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Steam-Water Modelling and the Coal-Saving Scheduling Strategy of Combined Heat and Power Systems

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Abstract: China aims to peak carbon emissions by 2030. As a result, small-scale coal-fired combined heat and power (CHP) units and self-provided units are gradually shut down, and large-scale coal-fired CHP units are a solution to undertake the industrial heat loads. From the perspective of the industrial heat load allocation during the non-heating season, the problems regarding the coal-saving scheduling strategy of coal-fired CHP units are addressed. The steam-water equations of CHP units are established to analyze the heat-power coupling characteristics. The energy utilization efficiency, exergy efficiency and the coal consumption are analyzed. The optimization model of saving coal consumption is established and the adaptive mutation particle swarm optimization (AMPSO) is introduced to solve the above model. The 330 MW coal-fired CHP unit is taken as an example, and the results show that for the constant main flow rate, each increase of 1 t/h industrial steam extraction will reduce the power output by about 0.321 MW. The energy utilization efficiency and the exergy are mainly influenced by industrial steam supply and the power load, respectively. For the CHP system with two parallel CHP units, the unequal allocation of industrial heat load between two units saves more coal than equal allocation. The coal consumption can be reduced when the unit with lower power load undertakes more industrial heat load. In the typical day, the total coal consumption after optimization is 3203.92 tons, a decrease of 14.66 tons compared to the optimization before. The two CHP units in the case can benefit about 5,612,700 CHY extra in one year.

Keywords: combined heat and power; steam-water equation; load optimal allocation; particle swarm algorithm

1. Introduction

In order to achieve “peaking carbon” by 2030 and “carbon neutral” by 2060, China has been promoting the elimination of backward production capacity and reduction of coal consumption. As a result, small-scale coal-fired combined heat and power (CHP) units supplying steam for enterprise production and civil heating are gradually being shut down, and large-scale coal-fired CHP units supplying steam centrally can be considered as an effective measure to achieve carbon emission reduction targets [1]. At the same time, steam of various parameters is required in some industry processes (e.g., chemical, food and pharmaceuticals). The practical demand for steam in the production chain and the reality of shutting down small-scale coal-fired CHP units provide a market for large-scale coal-fired CHP units to provide an integrated energy supply. The CHP unit can be renovated to extract some steam for industrial production while generating power. The benefits of the above approach are the following three points. First, the profit of the CHP unit can be increased by selling steam to the users. Second, the investment in equipment of the industrial heat users can be saved partly. Third, it can also contribute to a certain extent to the reduction of regional carbon emissions.
Operational flexibility of CHP units, mainly referring to the heat-power loads’ adjustment space, is important for integrated energy supply. Several substantial studies have been performed by scholars to improve the operational flexibility of CHP units. The methods to enlarge the loads’ adjustment space can be summarized as heat-power decoupling [2,3] technology (e.g., thermal energy storage, electric boilers and heat pumps) and turbine renovations. Lepiksaar et al. [4] proposed the solution of coupling the CHP system with thermal energy storage to balance the heat-power loads’ demand for the consumption of renewable energy. Lai et al. [5] studied a large-scale CHP system integrated with a thermal storage tank. The results showed the minimum power output of the CHP system could be reduced by 12% under the heating load of 300 MW. Cho H et al. [6] investigated the CHP system with a heat pump. The results showed that the heat supply capacity of the reference CHP system could be enhanced considerably. Liu et al. [7] compared the performance of electric boilers and heat pumps on reducing the minimum power load of the CHP unit. The results showed that electric boilers could be considered as the preferable choice. In addition, the steam turbine renovations of CHP units can also improve the integrated energy supply capacity of the CHP unit. Ge et al. [8] proved that the heat supply capacity can be improved by increasing the back pressure of the turbine. E et al. [9] showed the heat-power ratio improved from 1.278 to 2.385 and the minimum power load decreased about 35.7% in the low-pressure turbine zero-output renovation CHP unit.

In addition to improving operational flexibility, further studies on optimizing the economic performance of CHP units have been conducted by scholars. Feng et al. [10] developed an optimization model based on the energy matching mechanism applied to the combined cooling, heating and power system. The results showed that the energy saving rate of a typical summer day was increased by 3.9%. Zhang et al. [11] proposed the heat absorption device could be used to recover waste heat from exhaust steam of the coal-fired CHP unit. The results showed that the coal consumption rate was reduced by 11.50 g/kWh. Mohamed et al. [12] analyzed the economic viability of the CHP systems and the CCHP systems. The results showed that the ground source heat pumps with free ground cooling was an ideal choice for improving the economic performance. Benalcazar [13] proposed a mixed-integer linear programming model to optimize the sizing of the thermal energy storage system for a CHP system. The findings showed that the fuel costs were reduced.

Most previous studies have focused on the flexible supply and economic operation of civil heat and power loads. However, the issue of flexibility and economical operation of industrial heat and power loads during the non-heating season has been insufficiently investigated. In addition, the work above to improve the economics performance mainly focuses on one single CHP unit. However, due to the continuous increase in coal prices and the requirement to consume renewable energy, coal-fired CHP units are often unable to enhance their economic performance by generating more power. Moreover, the optimization space of a single unit is relatively restricted. Based on the coal consumption characteristics of the unit itself, it is worth further study to improve the economic performance from the perspective of multiple unit dispatching. Therefore, the system containing multiple CHP units can be considered as the subject of study, and then the economy performance can be improved by reducing the coal consumption while the total heat and power supply remains unchanged.

In this study, the problems regarding the thermodynamics analysis and the coal-saving scheduling strategy of coal-fired CHP units are addressed. In Section 2.1, the steam-water equations of coal-fired CHP units with the industrial heat users are established based on the pure condensing conditions, combined with the auxiliary matrix of industrial steam extraction. Then, the heat-power coupling characteristics of the CHP unit are obtained by off-design calculation. In Section 2.2, the influence of the industrial steam supply on the energy utilization efficiency, exergy efficiency and the coal consumption of the CHP unit is analyzed. The effect of the industrial heat load allocation scheme on the coal consumption rate is analyzed. In Section 3, the model for optimal industrial heat load distribution to
save the coal consumption is developed. Based on the classical particle swarm algorithm, the concept of adaptive mutation is introduced to solve the model.

2. Model Development

2.1. Thermodynamic Modelling

Figure 1 shows the schematic diagram of an extraction-condensing, single-reheat CHP unit. The reference CHP unit consists of three high-pressure regenerative heaters (RHs), one deaerator and three low-pressure RHs. Industrial extraction occurs in the hot reheat section, where it converges with the cooling water from the feed-water pump in the desuperheater. Next, the parameters (e.g., temperature and pressure) of the industrial steam supply are adjusted and delivered to the industrial heat users in the pipeline. Then, the mass flow rate of the industrial steam supplied \( m_{\text{pipe}} \) can be calculated with

\[
m_{\text{pipe}} = m_s + m_w
\]

where \( m_s \) and \( m_w \) are the mass flow rates of the industrial steam extracted and the cooling water, in t/h, respectively. The return water of the extracted steam is not recovered, so the actual operation often uses the method of making up water to the condenser to compensate for the working mass loss. The make-up water flow rate \( m_{\text{mw}} \) is quantitatively equal to the final industrial steam supplied.

Figure 1. Schematic diagram of the reference CHP unit.

The purpose of the RHs is to heat the condensate water from the condenser. The enthalpy drop of the extraction steam to RH \( i \) is defined as \( q_i \). The enthalpy drop of drainage water of RH \( i \) is defined as \( y_i \). The enthalpy rise of feed water of RH \( i \) is defined as \( \tau_i \). Then, the parameters of \( q_i \), \( y_i \) and \( \tau_i \) shown in Figure 2 can be calculated with

\[
\begin{align*}
q_i &= h_i - h_{d,i} \\
y_i &= h_{d,(i-1)} - h_{d,i} \\
\tau_i &= h_{w,i} - h_{w,(i+1)}
\end{align*}
\]
The steam-water equation [14–17] is a matrix analysis method for the coal-fired CHP system, which is commonly used to analyze the heat-power coupling characteristics when the system parameters are varied [18]. In this paper, based on the pure condensing CHP unit, the effect of industrial steam extraction on the energy balance of RHs is considered. The industrial extraction auxiliary matrix is added to the steam-water equations of the reference CHP unit. For each RH, the mass and energy conservation are related as follows:

**RH1:**

\[ m_{fw}(h_{w,1} - h_{w,2}) = m_1(h_1 - h_{d,1}) \]  

**RH2:**

\[ m_{fw}(h_{w,2} - h_{w,3}) = m_1(h_{d,2} - h_{d,3}) + m_2(h_2 - h_{d,2}) \]  

**RH3:**

\[ m_{fw}(h_{w,3} - h_{w,4}) = \sum_{i=1}^{2} m_i(h_{d,3} - h_{d,4}) + m_3(h_3 - h_{d,4}) \]  

Deaerator (RH4):

\[ \left( m_{fw} + m_{cw} \right)h_{w,4} = \sum_{i=1}^{3} m_ih_{d,5} + m_4h_4 + m_{cw}h_{w,5} \]  

where \( m_{cw} \) is expressed as

\[ m_{cw} = m_{fw} - \sum_{i=1}^{4} m_i - m_4 + m_{mfw} \]  

Combining Equation (6) with Equation (7):

\[ m_{fw}(h_{w,4} - h_{w,5}) = \sum_{i=1}^{3} m_i(h_{d,3} - h_{w,5}) + m_4(h_4 - h_{w,5}) - m_{fw}(h_{w,4} - h_{w,5}) \]  

**RH5:**

\[ m_{fw}(h_{w,5} - h_{w,6}) = \sum_{i=1}^{4} m_i(h_{w,5} - h_{w,6}) + m_5(h_5 - h_{d,5}) - m_{fw}(h_{w,5} - h_{w,6}) \]  

**RH6:**

\[ m_{fw}(h_{w,6} - h_{w,7}) = \sum_{i=1}^{4} m_i(h_{w,6} - h_{w,7}) + m_5(h_{d,5} - h_{d,6}) + m_6(h_6 - h_{d,6}) - m_{fw}(h_{w,6} - h_{w,7}) \]  

**RH7:**

\[ m_{fw}(h_{w,7} - h_{w,8}) = \sum_{i=1}^{4} m_i(h_{w,7} - h_{w,8}) + \sum_{i=5}^{6} (h_{d,6} - h_{d,7}) + m_7(h_7 - h_{d,7}) - m_{fw}(h_{w,7} - h_{w,8}) \]  

**RH8:**

\[ m_{fw}(h_{w,8} - h_{w,9}) = \sum_{i=1}^{4} m_i(h_{w,8} - h_{w,9}) + \sum_{i=5}^{7} (h_{d,7} - h_{d,8}) + m_8(h_8 - h_{d,8}) - m_{fw}(h_{w,8} - h_{w,9}) \]  

**Figure 2.** Schematic diagram of the RH i.
Integrating Equation (3) to Equation (12), the steam-water equations of the reference CHP unit is expressed as

\[ m_{fw} \tau = Am - mw \tau_w \]  

(13)

where \( m_{fw} \) is feed-water flow rate in t/h. \( A \) is characteristic matrix, \( m \) is the industrial extraction matrix, \( \tau \) is feed-water enthalpy rise matrix and \( \tau_w \) is the auxiliary matrix. The above matrix is defined as follows,

\[
A = \begin{bmatrix}
q_1 & y_2 & q_2 \\
y_3 & y_3 & q_3 \\
y_4 & y_4 & y_4 & q_4 \\
\tau_5 & \tau_5 & \tau_5 & \tau_5 & q_5 \\
\tau_5 & \tau_5 & \tau_5 & \tau_6 & \tau_6 & y_6 & q_6 \\
\tau_6 & \tau_6 & \tau_6 & \tau_6 & \tau_6 & \tau_7 & \tau_7 & y_7 & y_7 & q_7 \\
\tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_7 & \tau_8 & \tau_8 & \tau_8 & y_8 & y_8 & y_8 & q_8
\end{bmatrix}
\]  

(14)

\[
\tau = \begin{bmatrix}
\tau_1 \\
\tau_2 \\
\tau_3 \\
\tau_4 \\
\tau_5 \\
\tau_6 \\
\tau_7 \\
\tau_8
\end{bmatrix}^T
\]  

(15)

\[
m = \begin{bmatrix}
m_1 \\
m_2 \\
m_3 \\
m_4 \\
m_5 \\
m_6 \\
m_7 \\
m_8
\end{bmatrix}^T
\]  

(16)

\[
\tau_w = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
\tau_5 \\
\tau_6 \\
\tau_7 \\
\tau_8
\end{bmatrix}^T
\]  

(17)

2.2. Analysis Modelling

In this section, the energy utilization efficiency, exergy efficiency and the coal consumption rate are used as indicators to analyze the economic performance of the supply CHP unit supplying the industrial steam.

2.2.1. Analysis of Energy Utilization Efficiency

The energy utilization efficiency (\( \eta_{en} \)) of the CHP unit is defined as the ratio of the energy of the output system to the energy of the input system, and the former includes power load (\( P \)) and heat energy in industrial steam supply (\( Q \)), while the latter can be considered as the chemical energy from coal combustion. Therefore, the \( \eta_{en} \) is expressed as

\[
\eta_{en} = \frac{P + Q_{LHV}}{LHV \cdot B}
\]  

(18)

\[
Q = m_s h_s + m_w h_w
\]  

(19)

where \( h_s \) and \( h_w \) are the enthalpies of the industrial steam extracted and the cooling water in kJ/kg, respectively. \( LHV \) is the lower heating value of the standard coal in kJ/kg.

2.2.2. Analysis of Exergy Efficiency

The exergy efficiency (\( \eta_{ex} \)) of the CHP unit is expressed as

\[
\eta_{ex} = \frac{E_P + E_Q}{HHV \cdot B}
\]  

(20)

\[
E_P = P
\]  

(21)

\[
E_Q = H_Q - H_0 - T_0(S_Q - S_0)
\]  

(22)

where \( H \) and \( S \) are the enthalpy and entropy in kJ/kg, respectively. The \( HHV \) is the higher heating value of the standard coal in kJ/kg. The subscripts \( Q \) and \( 0 \) represent the industrial steam extracted and the environment, respectively.
2.2.3. Analysis of Coal Consumption

The coal consumption rate \( B \) of the CHP unit can be calculated as:

\[
B = \frac{Q_c}{LHV\eta_b\eta_p}
\]  

(23)

\[
Q_c = m_0(h_0 - h_{fw}) + m_{rh}(h_{rh} - h_{rc})
\]  

(24)

where \( Q_c \) is the heat absorbed in the boiler cycle in kJ. \( \eta_b \) and \( \eta_p \) are the boiler and pipe efficiency, respectively. \( m_0 \) and \( m_{rh} \) are the mass flow rates of the main steam and the hot reheat steam in t/h, respectively. \( h_0 \) and \( h_{rh} \) are the enthalpies of the main steam and the hot reheat steam in kJ/kg, respectively.

3. Optimization Model Development

3.1. Objective Function

The total coal consumption \( B_{\text{all}} \) of the CHP system can be expressed as

\[
B_{\text{all}} = \sum_{i=1}^{n} B_i
\]  

(25)

where \( B_i \) is the coal consumption rate of the No. \( i \) CHP unit in t/h. In this study, the objective function \( B_{\text{all}} \) is minimized and can be fitted as a complex relation between \( P \) and \( Q \), which can be expressed as

\[
B_i = f(P, Q)
\]  

(26)

where \( P \) is the power load of the CHP unit, and \( Q \) is the industrial heat load of the CHP unit in MW.

3.2. Constraints

(a) Heat load constraint: the heat load of the CHP system needs to meet the demand of industrial heat users, which is expressed as

\[
Q_{\text{all}} = \sum_{i=1}^{n} Q_i
\]  

(27)

where \( Q_{\text{all}} \) is the total industrial heat load of the CHP system, and \( Q_i \) is the industrial heat load of the No. \( i \) CHP unit in MW.

(b) Heat-power load adjustment space constraint: The \( Q_i \) needs to be within the adjustable range according to the actual power load of the No. \( i \) CHP unit. When the power load of the CHP unit is assigned, then its industrial heat load adjustment range is also confirmed, which can be expressed as

\[
f_{\text{min}}(P_i) \leq Q_i \leq f_{\text{max}}(P_i)
\]  

(28)

3.3. Optimization Method

Intelligent algorithms, including the particle swarm optimization (PSO) algorithm, genetic algorithm (GA), artificial neural network (ANN) algorithm, etc., have been developed in recent years. PSO and GA are often used to solve scheduling problems, while ANN is a good choice for model identification [19]. The several processes of selection, crossover and mutation operators often make the convergence of GA algorithms slower than PSO. Therefore, PSO have been widely used in recent years to solve problems in energy engineering, especially issues with high timeliness requirements. Zhou et al. [20] optimized control strategy for large doubly fed induction generator wind farm by PSO. Zahedi Vahid M et al. [21] optimized the dispatching scheme of the distributed power generation resources by PSO. Sahu RK et al. [22] developed a novel hybrid controller that can be used in the multi-area interconnected power systems by PSO. Zhang et al. [23] presented a multi-objective model applied to the distributed energy system based on PSO and achieved the power peak-shaving capacity of 800 kW.
However, when the PSO algorithm is applied to solve the extreme values of complex nonlinear functions, the solution may fall into a local optimum. Reference [24] introduces the adaptive revision of the algorithm parameters (e.g., inertia weights and learning factors) and the concept of adaptive mutation into the classical PSO algorithm to enhance its performance. In this study, the classical PSO and the adaptive mutation particle swarm optimization (AMPSO) are compared in terms of convergence speed and the capacity to find the optimal value. The comparison results are shown in Figure 3. As can be seen from Figure 3, the optimal values obtained by the AMPSO algorithm and the classical PSO algorithm are equal, while the convergence speed presents a significant difference. The optimal values obtained by the above two algorithms are both 116.98. The times of iterations of the AMPSO algorithm and PSO algorithm are 127 and 845, respectively, which shows that the AMPSO has better performance. Therefore, AMPSO is utilized in this study as the optimization algorithm.

![Comparison of the AMPSO algorithm and classical PSO algorithm](image)

Figure 3. Comparison of the AMPSO algorithm and classical PSO algorithm.

Therefore, AMPSO is used to find the appropriate \(B_{all}\). The following steps are performed in the AMPSO algorithm.

For the case that two CHP units are operating, firstly, according to the \(P_1\) given by the dispatch side, the heat load of the NO. 1 unit is generated within the operation domain. Secondly, the heat load of the NO. 2 unit is calculated by Equation (27). If \(P_2\) and \(Q_2\) are in the operation domain, the total coal consumption is calculated. Next, the \(Q_1\) is updated according the formula in [24]. Then, the adaptive revision of inertia weights and learning factors is conducted. The mutation probability is calculated, and the mutation action is performed based on the above probability. If the updated coal consumption is less than the previous coal consumption, it could be saved. Until the number of iterations is satisfied, the minimum coal consumption is outputted and the corresponding \(Q_1\) and \(Q_2\) are obtained.

For the case where the numbers of CHP units operating are \(n\), the steps of AMPSO can be referred to the case above.

4. Case Study

4.1. Reference CHP Unit

In this study, the 330 MW extraction-condensing, single-reheat CHP unit was taken as the reference case. The design operating parameters of the unit are shown in Table 1. In order to investigate the industrial steam supply capacity of the unit, thermodynamic tests of different operating conditions of the unit were conducted. The parameters of hot reheat steam pressure, axial thrust, axial displacement and temperature of positioning tiles...
during the steam supply process were checked. During the test, the axial thrust, axial displacement and positioning tile temperature-limiting conditions were not triggered and certain margins existed. Since the customer-side demand steam pressure is relatively high (2.2 MPa), this study mainly focuses on the limitations of the hot reheat steam pressure on the industrial extraction capacity of the CHP unit.

Table 1. Design parameters of the reference CHP unit.

| Items                                      | Value       |
|--------------------------------------------|-------------|
| Design power/MW                            | 330         |
| Pressure of main steam/MPa                 | 16.70       |
| Temperature of main steam/°C               | 537         |
| Pressure of hot reheat steam/MPa           | 3.20        |
| Temperature of hot reheat steam/°C         | 537         |
| Maximum flow rate of industrial extraction steam/th-1 | 100         |
| Pressure of industrial steam demanded/MPa | 2.20        |
| Temperature of industrial steam demanded/°C| 315         |
| Pressure of exhaust steam/KPa              | 6.57        |

In order to ensure the safety of steam supply and prevent steam backflow, the pressure difference between the hot reheat steam and the pressure demanded should be kept greater than or equal to 0.3 MPa. In this study, the safety critical pressure for steam supply was chosen as 2.5 MPa, which means that steam supply can be safely carried out when the pressure of the hot reheat steam is greater than 2.5 MPa. The experimental data of pure condensing condition and industrial steam supply condition of the CHP unit are shown in Figure 4.

Figure 4 shows the relationship between the hot reheat steam pressure and the main steam flow rate during the pure condensing and industrial steam supply operation. It can be seen that the pressures of the hot reheat steam and the main steam flow rate show a linear relationship, regardless of whether the CHP unit is supplied with steam or not. According to the fitted curve, the pressure of the hot reheat steam is greater than 2.5 MPa when the main steam flow rate is greater than 600 t/h, and it is considered to be safe to supply steam.
4.2. Model Validation

To verify the accuracy of the model, the experimental power of the turbine heat consumption rate acceptance (THA), 75% THA and 60% THA working conditions were compared with the simulation power obtained from the model proposed in this paper, and the results are shown in Figure 5a. It can be seen from Figure 5b that the average relative error is 0.69%, which proves that the model is usable.

4.3. Calculation Results of Heat-Power Characteristics

According to the experimental results in Section 4.1, the main steam flow rate is greater than 600 t/h for stable and safe steam supply. When the CHP unit operates at 60% THA condition with pure condensing, the main steam flow rate is about 600 t/h. In this study, the off-design calculation in the interval between 60% THA and turbine maximum continuous rating (TMCR) working conditions for the case CHP unit was carried out, and the results are shown in Figure 6a. Figure 6 shows the working condition diagram of the CHP unit. Figure 6a is the industrial steam supply condition diagram established by the model proposed, and Figure 6b is the heat supply condition diagram. The comparison results show that the heat-power characteristics of the CHP unit are different for industrial steam supply and heat supply.

Figure 7 shows the adjustable space of the power load for unit heating or steam supply conditions. Figure 7a shows that the area between the 60% THA and TMCR conditions of the CHP unit under the steam supply condition is the power load adjustment space, which can provide a reference for the flexible operation of the CHP unit for peak shaving and steam supply. For the constant main flow rate, each 1 t/h industrial extraction provided by the case CHP unit reduces the power output by about 0.321 MW. When the CHP unit operates under the TMCR condition, the power load adjustment space is 293.6 MW–344.1 MW; when the CHP unit operates under the THA condition, the power load adjustment space is 279.4 MW–329.8 MW; when the unit operates under the 60% THA condition, the power load adjustment space is 149.1 MW–198.3 MW. In difference with the heat supply condition in Figure 7b, the lower limit of power load in the steam supply condition decreases monotonically with increasing steam supply and does not show a rising inflection point. The reason is that the industrial extraction flow rate is lower and not enough to trigger the minimum inlet flow limit for the low-pressure turbine.
The industrial extraction flow rate is lower and not enough to trigger the minimum inlet flow limit for the low-pressure turbine. The heat load condition decreases monotonically with increasing steam supply and does not show a maximum energy utilization efficiency at the maximum industrial steam extraction condition.

The energy utilization efficiency increases with the increase of power load when the CHP unit supplies industrial steam. However, the energy utilization efficiency is only based on the quantity of energy and does not consider the quality of energy. Thereafter, the energy utilization efficiency is always lower than 46%. After the CHP unit supplies industrial steam, the energy utilization efficiency increases significantly. As can be seen, the industrial heat load of the CHP unit plays a major role in improving the energy utilization efficiency. For the constant main steam flow rate or power load, the energy utilization efficiency grows with the increasing industrial heat load. The maximum energy utilization efficiency can reach 65.30%, which occurs at the maximum industrial steam extraction condition.
fore, an exergy analysis was also conducted to evaluate the industrial steam supply process. The results are shown in Figure 9. In contrast with the energy utilization efficiency, the power load of the CHP unit plays a major role in improving the exergy efficiency. The maximum exergy efficiency value is 36.76%, which occurs at the pure condensing condition. The minimum value is 30.76%, which appears at the maximum industrial steam supply condition.

Figure 8. The energy utilization efficiency of the reference CHP unit: (a) pure condensing condition and (b) industrial steam supply condition.

The above results show that the energy utilization efficiency of the CHP unit can be increased by supplying industrial steam. However, the energy utilization efficiency is only based on the quantity of energy and does not consider the quality of energy. Therefore, an exergy analysis was also conducted to evaluate the industrial steam supply process. The results are shown in Figure 9. In contrast with the energy utilization efficiency, the power load of the CHP unit plays a major role in improving the exergy efficiency. The maximum exergy efficiency value is 36.76%, which occurs at the pure condensing condition. The minimum value is 30.76%, which appears at the maximum industrial steam supply condition.

Figure 9. The exergy efficiency of the reference CHP unit: (a) pure condensing condition and (b) industrial steam supply condition.

The coal consumption rates of the case CHP unit with the various industrial heat loads were calculated, as shown in Figure 10. The coal consumption rate of the CHP unit increases with the rise in power load. In addition, it is also impacted by the ratio of the industrial heat load to the power load. This means that the different industrial heat load distribution of the two parallel CHP units affects the total coal consumption, which provides a possible space for optimal load allocation in Section 4.5.
The minimum value is 30.76%, which appears at the maximum industrial steam supply. The results are shown in Figure 9. In contrast with the energy utilization efficiency, the power load of the CHP unit plays a major role in improving the exergy efficiency. The power load scheduling orders is shown in Figure 11. An assumption of the total industrial heat load requirement of 157 MW, while the total power load of 400 MW is applied to this study by analyzing historical operating data.

The CHP system selected for this study includes two parallel CHP units. In actual operation, the power loads of the units are given by the dispatch side and cannot be adjusted. An assumption of the total industrial heat load requirement of 157 MW, while the total power load of 400 MW is applied to this study by analyzing historical operating data of the reference system. The proportion of industrial heat load undertaken by the NO.1 unit to the total heat load is defined as $\alpha$, which is expressed as

$$\alpha = \frac{Q_1}{Q_1 + Q_2} \times 100\%$$

(29)

The relationship between $\alpha$ and total coal consumption $B_{all}$ under the various power load scheduling orders is shown in Figure 11.

As can be seen in Figure 11, under the condition of $P_1 = P_2 = 200$ MW, $B_{all}$ reaches the minimum value of 137.015 when $\alpha = 0\%$ or 100% and the maximum value of 138.233 when $\alpha = 50\%$. The similar results also appeared for $P_1 = 190$ MW, $P_2 = 210$ MW and $P_1 = 180$ MW, $P_2 = 220$ MW. When the numerical value difference between $P_1$ and $P_2$ increases
further, the starting point of $\alpha$ will no longer be 0, but will start from a certain value from 0% to 100%. It is worth noting that the trend of the line segment remains similar to the other cases. Therefore, the uneven allocation of industrial heat load between the two CHP units is more coal saving than the average allocation. Further, the larger the difference between the industrial heat loads of the two CHP units, the more coal could be saved.

The power load data for NO.1 unit and NO.2 unit on a typical day for the CHP system are shown in Figure 12. The total industrial heat load demand is considered as 200 MW. A comparison of the average allocation of industrial heat load was conducted. The optimization results are presented in Figures 13 and 14.

**Figure 12.** Power load data for NO.1 unit and NO.2 unit.

**Figure 13.** Industrial heat load allocation after optimization.
As can be seen from Figure 13, the optimization results in No. 2 CHP unit are mainly undertaking the industrial heat load. Combined with Figure 12, it can be observed that when the two parallel CHP units are operated together, coal consumption can be reduced when the unit with a lower power load undertakes a higher industrial heat load. As shown in Figure 14, the optimized coal consumption rate of the CHP system is lower than that under the equal allocation of industrial heat load. The total coal consumption after optimization is 3203.92 tons in the typical day, a decrease of 14.66 tons compared to before optimization.

The optimized industrial load distribution with AMPSO reduces the unit coal consumption, which improves the profitability of the CHP unit in terms of saving coal cost and the carbon trading benefits from CO₂ emission reductions. The increased profit can be expressed as

\[
\Delta \text{Profit} = Y_1 \cdot \Delta B_{\text{all}} + Y_2 \cdot \Delta \text{CO}_2 \tag{30}
\]

\[
\Delta B_{\text{all}} = \Delta B_{\text{all,nop}} - \Delta B_{\text{all,op}} \tag{31}
\]

\[
\Delta \text{CO}_2 = EF \cdot \Delta B_{\text{all}} \tag{32}
\]

where \(Y_1\) is the price of the coal and \(Y_2\) is the price of the carbon allowance in CHY/t. \(\Delta B_{\text{all}}\) and \(\Delta \text{CO}_2\) are the amount of coal saving and CO₂ emissions reduction in t/h, respectively. \(\Delta B_{\text{all,nop}}\) and \(\Delta B_{\text{all,op}}\) are the coal consumption rate before and after optimization in t/h, respectively. \(EF\) represents the emission factors of CO₂.

Therefore, 14.66 tons of coal consumption reduction can result in 17,592 CHY in coal savings and 1117 CHY in carbon trading allowances in a typical day. The assumption that CHP units operate with industrial heat users 300 days in one year is considered. It is estimated that the two CHP units in the case can have cost benefits of about 5,612,700 CHY extra in one year. It is worth noting that, with the increase in coal prices and China’s carbon trading price, the optimal allocation of industrial heat loads will bring greater benefits.

5. Conclusions

In this study, the steam-water equations of CHP units with the industrial heat users are established based on the pure condensing conditions, combined with the auxiliary matrix of industrial steam extraction. The heat-power coupling characteristics of the CHP
unit are obtained by off-design calculation, and the influence of industrial steam supply on the coal consumption and energy utilization efficiency of the unit is analyzed. The CHP system with two parallel CHP units is taken as a case. The effect of the industrial heat load allocation scheme on the coal consumption rate is analyzed. AMPSO is used to optimize the industrial heat load allocation for a typical day.

(1) The main steam flow rate is greater than 600 t/h for a stable and safe steam supply. For the constant main flow rate, each 1 t/h industrial extraction provided by the case CHP unit reduces the power output by about 0.321 MW. When the CHP unit operates under the TMCR condition, the power load adjustment space is 293.6 MW~344.1 MW; when the CHP unit operates under the THA condition, the power load adjustment space is 279.4 MW~329.8 MW; when the unit operates under the 60% THA condition, the power load adjustment space is 149.1 MW~198.3 MW.

(2) Different from the heat supply condition, the lower limit of power load in the steam supply condition decreases monotonically with increasing steam supply and does not show a rising inflection point. The reason is that the industrial extraction flow rate is lower and not enough to trigger the minimum inlet flow limit for the low-pressure turbine.

(3) The energy utilization efficiency increases with the increase of power load when the CHP unit operates in the pure condensing condition. The maximum energy utilization efficiency of the unit after industrial steam supply is 65.30%, which is about 20% higher than the pure condensing condition. In contrast with the energy utilization efficiency, the power load of the CHP unit plays a major role in improving the exergy efficiency. The maximum exergy efficiency value is 36.76%, which occurs at the pure condensing condition. The minimum value is 30.76%, which appears at the maximum industrial steam supply condition.

(4) The CHP system with two parallel CHP units is taken as a case. Unequal allocation of industrial heat load between two units saves more coal than equal allocation. The coal consumption can be reduced when the unit with a lower power load undertakes a higher industrial heat load. In the typical day, the total coal consumption after optimization is 3203.92 tons, a decrease of 14.66 tons compared to before optimization. The two CHP units in the case can produce benefits of about 5,612,700 CHY extra in one year. Furthermore, with the increase in coal prices and China’s carbon trading price, the optimal allocation of industrial heat loads will bring greater benefits.

The derivation process of the steam-water equations and the results proposed in this paper can be applied to guide the operation of similar coal-fired CHP units. The coal-saving scheduling strategy proposed in this paper can work continuously in the process of achieving the carbon neutrality goal of China. The work in this paper is based on the conventional coal-fired CHP units. However, many CHP units in China are renovated to improve their peak-shaving capacity for consuming more renewable energy sources. Therefore, the energy, exergy, coal consumption analysis and the scheduling strategy among the renovated CHP units should be studied. Moreover, a multi-objective optimization based on the economy, energy, exergy and environment (4E) also will be carried out in the future research.

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