An Improved Calculation Method of Coal Consumption Index for Heating in CHP with a High Back Pressure Turbine

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Abstract. CHP (combined heating and power) system is playing an important role for district heating, meanwhile, the latent heat of exhausted steam at the thermal power plant is discharged to atmosphere directly, which is often more than 30%. Waste heat recovery is of great significance for reducing coal consumption indicators for heating in CHP system. The method by replacing different rotors of the LP (low pressure) cylinder is presented and experimented with a 140MW turbine, whose exhausted steam could be recovered completely. Besides, an improved calculation method of coal consumption index for heating is discussed. The improved mathematical model is used to calculate the influence of exhaust pressure on steam turbine power generation efficiency, which improves the accuracy of heating coal consumption. This experimented coal consumption index for heating is 12.7 kgce/GJ, which is much lower than the traditional CHP system (20 kgce/GJ).

Keywords: CHP; District heating; High back pressure; Coal consumption index; Double rotor.

1. Introduction
The electricity was mainly generated by CHP system in northern China, which was more than 80%
[1]. In addition, the heating capacity of the CHP system can not meet the rapid growth demand in many big cities in China, so it is very difficult to establish new heating sources in the built cities. [2].

Many efforts have been made to improve the energy efficiency of thermal power plants [3-10]. ORC (organic Rankine cycle) was adopted for a small CHP system, whose temperature range of heating source was 90℃-150℃. They found that cycle efficiency was increased slightly for higher pressure ratios, and its net electrical efficiency was about 8% [3]. The application of cogeneration using gas turbine and thermal engine is compared, and the necessary synergy between gas turbine and thermal engine is emphasized [4]. A methodology for optimizing electric power of thermal power plant basing on ORC cycle was given, which was connected with an existing district heating network [5]. A model with ORC using R134a was introduced, and results showed a way to maximize the total thermal efficiency [6]. A mathematical model of CCHP (combined cooling, heating and power) was discussed, which owned two heat engines with waste heat recovery driving chiller [7]. It is found that absorption heat pump is an effective method to recover all kinds of low grade heat [8]. A new heat recovery system of cogeneration is proposed, which is installed in the waste HRU (heat recovery unit) and AHE (absorption heat exchanger) in the thermal power plant and heating substation respectively. The total energy efficiency of the traditional cogeneration system is increased by more than 20% [9]. A new type of absorption heat pump is introduced, which uses lithium bromide solution as working fluid for heat recovery in thermal power plant. The temperature difference between evaporator and condenser can reach 50℃ and there is no risk of crystallization [10]. The absorption
heat pump (AHP) combined with plate heat exchanger (PHE) has been studied. An absorption heat exchanger (AHE) combining absorption heat pump (AHP) and plate heat exchanger (PHE) is proposed. Compared with the traditional plate heat exchanger, it can significantly reduce the return water temperature of primary pipe [11].

A new district heating system of CHP was reported, which applied absorption heat pump at the thermal power plant, and it could recover low grade heat of cooling water significantly [12]. Working fluids for absorption cycles were reviewed and compared for different working cases [13-15]. A single effect absorption heat pump was employed at an actual thermal power plant of 300MW, and experimental results were given and compared with simulation results [16]. In addition, several heat pumps are introduced and the possibility of heat recovery in different industries is compared [17]. However, the absorption heat pump with large heating load is quite expensive for the thermal power plant, whose payback period is often more than 5 years. However, the latent heat of exhausted steam could be recovered in the condenser by lifting the back pressure of steam turbine [18], therefore, the exhausted steam could heat the back water of primary heating pipe directly in the condenser, however, the back pressure is limited due to running safety of the steam turbine, which could not recover all condensation heat of exhausted steam.

2. Experiment of a CHP System with Double LP Rotors

Two rotors for LP cylinder of 140 MW steam turbine are manufactured in this experiment, one rotor (low back pressure) is used for pure power generation during the non-heating period, which could ensure maximum power generation efficiency with a low back pressure; and the other one (high back pressure) is installed during the heating period, and all latent heat of exhausted steam could be recovered with a high back pressure. Because the exhaust steam is completely recovered, the coal consumption index of heating and heating capacity could be improved significantly during the heating period.

The high back pressure rotor is used during the heating period, which is described in figure 1. Firstly, the back water of primary pipe is heated in the condenser, which could recover the latent heat of exhausted steam. Secondly, the back water will be heated again by a steam-water heat exchanger by the extracted steam from a nearby 300MW steam turbine to the required temperature for district heating. The designed flow rate of back water is 9000 t/h. The designed pressure of the high back pressure rotor is 43.6 kPa, which could ensure that all latent heat is recovered. Meanwhile, the high back pressure rotor will be replaced by the low back pressure one for pure electricity generation during the non-heating period, whose designed value is only 4.9 kPa.

![Figure 1. Principle of the thermal power plant with high back pressure rotor.](image)

Experimented rotors are shown in figure 2. The low back pressure rotor owns \(2 \times 6\) blades, however, the high back pressure one owns \(2 \times 4\) blades only. Besides, the condenser is remanufactured due to larger temperature and pressure differences when compared with the working case of pure power generation.
Figure 2. Rotors with different back pressures (left: low pressure, right: high pressure).

Precision of experimental instruments is given in table 1, and the time interval of recording is 10 min.

Table 1. Experimental instruments installed in experiment.

| Type                 | Accuracy | Remark                                  |
|----------------------|----------|-----------------------------------------|
| Temperature sensor   | Platinum resistance | 0.1°C | Back water and exhausted steam         |
| Flow rate sensor(Ⅰ) | Revolving flow meter | 1%   | Condensed water of exhausted steam     |
| Flow rate sensor(Ⅱ) | Ultrasonic flow meter | 0.5% | Back water                             |
| Pressure sensor      | Absolute pressure sensor | 0.075% | Exhausted steam                       |

Thermal parameters are recorded for 12 months. The average pressure of exhausted steam of 140MW steam turbine in each month is shown in figure 3. This pressure is lower than 10 kPa during the non-heating period, which is aimed for maximum power output. And it varies from 36 kPa to 43 kPa during the heating period (from Nov. to Mar.), which could ensure that all low grade heat of exhausted steam is utilized.

Figure 3. Pressure of exhausted steam in different month.

Average inlet and outlet temperatures of water in the condenser in each month are compared in figure 4. Ratios of extracted steam and exhausted steam in total heating load are compared in figure 5. Due to the high outdoor temperature, the heating demand is much lower at the beginning and end of the heating period. Therefore, less extracted steam of 300MW turbine is needed. It is found that the steam discharged in November accounts for nearly 90% of the total heat. and Mar., which could reach 55% in Jan. also. Besides, temperatures of supply water and back water of the primary pipe are compared in figure 6. It is found that the supply water temperature is much higher during the middle of heating period due to lower air temperature, thus, the heat load is increased at the same time, which could be calculated by the temperature difference between supply and back temperatures.

Figure 4. Temperature of water of condenser in each month.
Figure 5. Ratio of exhausted steam and extracted steam in total supply heat.

Figure 6. Temperature of supply water and return water of heating pipe.

3. Model of Steam Turbine for CHP System

The CHP system is a quite efficient way for supplying heat and generating power at the same time. However, due to changing outdoor temperature during a complete heating period (often more than 3 months), the temperature of back water is varying obviously, which could affect the pressure of exhausted steam directly.

Boiler, turbine, power unit and other auxiliary equipment are all calculated according to heat balance equations. Simulation is completed when mass balance and energy balance of all units are reached. Calculation model is shown in figure 7.

Figure 7. Procedure of model of 140MW steam turbine.

It is also found that different pressure of exhausted steam has little effect on power generation of HP (high pressure) cylinder and MP (middle pressure) cylinder, but the power generation of LP cylinder is affected obviously, which is shown in figure 9.

Figure 8. Relationship between pressure of exhausted steam and power output.

Figure 9. Power output of different cylinder when changing pressure of exhausted steam.

Power generation efficiency factor $\varepsilon$ for a cylinder is defined as the ratio of generated power with input enthalpy of superheated steam here. It is found that this factor of LP cylinder is decreasing
significantly when lifting the pressure of exhausted steam, which is shown in figure 10. Besides, this factor of HP and MP cylinder changes much more slightly.

4. Improved Calculation Method of Coal Consumption of Heating

An improved equation for calculating the coal consumption of heating with the power generation correction coefficient $\eta$ is presented, which is defined as the ratio of actual value of generated power with the value under the standard working case, which is defined as follows:

$$\eta = \left(\frac{P_{HP,MP} \times \varepsilon_{HP,MP} + P_{LP} \times \varepsilon_{LP}}{P_{HP,MP} \times \varepsilon_{HP,MP} + P_{LP} \times \varepsilon_{LP}}\right)$$  \hspace{1cm} (1)

$$\varepsilon_{HP,MP} = \frac{P_{HP,MP}}{Q_{HP,MP}}$$  \hspace{1cm} (2)

$$\varepsilon_{LP} = \frac{P_{LP}}{Q_{LP}}$$  \hspace{1cm} (3)

Therefore, actual value of generated power of HP, MP and LP cylinders could be got with the correction coefficient $\eta$. Simulation results are shown in table 2.

| Table 2. Simulation results of steam turbine in different month. |
|---------------------------------------------------------------|
| Standard | Nov. | Dec. | Jan. | Feb. | Mar. |
| Pressure of exhausted steam (kPa) | 43.6 | 40.17 | 37.54 | 36.34 | 38.68 | 41.25 |
| Power generation of HP and MP (MW) | 100.01 | 102.72 | 102.37 | 102.22 | 102.52 | 102.87 |
| Power generation of LP (MW) | 21.64 | 22.72 | 22.67 | 22.95 | 22.42 | 21.86 |
| Coal consumption index of power generation (gce/kWh) | 377.21 | 374.60 | 373.46 | 375.71 | 378.31 | 377.21 |

The coal consumption index of 300 MW steam turbine is 18.3 kgce/GJ, which is simulated in Ebsilon also. So, the total index of coal consumption of heating for this CHP system is only 12.7 kgce/GJ. Due to significant reduction of energy consumption of heating, $4.4 \times 10^4$ tons of coal could be saved annually when compared with the district heating system with a boiler directly. And air pollution reduction is shown in table 3.

| Table 3. Air pollution reduction per year. |
|------------------------------------------|
| Name | Value | Unit |
| SO2 | 1063 | Ton/a |
| CO2 | 11517 | Ton/a |
| NOx | 310 | Ton/a |

5. Conclusion

The CHP system is playing a more and more important role for district heating, which could reduce coal consumption and air pollution significantly. Meanwhile, low grade heat of exhausted steam is hard to be recovered. The method by replacing two rotors for the LP cylinder is discussed and experimented. The coal consumption index of heating could be reduced to 12.7 kg/GJ, which is much lower than traditional CHP (20 kgce/GJ) or boiler (40 kgce/GJ).

In the end, an improved method for calculating coal consumption index for heating is given and discussed. It is found that the efficiency of electricity generation of LP cylinder varies obviously when changing the pressure of exhausted steam. Therefore, it should be considered when calculating the coal consumption of electricity generation at different time, rather than adopting a constant.

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