processes

MDPI

Article

A New Method for Predicting the Dynamic Coal Consumption of Coal-Fired Dual Heating Systems

Gang Xing [1], Xianlong Xu [2,3], Dongxu Wang [2,3], Xiaolong Li [2,3], Tianhao Liu [4] and Jinxing Wang [4,5,*]

[1] GD Power Development Co., Ltd., Beijing 100101, China; 17000056@ceic.com
[2] Sanhe Power Generation Co., Ltd., Langfang 065201, China; 16040077@ceic.com (X.X.); 16040916@ceic.com (D.W.); 16040230@ceic.com (X.L.)
[3] Hebei Coal-Fired Power Station Pollution Prevention Technology Innovation Center, Langfang 065201, China
[4] School of Metallurgical Engineering, North China University of Science and Technology, Tangshan 063210, China; 16631231156@163.com
[5] School of Energy and Mechanical Engineering, North China Electric Power University, Beijing 102206, China
* Correspondence: wangjinxing@ncst.edu.cn

Abstract

In order to meet the dual requirements of low-energy heating and flexible operation, a comprehensive heating system with multi-mode and wide-load capabilities was constructed, incorporating a heat pump, a back-pressure turbine, and two 350 MW coal-fired condensing units. Based on the heat transfer characteristics of this system, the simulation model of this comprehensive thermal system was constructed through a commercial software (EBSILON). A dynamic coal consumption prediction method based on the non-equilibrium state parameters was first proposed, which was primarily designed for system operation optimization. Subsequently, the converted load and load change rate were integrated into the dynamic correction model to refine prediction accuracy. The results showed that while basic coal consumption primarily correlates with heat load and electricity load, dynamic coal consumption is influenced by both the converted load and the load change rate. Based on this, the three-dimensional surface plot of converted load, load charge rate, and dynamic coal consumption offset coefficient was calculated. Then, the accuracy of the prediction model was verified by the variable working condition parameter group, and its reliability was confirmed. Further, by developing online software, theoretical guidance for industrial production was realized. In a heating season case study, it was demonstrated the prediction method can effectively reflect the dynamic parameter deviation in the system, with the annual coal saving being able to reach 841.5 tons. It is expected to provide theoretical guidance for the research on multi-heat sources heating distribution and operation parameter optimization.

Keywords: coal-fired heating system; coordinated peak regulation; thermal equilibrium deviation; dynamic coal consumption; load changing rate

check for updates

Academic Editor: Marek Markowski

Received: 2 October 2025
Revised: 24 October 2025
Accepted: 29 October 2025
Published: 30 October 2025

Citation: Xing, G.; Xu, X.; Wang, D.; Li, X.; Liu, T.; Wang, J. A New Method for Predicting the Dynamic Coal Consumption of Coal-Fired Dual Heating Systems. *Processes* **2025**, *13*, 3492. https://doi.org/10.3390/pr13113492

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In recent years, developing renewable energy (including wind power and photovoltaic energy) has been considered an inevitable trend to adjust the modulation of domestic energy structure, which addresses the issues of reducing fossil energy and increasing environmental pollution while meeting the requirements of low-carbon and high-efficiency development. Unfortunately, existing coal-fired cogeneration systems need to meet new

strict requirements for flexible operation due to the large number of intermittent renewable energy sources embedded [1].

The utilization of cold end surplus energy for heating is a potential technology to be developed vigorously. Up to now, there are three main modes: steam extraction heating [2], heat pump (HP) heating [3], and back-pressure heating [4]. Of course, various forms of integrated heating systems have also achieved remarkable results in terms of energy saving and efficiency improvement at the thermodynamic level. For example, Shuzhou Wei et al. [5] adopted an integrated heating system based on a heat pump and a back-pressure turbine to reduce the energy consumption of the system by optimizing the proportion of heat load distribution and ultimately obtained an optimized operation strategy. Hence, optimizing the operation strategy has become the method to improve the energy utilization efficiency of the system at the lowest cost. Xiao Xu et al. [6] found that the energy system with matched parameters can achieve energy savings of more than 30%, which is based on the economic analysis of multiple energy systems. Jianli Zhou et al. [7] proposed an integrated energy system based on wind power, photovoltaic, gas, and hydrogen energy. It is found that the parameter tendency can be changed in real time according to the market value orientation. Analogously, Jingyi Shang et al. [8] further improved the prediction accuracy and sensitivity of the system through a phased multi-objective algorithm. As the system responds to increasing demands, some scholars have begun to pay more attention to dynamic coal consumption. For example, according to the integration of molten salt heat storage characteristics, Kaijun Jiang et al. [9] proposed a flexible operation scheme, focusing on the influence of dynamic load changes. In the case of further consideration of solar embedment, the impact from load fluctuations will increase the demand for energy storage regulation of coal-fired units [10]. In the design of system energy storage parameters, the dynamic operation characteristics of coal-fired units are particularly important. Jianli Zhou et al. [11] proposed an offset-correction method, which provides a useful conclusion at the mathematical level for the collaborative optimization of system parameters. The existing studies on collaborative optimization of system parameters have also carried out beneficial exploration, suggesting that the goal of energy saving can be further realized by adjusting parameter sets [12,13]. However, combined with big data analysis, it is still rare to establish a dynamic prediction model of the system from the perspective of thermal balance, especially for the optimization of the integrated energy system. Hence, to develop a prediction method that can calculate the coal consumption of the coal-fired system under dynamic operating conditions is an important aspect for fully exploring their peak-shaving potential.

For this purpose, a comprehensive heating system of coupled heat pumps, back-pressure turbines, and coal-fired condensing units with low-pressure turbine zero-output units was structured in this work. Then, an optimal heat load distribution model based on thermodynamic equilibrium and a dynamic coal consumption analysis method was first proposed, which can make more accurate predictions of the system's coal consumption under variable operating conditions. The innovation of this work is that a dynamic coal consumption correction method was proposed for the first time based on the thermodynamic steady state, which compensates for the errors caused by load changes in the system. It provides a reference for the thermal system to implement deep energy cascade utilization and intelligent heating.

2. System Introduction

2.1. Heating System

Taking the district heating demand and the heating energy efficiency into account, the low-pressure turbine zero-output heating supply retrofit is identified as a reasonable

option [14]. However, the single utilization of a low-pressure turbine zero-output heating system cannot adapt to the development program of flexible peak regulation because its electrical load regulation capacity is low. Hence, an integrated heating system with a heat pump, a back-pressure turbine, and a low-pressure turbine zero-output unit is proposed. First, by using heat pump waste heat recovery heating technology, a partial "thermoelectric decoupling" is achieved by reducing the amount of steam extracted from the medium-pressure turbine. Second, the adjustment of the back-pressure turbine is adopted to achieve the double effects of flexibility adjustment and energy cascade utilization [15]. Finally, the low-pressure cylinder zero-output technology can achieve the dual goals of avoiding cold end loss and enabling deep cascade utilization of energy. Its structure is shown in Figure 1.

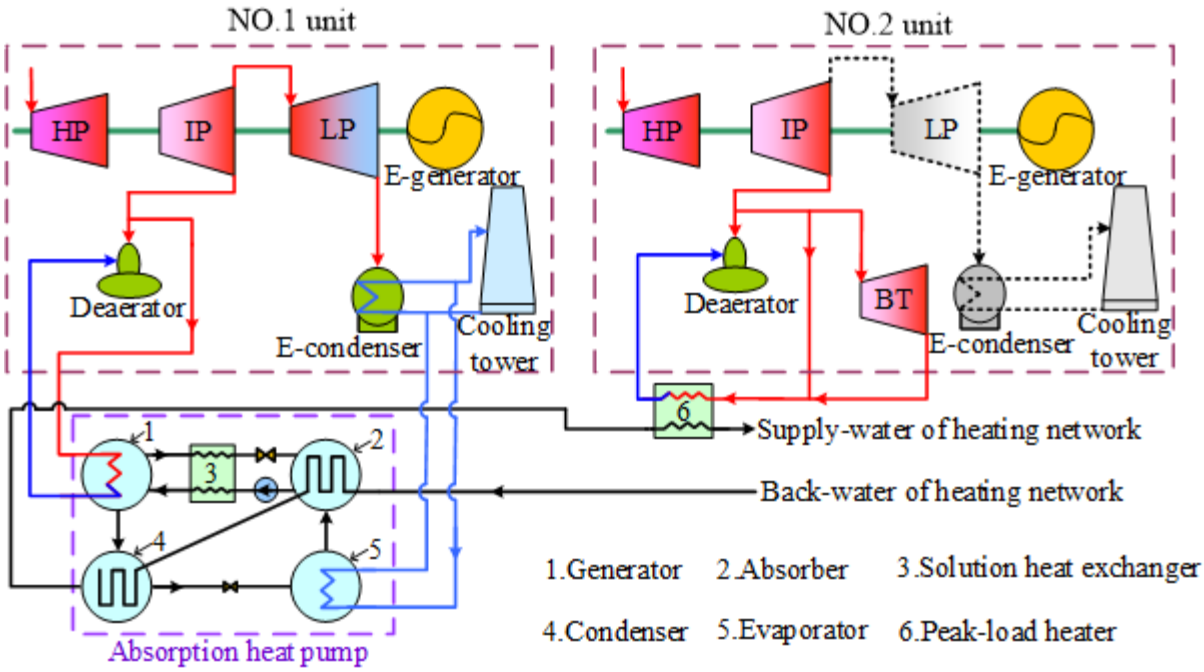


Figure 1. Diagram of coupled heating system.

The fundamental principles of the system design are as follows: first of all, the heat pump driven by the steam extraction from the medium-pressure turbine of the NO.2 unit is used to recover the waste heat of the circulating water for the initial heating of the heat network water; then, the medium-pressure turbine exhaust steam of NO.1 unit is used to carry out the secondary heating of the heat network water after the back-pressure machine has performed its work, and the medium-pressure turbine of NO.1 unit is used as the heat source of the peak heater for auxiliary heating, and then cut out the low-pressure turbine of NO.1 unit based on the demand of the external heat load, so that the lower limit of the unit's electric load can be greatly reduced. Removing the low-pressure turbine of the NO.1 unit enabled the unit to reduce the lower limit of its electric load according to the external heat load demand, which greatly met the needs of the unit for flexible peak regulation. The advantages of this integrated heat supply system are as follows: first, it avoids the cold end loss of the low-pressure turbine exhaust steam of the NO.1 unit; second, utilizing the exhaust steam from the back-pressure turbine to heat the outlet water of the heat pump meets the requirement for deep gradient energy, bringing greater optimization potential to the variable operating condition adjustment and performance enhancement of the heat pump; third, the amount of steam driving of the back-pressure turbine and the amount of steam driving the heat pump can be used as the regulating factor for heat load distribution, which greatly reduces the degree of thermoelectric coupling, and provides an effective

solution to improve the flexibility of the coal-fired unit. In summary, the system is based on the recovery of waste heat from circulating water, which further expands the ratio of heat to electricity; at the same time, the exhaust steam of the middle pressure turbine drives the back-pressure turbine to do work first and then exhaust steam for heating, and the exhaust steam of the medium-pressure turbine is used as the heat source of the peak heater to realize the deep step utilization of energy [16].

2.2. Steady State and Dynamic Testing

In order to further study the rise and fall rate of the electrical load of the NO.2 unit, the performance tests have been carried out for the unit during the non-heating season, in which the constant pressure operation and the sliding pressure operation are, respectively, carried out. The electrical load situation is shown in Figure 2. Its stable condition can be used to build a steady-state model, and its load increase process is used to analyze the maximum load change rate and the coal consumption deviation in the dynamic process. Specifically, the five stable working conditions also provide a relatively stable environment for other individual equipment, such as the heat pump and the back-pressure turbine as well as the condensing unit before zero output. In addition, the establishment process of dynamic coal consumption is based on the big date of previous adjustment processes with variable operating conditions. In these processes, as shown in Figure 2, the lifting load rate provides an opportunity to verify the dynamic migration.

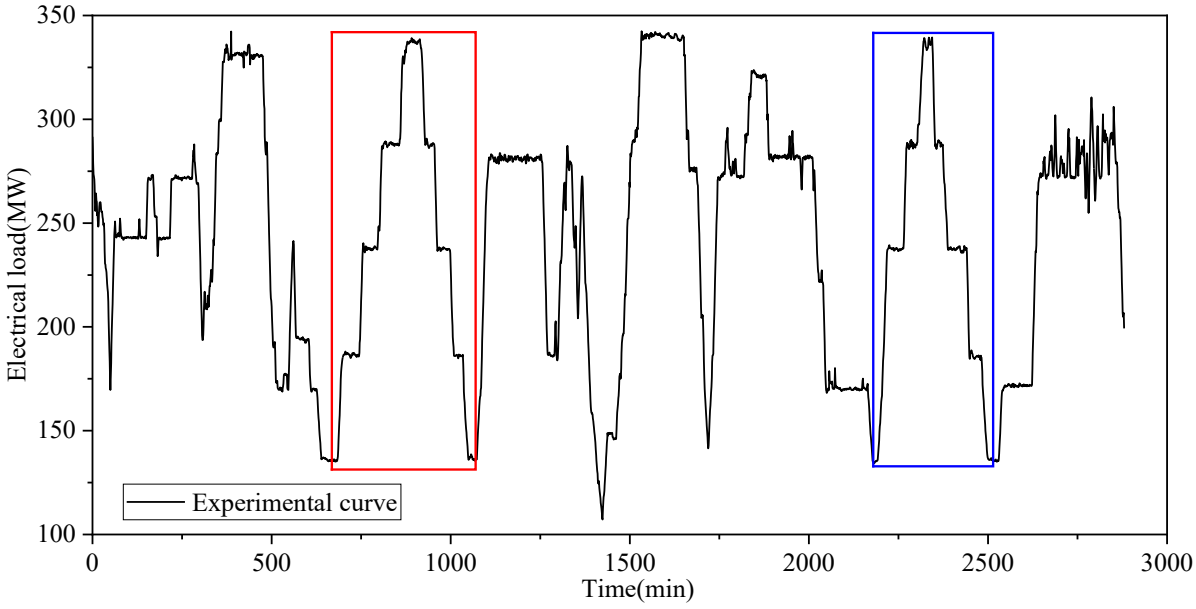


Figure 2. Electrical load of NO.2 unit during constant pressure/sliding pressure operation test.

3. Model Construction and Regulation Domain

In order to optimize the operation of the integrated heating system, the model of the heat pump, the back-pressure turbine, the condensing unit and the heating unit with the zero-output of the low-pressure turbine are modeled, respectively, and the corresponding regulation domain is constructed. Figure 3 shows the simulation model of the twin coal-fired condenser unit and its specific connection mode. It should be pointed out that the steady-state operating condition selected is mainly based on the stable operation of these equipment, and the stable operation of different monomers has certain time differences.

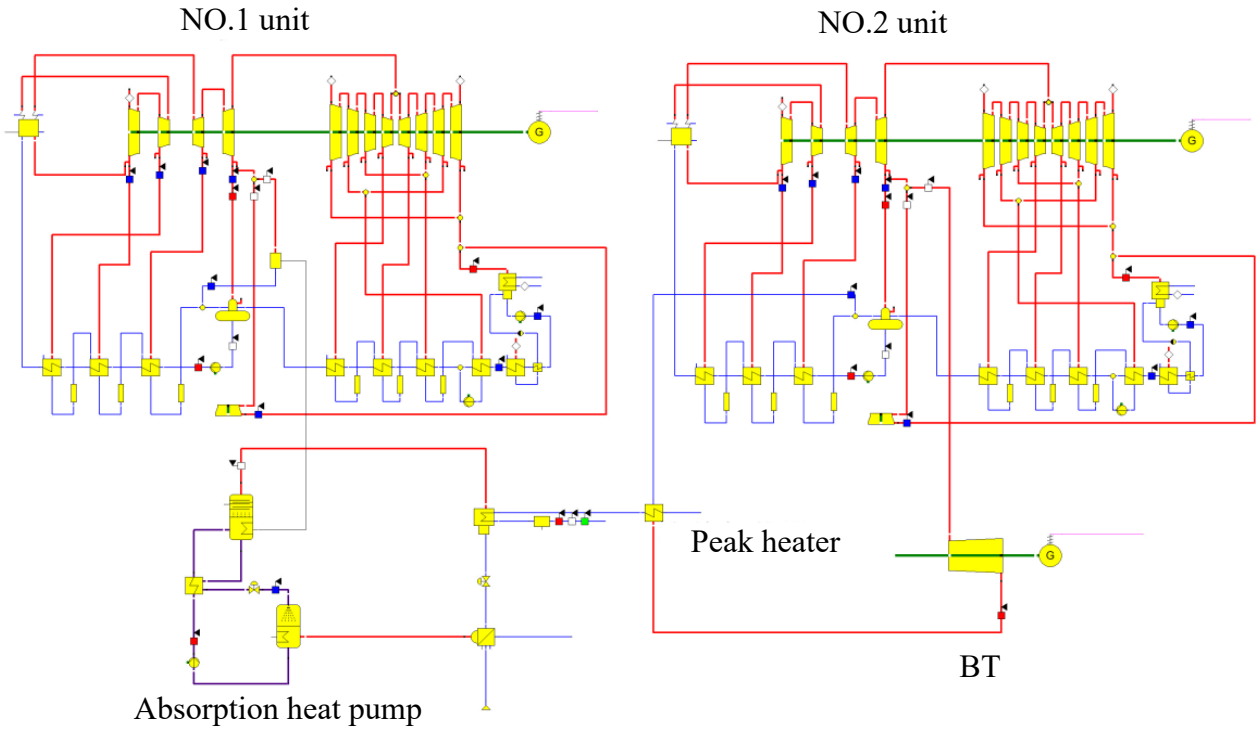


Figure 3. The Ebsilon simulation diagram of the integrated heating system with coupled HP and BT.

3.1. Heat Pump System

The performance test of the heat pump system was carried out with a total of five sets of variable operating condition tests, each of which operate continuously and stably for 2 h. The test results are shown in Table 1. Among them, operating conditions 1–5 correspond to 100%, 90%, 80%, 70% and 60% of the rated heat pump inlet, respectively.

Table 1. Stable test condition of heat pump system.

Parameter	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
Load	%	100	90	80	70	60
Steam outlet flow	t/h	194	177	163	139	116
Steam inlet temperature	°C	170	154	149	142	131
Hydrophobic temperature	°C	60.8	58.7	56.7	53.3	47.2
Driving steam pressure	Mpa	0.32	0.30	0.26	0.17	0.06
Inlet water temperature of heating network	°C	39.2	41.8	41.9	42.1	37.6
Outlet water temperature of heating network	°C	76.4	70.6	67.9	65.3	62.3
Inlet water temperature of waste heat water	°C	31.4	35.4	32.2	32.0	31.7
Outlet water temperature of waste heat water	°C	22.8	18.4	17.1	18.5	25.5

Five groups of stable operating conditions are selected as the basic modeling data, and the steady-state variable operating condition model of the monomer is established, which is characterized by including a relatively wide range of loads and a relatively long stable operating time to meet the data requirements for constructing stable variable operating conditions. According to the actual operating load range of the heat pumps, the operating condition at 60% minimum heat load of a single heat pump and the exhaust enthalpy value of the medium-pressure cylinder (3106.846 kJ/kg) are used as benchmarks for calculation. The heating power of a single heat pump at full load is 59.4 MW, and the pumping capacity consumed by the medium-pressure cylinder is 52.294 t/h.

3.2. Back-Pressure Turbine

The steam feed to the back-pressure turbine comes from the heating exhaust mother pipe of machine #1, the steam extraction pressure at the connecting pipe of the medium and low pressure cylinder of the steam turbine is 0.8 MPa, while the actual heating steam pressure required by the heat network heater is 0.3 MPa, This technology that is now throttled down by a pressure reducing valve to satisfy the requirement of the heat network heater for the steam pressure is intended to make full use of the unit's residual heat and pressure to improve the economy and flexibility of power plant operation [17]. According to the data of five groups of back-pressure turbine variable conditions, the steady-state variable condition model was constructed, and the inlet steam flow rate of the back-pressure turbine was deduced according to back-pressure turbine import and export parameters as well as power generation, which set its rated load.

The dependence relationship between the thermal load, the electrical load, and the steam consumption in the monomer model of the back-pressure turbine was constructed, and the modified characteristic curve of the exhaust pressure of the medium-pressure turbine was determined by simulation. Taking the design enthalpy of hydrophobicity (721.099 kJ/kg) as the reference to determine the heat loads of the back-pressure turbine under 10 sets of operating conditions to be 50.099 MW, 57.28 MW, 50.203 MW, 56.768 MW, 43.125 MW, 36.213 MW, 45.696 MW, 47.288 MW, 50.891 MW, and 40.927 MW, respectively, the ratio of the mechanical and electrical load and steam consumption of the back pressure in the selected working condition 3 to the heat load of the back-pressure turbine is 0.38386 and 2.09784, respectively, with the heat load adjustment range of the back-pressure turbine determined to be 36.213 MW–57.28 MW.

3.3. Condensing Unit

The thermal system model under the condition of 40%~100% boiler output is constructed by extracting the parameters of the condensing unit as well as the steady-state operation condition. In this work, under the premise of ensuring the minimum flow restriction of the low-pressure cylinder exhaust steam, the thermoelectric load regulation area is calculated. Among them, the maximum heat load boundary refers to the heat load converted from the maximum steam extraction by the condensing unit itself. In the subsequent calculation model, the system coal consumption can be further calculated based on the load parameters of the condensing unit operating in the thermoelectric load [13].

3.4. Low-Pressure Turbine Zero-Output Unit

According to the data of unit #2, the steady-state variable operating condition model of cylinder cutting unit was constructed, and through the parameters of the unit with zero output from the low-pressure cylinder and the steady-state operating condition, the thermal system model was under the condition of 40%~100% boiler output. Furthermore, according to the output of different boilers and the setting of the exhaust steam of the medium-pressure cylinder for heating, the thermoelectric load boundary can be obtained. In this work, the heat from the exhaust steam of the medium-pressure cylinder is first considered as the cold end loss, and then the thermoelectric load range of the cylinder cutting unit can be preliminarily determined. Therefore, in the subsequent calculation model, the system coal consumption will be calculated for the operation of the cylinder unloading unit within its thermoelectric load boundary.

4. Characteristic Parameters

4.1. Heat Pump System

The steady-state multi-condition operation model of the heat pump was constructed according to its engineering operation data, and the COP of the heat pump system was derived from its three-in-three-out parameters and the number of operating unit (a total of six sub-heat pumps were adopted),which provides a basis for the collaborative construction of the unit #2 model. These results are shown in Figure 4. According to the actual operating load range of the heat pump, the operating condition of a single heat pump is calculated when the minimum heat load is 60%. At the same time, using the enthalpy of the exhaust steam of the medium-pressure cylinder (3106.846 kJ/kg) as the benchmark, the heating power of a single heat pump at full load is 59.4 MW, and the exhaust steam of the medium-pressure cylinder is 52.294 t/h. On this basis, according to the variable operating condition adjustment characteristics of the heat pump system model [Figure 4a], the relationship between the number of heat pumps used and the amount of steam consumed under different heat load requirements [Figure 4b] is calculated, which can be used to construct the model of unit #2.

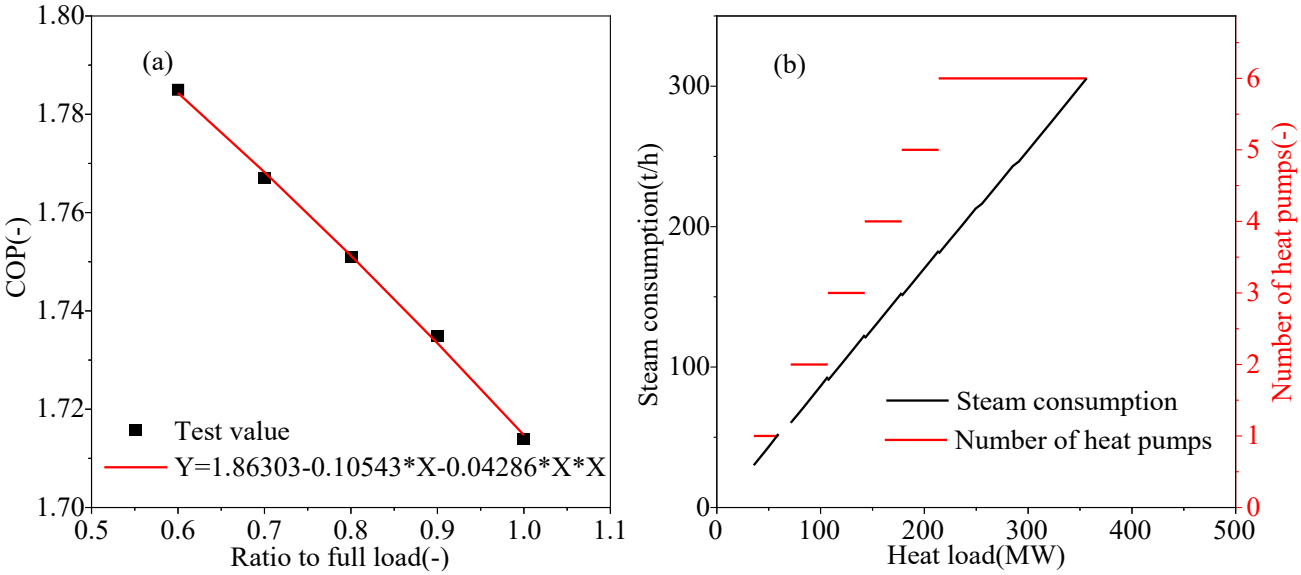


Figure 4. Characteristic curves of heat pump system.

4.2. Back-Pressure Turbine

The relationship between heat load, electric load, and steam consumption in the single model of back-pressure machine is established, and the modified characteristic curve of exhaust steam pressure of medium-pressure cylinder is determined by simulation. Based on the design hydrophobic enthalpy (721.099 kJ/kg), the BT heat load under the 10 groups was determined to be 50.099 MW, 57.28 MW, 50.203 MW, 56.768 MW, 43.125 MW, 36.213 MW, 45.696 MW, 47.288 MW, 50.891 MW, and 40.927 MW, respectively. The ratio of BT electrical load and steam consumption to BT thermal load (working condition 3) is 0.38386(MW/MW) and 2.09784[t/(h $*$ MW)], respectively. At the same time, the characteristic curve relating the BT electric load and steam consumption has been modified based on the exhaust steam pressure of the medium-pressure cylinder. According to the inlet and outlet parameters of the back compressor and the power generation, the inlet steam flow of the back compressor is derived to provide a basis for the collaborative construction of the model of unit #1. The results are shown in Figure 5. At the same time, it can be determined that the heat load adjustment range of the back-pressure is 36.213 MW–57.28 MW.

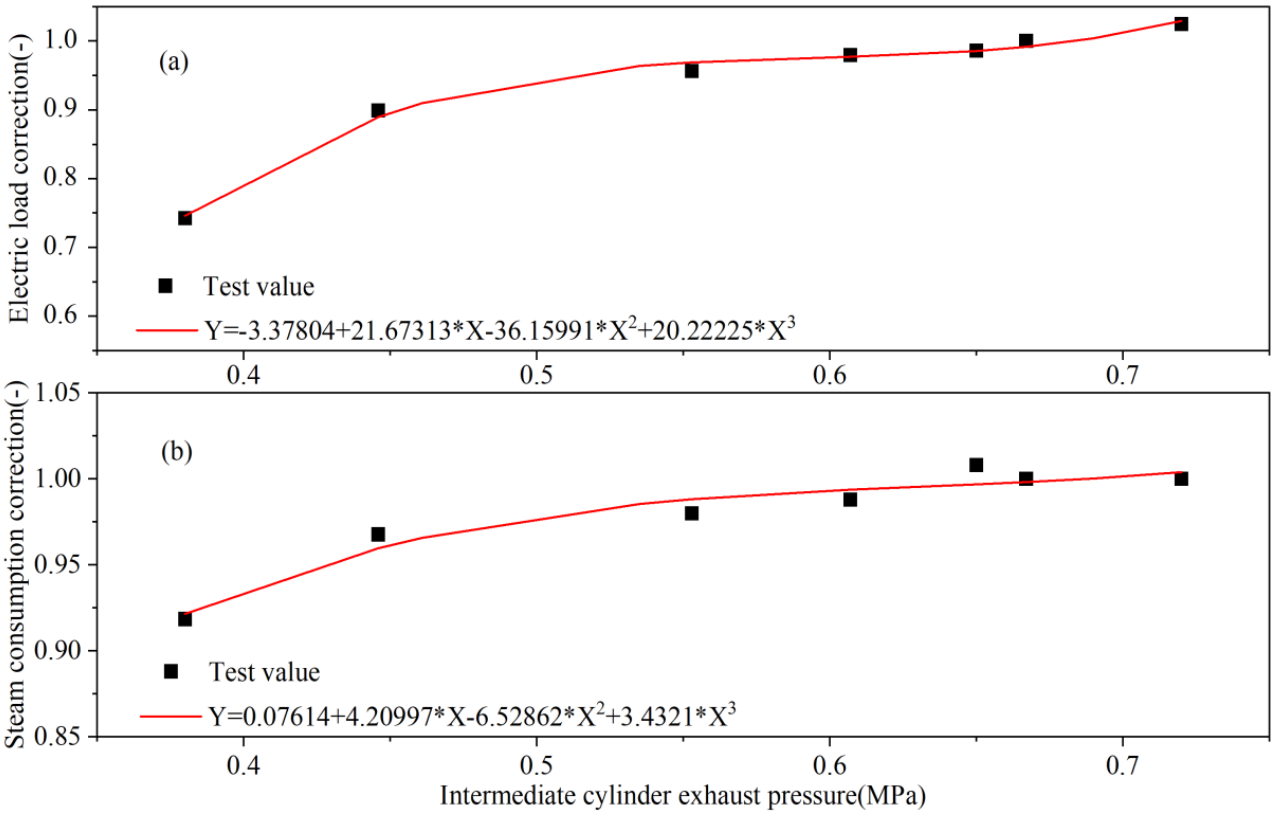


Figure 5. Characteristic curve of back-pressure turbine.

4.3. Condensing Unit

In this work, under the premise of ensuring the minimum flow limit of low-pressure cylinder exhaust steam, the thermoelectric load regulation area is calculated, and the results are shown in Figure 6a. Among them, the maximum heat load boundary refers to the heat load converted from the maximum steam extraction flow of the condensing unit itself. In the subsequent calculation model, the coal consumption of the condensing unit can be further calculated according to the operating load parameters in the thermoelectric load area. Firstly, the thermal load and electric load of the condensing unit are uniformly converted, and the conversion coefficient is calculated as the boundary of AB thermoelectric load in Figure 6a. In this work, the heat load multiplied by 0.2448 was added to the electrical load to establish a fitting relationship with the standard coal consumption after the reduced electrical load. The result is shown in Figure 6b. The second fitting relationship curve is $Y = -134.36146 + 1.20329 * X - 0.00119 * X * X$. On the basis of stable operation, the basic correlation between standard coal consumption and thermoelectric load is calculated, and the results are shown in Figure 6c. The overall trend of this surface shows that as the electric load increases, the rate of increase in coal consumption starts to rise lightly and then decreases; this trend is related to the adjustment ability of the unit under different electric load, especially the adjustable range of the main steam pressure and the exhaust steam pressure of the medium-pressure cylinder all restrict the coal consumption of the unit. With the direction of heat load increase, the trend of influence on coal consumption is different in the stage of low power load and high power load, which is related to the heat load distribution among units. It should be noted that the ranges of electrical load and thermal load can serve as the boundary conditions for subsequent optimization.

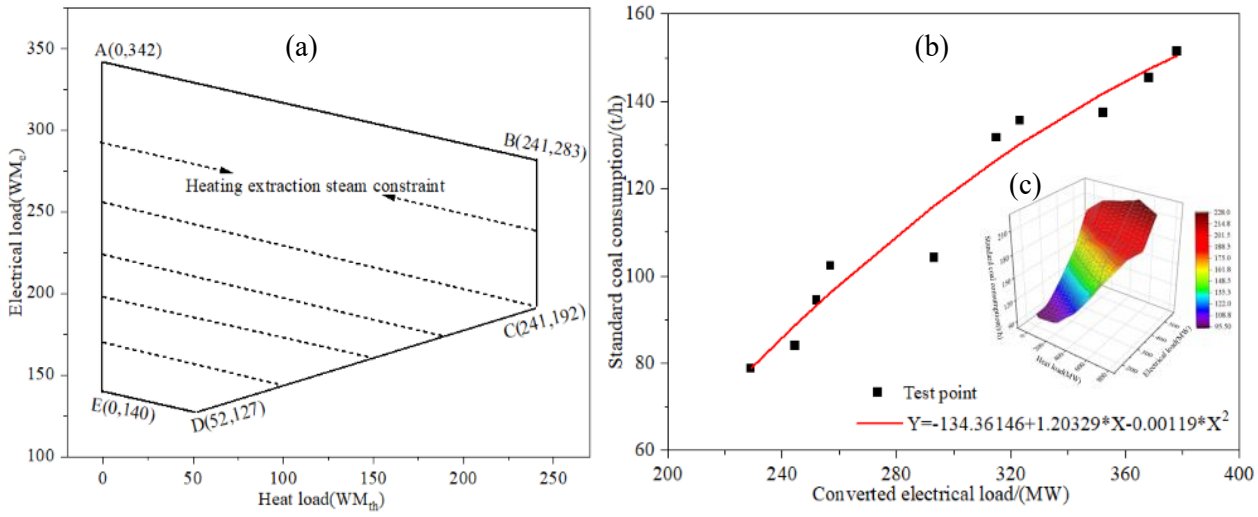


Figure 6. Thermoelectric load regulation range of condensing unit.

The influence of main steam pressure and exhaust steam pressure of medium-pressure cylinder was analyzed, and the correlation of correction coefficients was obtained after the disjunction point was eliminated, as shown in Figure 7a,b. The corresponding characteristic curves are provided for the subsequent construction of coal-fired unit models.

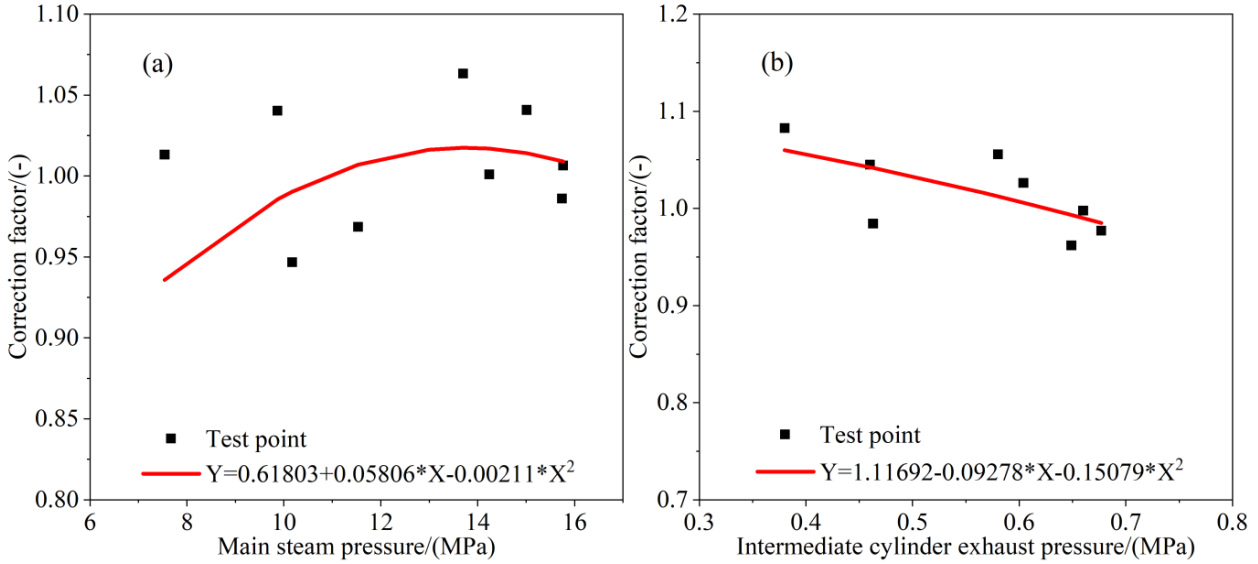


Figure 7. Characteristic curve of condensing unit.

4.4. Dynamic Coal Consumption Analysis

To further study the difference in system coal consumption during the variable load process, a dynamic coal consumption correction coefficient was introduced. The calculation formula of this coefficient is shown in Equation (1), which is the ratio of the fitted value to the predicted value.

$$\text{Dynamic.coal.consumption} = \frac{Fitting.value}{Predicteal.value} \quad (1)$$

Among them, the fitted values refer to the parameters obtained through polynomial fitting based on the measured points while the predicted values are the parameters calculated according to the steady-state model.

5. Results and Discussion

5.1. Dynamic Coal Consumption

For the dynamic coal consumption correction coefficient of conventional condensing units, there is an obvious dividing line influenced by the load change rate, and the dividing point is zero as shown in Figure 8. As can be seen from Figure 8b, if only the influence of load factors is considered, it further proves the necessity of considering the influence of load change rate. Figure 9 shows the relationship between the converted electrical load, the rate of load change, and the dynamic coal consumption. Thus, combined with the thermoelectric load range region in Figure 9a, a three-dimensional relationship surface between load change rate, converted electrical load, and dynamic coal consumption correction factor can be obtained, as shown in Figure 9b. The results can provide a new idea for predicting coal consumption in the extraction steam heating system of conventional condensing units. It should be noted that, compared with the traditional steady-state coal consumption analysis method (with a coefficient of 1), the dynamic coal consumption offset coefficient proposed in this work can well match the trends under partial load conditions and different rate changes. The difference caused by the variation in load power should be related to the time response of the system itself.

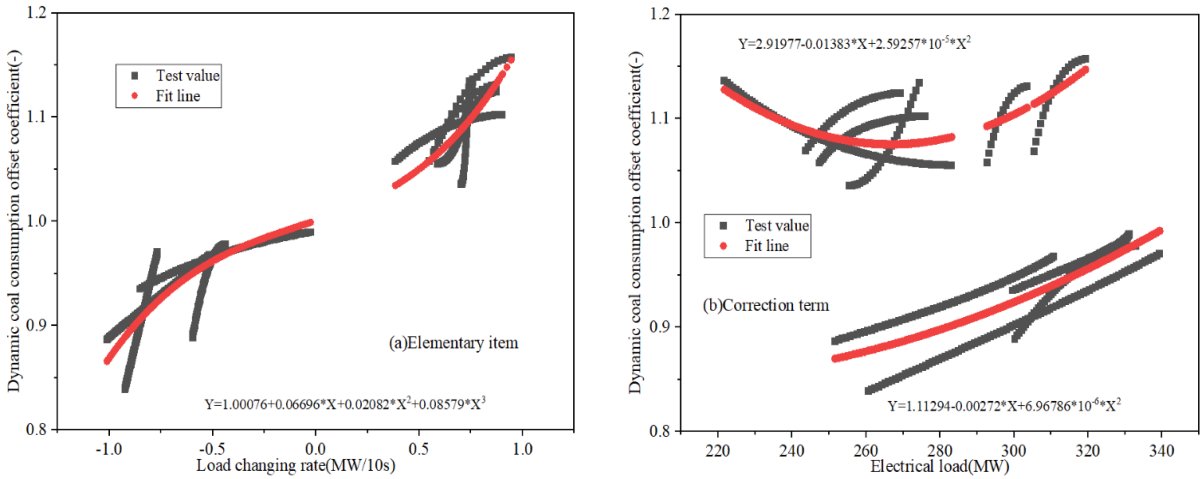


Figure 8. Dynamic coal consumption fitting of condensing unit.

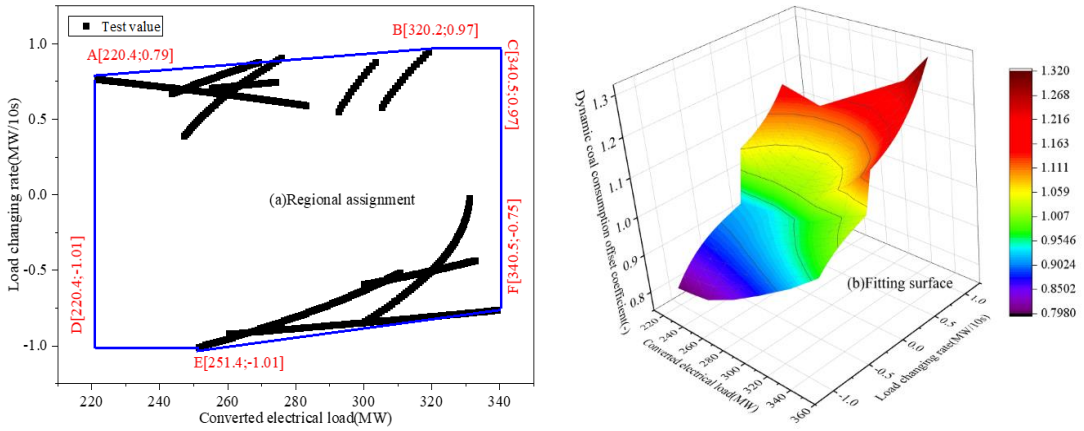


Figure 9. Condensing unit's regulation area and dynamic coal consumption fitting surface.

The effects of converted electric loads were further fitted for the base term fitting of the rate of change in load to the dynamic coal consumption offset coefficient of the cut-cylinder unit, as well as for the load increase and decrease processes. The results are shown in

Figure 10a,b. On this basis, further area delineation and surface fitting were carried out to establish the relationship between the load change rate, the converted electric load, and the dynamic coal consumption offset coefficient in the cylinder cutting mode, as shown in Figure 11a,b.

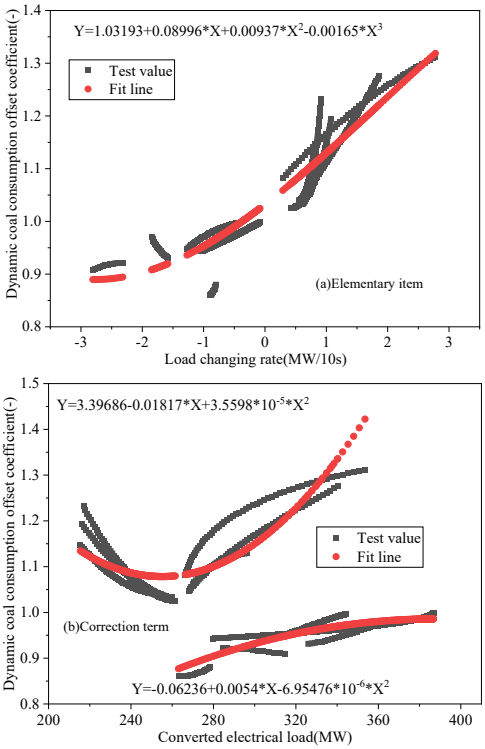


Figure 10. Dynamic coal consumption fitting of low-pressure cylinder zero-output unit.

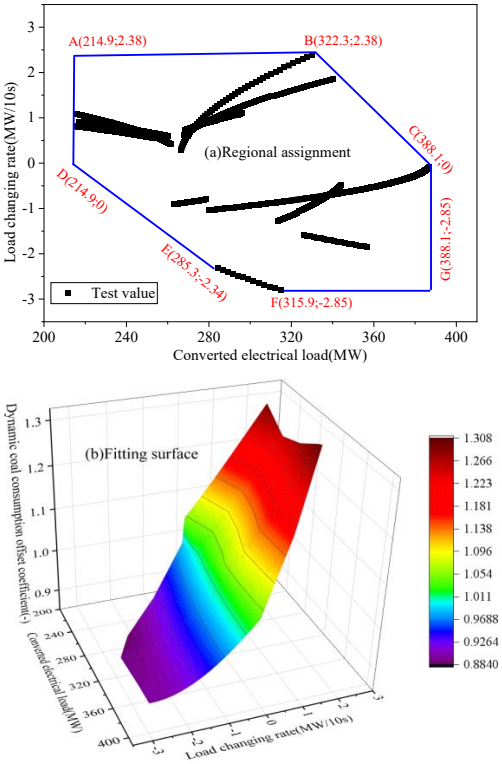


Figure 11. Low-pressure cylinder zero-output unit regulation area and dynamic coal consumption fitting surface.

5.2. Accuracy Verification

Through selection and analysis of the variable operating condition parameters of unit #2, the results of the unfolding analysis of its coal consumption are shown in Figure 12. The coal consumption under dynamic operation is greater than the steady-state value during load rise, while it is smaller during load fall. The dynamic coal consumption increases in the load increase process, while the standard coal consumption decreases in the load-decrease process. This is consistent with the law of prediction method. Regarding the current factors causing errors, there are other secondary factors whose effects have not been fully analyzed.

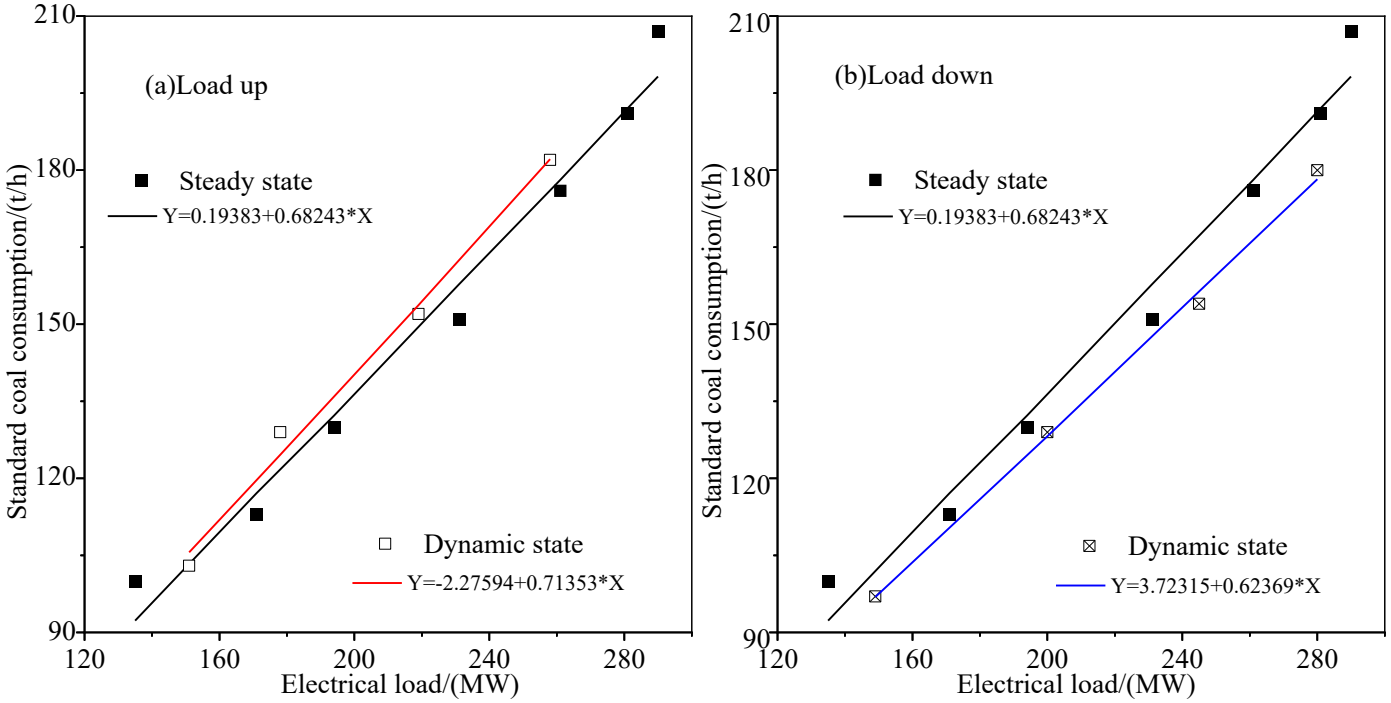


Figure 12. Coal consumption characteristics of dynamic bottleneck migration.

5.3. Online Software Development

Figure 13 shows an online software system applied to guide actual production, which covers the optimal distribution of thermoelectric loads. It can be found that the distribution of electric load is mainly achieved by regulating the feed water flow, and of course, it also includes the correction and optimization of the main steam pressure and the exhaust steam pressure of the medium-pressure cylinder. For heat load distribution, not only the selection of the cutting cylinder state of the coal-fired condensing unit is considered, but also the number of heat pump operating units and the cooperative optimization among the heat pump, back-pressure, and extraction volume. By monitoring coal saving status, while optimizing the parameter group, and guiding the choice of operation mode, the production, university, and research technology is ultimately realized. In addition, by monitoring the optimization results, the sliding pressure operation strategy of the main steam parameters is further obtained, which is milder than those reported in the literature [18]. It should be noted that in this software, after inputting the relevant parameters, the system can calculate the optimized parameter combination, thereby guiding the production process.

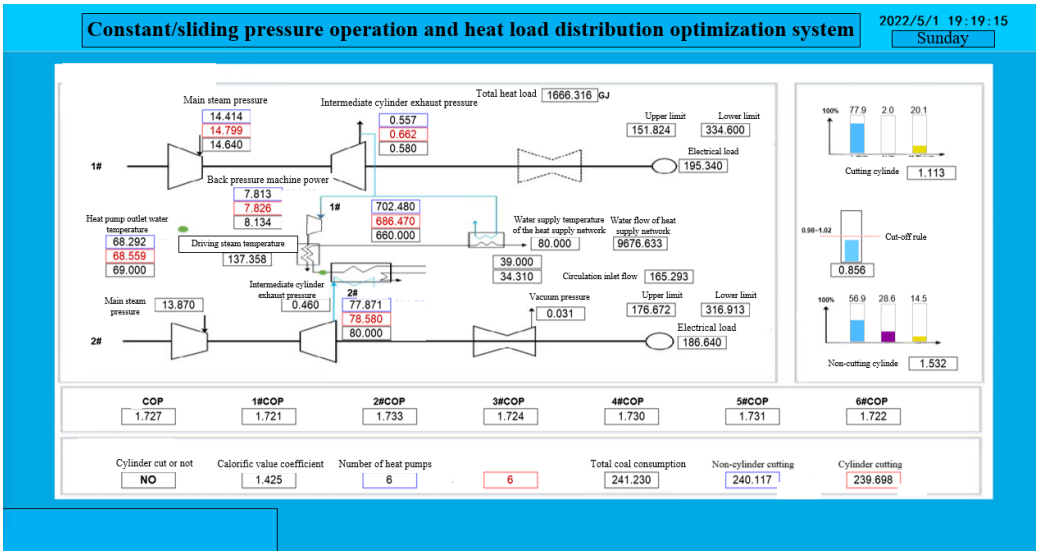


Figure 13. Online software design and development interface.

5.4. Total Coal-Saving Amount in Heating Season

The total thermoelectric load of the entire heating season was adjusted, as shown in Figure 14a. It can be found that although there is a certain fluctuation in the electrical load of the twin units, the trend is stable throughout the day. There is only one special situation in the entire heating season that requires a sudden increase in power load. As for the heat load, it presents an overall trend of a gradual rise, followed by a steady decline, and then a rapid decline. Although there is a short period of sudden rise during the heating season, the overall trend can still show a more obvious regularity.

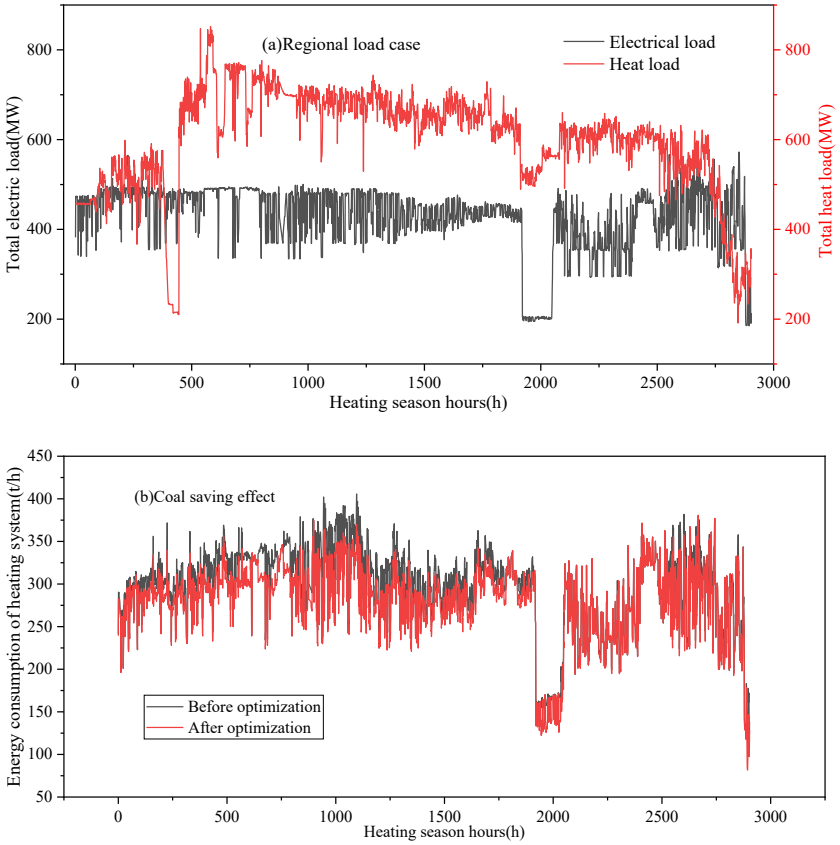


Figure 14. (**a**) Thermoelectric load demand of dual heating units in heating season. (**b**) Calculation of coal quantity in heating season.

In order to reduce the instantaneous error, the coal consumption of the unit before and after optimization has been compared within the hourly date points across the heating season. Figure 14b shows the fluctuation in coal consumption of dual units in heating season. The overall trend of coal consumption shows little change before and after optimization, while the coal-saving effect shows an obvious difference across different periods. Through the integration, the coal saving amount of the entire heating season is 841.5 tons of standard coal.

6. Conclusions

In this work, two 350 MW coal-fired heating units were selected as the research objects to develop a dynamic coal consumption model under variable load conditions. Thus, a key parameter group optimization model based on optimal heat load distribution is constructed, with a dynamic coal consumption analysis method based on cooperative modification of unit load and load change rate is proposed, and the intelligent heat supply peaking operation based on multi-heat source heat distribution and operation parameter optimization is realized. The specific conclusions are as follows:

(1) Separate fittings were conducted to account for the impact of converted electric load during the load increase and decrease processes. Furthermore, area delineation and surface fitting techniques were applied to establish the relationship among load change rate, converted electric load, and dynamic coal consumption offset coefficient under the cutter head mode.

(2) For the cylinder unloading mode, the coal consumption will increase compared with the steady operating condition. When the unit load change rate is greater than 1, the offset coefficient is also greater than 1; conversely, the offset coefficient is less than 1 when the load is reduced for the reason that the coal consumption is lower than under stable operating conditions; frequent changes in operating conditions will increase the unit's coal consumption.

(3) The relationship among the load change rate, converted electric load, and dynamic coal consumption offset coefficient for the two operating modes was ultimately obtained after the adjustment range was further defined based on the correlation diagrams of converted electric load versus load change rate for both the cylinder unloading mode and the non-cylinder unloading mode. The heating season case study verified that total coal savings reached 841.5 tons of standard coal.

In conclusion, the results of this work, when combined with AI intelligence, are beneficial for the energy utilization and integration of the coal-fired integrated energy systems.

Author Contributions: Conceptualization, G.X. and J.W.; methodology, G.X.; software, G.X.; validation, X.X., D.W. and X.L.; formal analysis, T.L.; investigation, J.W.; resources, X.X.; data curation, T.L.; writing—original draft preparation, G.X.; writing—review and editing, J.W.; visualization, G.X.; supervision, G.X.; project administration, G.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "Shijiazhuang city in Hebei university basic research project, grant number (241791347A)" and "Natural Science Foundation of Hebei Province (E2025209014)".

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: These authors were supported by Research Project of Science and Technology Department of Henan Province (242102240093), Key Scientific Research Project of Education Department of Henan Province (24B480015).

Conflicts of Interest: Author Gang Xing was employed by the GD Power Development Co., Ltd., Authors Xianlong Xu, Dongxu Wang and Xiaolong Li were employed by the Sanhe Power Generation Co., Ltd.; The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

Nomenclature	Abbreviations
Heat pump	HP
Coefficient of performance	COP
Back-pressure turbine	BT
Low-pressure	LP
Intermediate cylinder	MP

References

1. Shan, Z.; Tan, Q.; Dong, H.; Ding, Y. Optimization model of low-carbon technology adoption timing for coal power under decarbonization and flexibility demand: Empirical study in Beijing-Tianjin-Hebei region, China. *Appl. Energy* **2024**, *358*, 122647. [CrossRef]
2. Verbruggen, A.; Klemes, J.; Rosen, M.A. Assessing Cogeneration Activity in Extraction-Condensing Steam Turbines: Dissolving the Issues by Applied Thermodynamics. *J. Energy Resour. Technol.* **2016**, *138*, 052005. [CrossRef]
3. Xu, C.; Bai, P.; Xin, T.; Hu, Y.; Xu, G.; Yang, Y. A novel solar energy integrated low-rank coal fired power generation using coal pre-drying and an absorption heat pump. *Appl. Energy* **2017**, *200*, 170–179. [CrossRef]
4. Ma, L.; Ge, Z.; Zhang, F.; Wei, H. A novel super high back pressure cascade heating scheme with multiple large-scale turbine units. *Energy* **2020**, *201*, 117469. [CrossRef]
5. Wei, S.; Wang, J.; Song, H.; Zhou, X. Technical and economic evaluation on the integrated heating system with coupled heat pump and backpressure turbine. *J. Energy Resour. Technol.* **2022**, *144*, 035001. [CrossRef]
6. Xu, X.; Hu, W.; Cao, D.; Huang, Q.; Chen, C.; Chen, Z. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. *Renew. Energy* **2020**, *147*, 1418–1431. [CrossRef]
7. Zhou, J.; Wu, Y.; Dong, H.; Tao, Y.; Xu, C. Proposal and comprehensive analysis of gas-wind-photovoltaic-hydrogen integrated energy system considering multi-participant interest preference. *J. Clean. Prod.* **2020**, *265*, 121679. [CrossRef]
8. Shang, J.; Gao, J.; Jiang, X.; Liu, M.; Liu, D. Optimal configuration of hybrid energy systems considering power to hydrogen and electricity-price prediction: A two-stage multi-objective bi-level framework. *Energy* **2023**, *263*, 126023. [CrossRef]
9. Jiang, K.; Zhang, G.; Liu, H.; Mu, Z.; Wang, Q.; Qin, T.; Niu, Y.; Wang, X.; Zhang, Q. Design and dynamic simulation of flue gas-molten salt heat exchanger in flexible operation coal-fired power plant. *J. Energy Storage* **2024**, *93*, 112227. [CrossRef]
10. Yan, H.; Wang, Z.; Ding, Y.; Liu, M.; Otitoju, O.; Wang, M.; Chong, D. Efficiency enhancement of solar-aided coal-fired power plant integrated with thermal energy storage under varying power loads and solar irradiances. *J. Energy Storage* **2024**, *94*, 112372. [CrossRef]
11. Zhou, J.; Wu, Y.; Zhong, Z.; Xu, C.; Ke, Y.; Gao, J. Modeling and configuration optimization of the natural gas-wind-photovoltaic-hydrogen integrated energy system: A novel deviation satisfaction strategy. *Energy Convers. Manag.* **2021**, *243*, 114340. [CrossRef]
12. Wang, Y.; Zou, Z.; Lu, K.; Li, Q.; Li, L. Probing of operation economy for coal-fired unit under low loads with two fixed boundary conditions. *Energy* **2024**, *288*, 129710. [CrossRef]
13. Wang, H.; Ouyang, Z.; Ding, H.; Su, K.; Zhang, J.; Hu, Y. Experimental study on the flexible peak shaving with pulverized coal self-preheating technology under load variability. *Energy* **2024**, *289*, 129830. [CrossRef]
14. Li, Y.; Zhao, L.; Zhang, X.; Wei, H.; Du, X. Energy consumption during transient operation of coal-fired generating units with cold end system back pressure regulation. *Appl. Therm. Eng.* **2024**, *248*, 123188. [CrossRef]
15. Li, J.; Cheng, K. Research on Energy Comprehensive Utilization of Coupled Heating System Based on Heat Pump. *Turbine Technol.* **2023**, *65*, 214–218.
16. Li, Y.; Chen, X.; Jiang, S.; Lu, G. Thermodynamics of Cascaded Waste Heat Utilization from Flue Gas and Circulating Cooling Water. *J. Therm. Sci.* **2023**, *32*, 2166–2178. [CrossRef]

17. Antar, E.; Robert, E. Thermodynamic analysis of small-scale polygeneration systems producing natural gas, electricity, heat, and carbon dioxide from biomass. *Energy* **2024**, *290*, 130278. [CrossRef]
18. Fu, Y.; Huang, Y.; Xin, H.; Liu, M.; Wang, L.; Yan, J. The pressure sliding operation strategy of the carbon capture system integrated within a coal-fired power plant: Influence factors and energy saving potentials. *Energy* **2024**, *307*, 132737. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.