressure required condenser heating load, circulating water return temperature, and circulating water flow to work together. The condenser operated at the minimum heating load to meet the adaptability requirements for exhaust pressure of the low pressure cylinder. Along this line was the procedure to work out the rise range of the heating load. Usually subject to the configuration of circulating water system, circulating water flow could be preliminarily set accordingly or by the subsequent retrofit scheme. Return water temperature was anchored to the ambient temperature and the configuration of the heating network system, and its change rule bore a direct relationship to the operation efficiency after the retrofit. It can be evaluated with the operation data of previous years and the retrofit plan specific to the heating network system.

The absence of a well constructed analysis on adaptability of low-pressure cylinder exhaust pressure
will directly translate to exhaust overpressure and thus the failure to operate in a high-back-pressure mode. An air cooling unit boasting less retrofit-induced investment and flexible operation compared with a wet cooling unit, for example, is generally located in cold areas and has high return water temperature in the middle heating period. In addition, the exhaust pressure is normally designed as 35kPa for low pressure cylinder in high back pressure heating units. Such case is prone to exhaust overpressure and thereby reduces operation safety and economics. Hence, the adaptability analysis is of necessity to ensure the feasibility of high back pressure heating mode.

4.2. Heat-generation load characteristics

The relation curve between heating load and generation load in various main steam flow conditions, which may be worked out via modeling, underlay the characteristic analysis of heating-generation load. Then an exploration on the adaptability of the characteristics to current and future heating demands ensued. Only with high adaptability could a unit give full play to the advantages of high back pressure retrofit. On the flipside, a case in which the heating demand is well below a unit's heating capacity will lead the unit to fail in running at high back pressure or restrict it to low-load high back pressure heating for a long time. Such adaptability issues are frequently encountered in high back pressure retrofit.

Heating load demand relates to heating area, heating index and ambient temperature. Given the heating area and heating index, the demand changes greatly with ambient temperature variations. Generally, the average heating load in a heating season is about 70% of the designed value, sometimes even less than 50%, and the change of heating load in the heating season should be fully considered. However, the heating area and heating index, mainly given by statistics and experience, tend to suffer huge errors, hence suggestions to get the actual heating parameters in recent years and set post-retrofit heating demand based on the statistical values of heating load and the growth demand for heating area.

The analysis on adaptability of heating capacity to heating demand was progressed with a consensus that, the greater the heating demand was, the more favorable it would be to give play to the advantages of high back pressure heating. In a CHP plant with three or more heating units and thus a great heating demand, for instance, strengths in high back pressure heating can be brought into full play as long as one unit is retrofitted. Separately, the actual heating demand needs anatomizing for the overwhelming majority of CHP plants with just two units, to avoid low generating capacity and poor operation economy caused by long-term operation with low heating load.

The adaptability that exhaust pressure of low-pressure cylinder shows is strongly associated with the characteristics of heating-generation load. In the high back-pressure heating unit, the exhaust pressure was more easily kept within the specified range and benefited unit operation when the return water was at low temperature in the initial and final heating period, but high back-pressure operation failed usually due to low heating load demand. In the middle heating period with a large demand for heating load, high back-pressure operation was needed but would spell failure in effectively regulating exhaust pressure, as the return water of the heating network experienced a great temperature rise.

5. Conclusion

Large-scale high back pressure heating turbine units boast preponderant heating capacity and preferable integrated energy utilization while suffering high operation and maintenance cost and low operation flexibility.

Thermal performance of high back pressure heating units underlies the feasibility, economy and safety analysis of such retrofit, and its key factors were analyzed both theoretically and by a model to conclude their qualitative and quantitative influences on the thermal characteristics.

The key of the thermal performance analysis lies in the adaptability of exhaust pressure of low-pressure cylinder and the characteristics of heating-generation load. The actual operating environment of the unit was considered in theoretical analysis and modeling calculation, accompanied by the multivariate analysis to define the change range of each key factor. It provided an analysis and calculation basis for the selection of key parameters, the feasibility study of the high back pressure retrofit and the economic analysis of the retrofitted unit operation.
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