

Article

Energy and Exergy Evaluations of a Combined Heat and Power System with a High Back-Pressure Turbine under Full Operating Conditions

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Received: 27 July 2020; Accepted: 27 August 2020; Published: 31 August 2020

Abstract: High back-pressure technology is a promising method for the waste heat recovery of exhaust steams in combined heat and power systems. In this research, a 300 MW coal-fired subcritical combined heat and power system was selected as the reference system, and modeled in EBSILON professional. Then, energy-based and exergy-based performances of the high back-pressure system and traditional combined heat and power system were compared under full operating conditions. Moreover, a novel exergy-based evaluation method, which considers the energy level of the heating supply, was proposed and applied to evaluate the two systems. Results show that: In design conditions, both the heating capacity and power output of the high back-pressure system were higher than those of the extraction condensing system, which led to 17.67% and 33.21% increments of the gross thermal efficiency and generation efficiency, respectively. Compared with the extraction condensing system, the exergy efficiencies of the high back-pressure system were 7.04–8.21% higher. According to the novel exergy-based evaluation, the exergy efficiencies for the generation of the high back-pressure system and extraction condensing system were 46.48% and 41.22%, respectively. This paper provides references for the thermodynamic performance evaluation of the combined heat and power system.

Keywords: combined heat and power; high back-pressure; thermodynamic performance; exergy-based efficiencies; full operating conditions

1. Introduction

Combined heat and power (CHP) is a well-proven energy-saving technology for fossil energies [1]. By the end of 2016, the gross installed capacity of CHP reached 755.2 GW and kept incrementing by 2.8% per year [2]. In China, CHP is widely used in the coal-fired power plants due to the coal-dominated resource structure [3]. The total installed capacity was 435 GW in 2018, accounting for 39.4% of the coal-fired power plants. Hence, the technological innovation of CHP technology is essential for the energy industries around the world.

In the traditional CHP system, the steam for heating is usually extracted between the medium-pressure turbine and low-pressure turbine. In the meantime, the heat loss of exhaust steam is large and hard to recover due to its low energy level. Thus, the waste heat recovery of the CHP plant has been widely focused on and considered as a significant part in future district heating (DH) system. Currently, the CHP system with a high back-pressure turbine (CHP-HBP) has drawn more and more attention [4]. In the HBP system, with the improvement of the back-pressure of the low-pressure turbine, the temperature of the exhaust steam is largely increased. Then the exhaust steam can heat the thermal network water, which leads to nearly zero heat loss of the turbine [5]. Due to

these characteristics, the HBP system has been widely applied to the CHP plant with capacities of 200 MW, 300 MW and 600 MW in China [6]. Yang et al. presented a thermodynamic discussion about the cooperation of the HBP system and the low-temperature DH system, indicating that the lower temperature of the supplied-water would give a higher seasonal energy efficiency of the integrated system [7]. Li et al. compared the waste heat recovery technology of the exhaust steam and pointed out that the HBP system had the highest energy efficiency theoretically with the equivalent coefficient of 8.7 [8]. Li et al. developed the HBP system through the integration of the heat pump to ease the inflexibility of adjustment [9], and discussed the CHP system with multiple turbines, whose heating energy consumption is 47.7% lower than the conventional CHP system [10]. From the comprehensive utilization of the exhaust steam and flue gas, Zhao et al. proposed a novel system to optimize the joint operation of the HBP system and the traditional CHP system, which led to 5.06% increment of the generation efficiency [11]. Ma et al. proposed a novel cascading heating system composing by four turbine units, and the gross efficiency of the novel system could reach 85.7% [12]. Chen et al. also indicates the waste heat of the HBP system can be recovered in the coal pre-drying process, which would increase the generation efficiency by 1.7% [13]. Thus, CHP-HBP technology can enhance the heating capacity, and improve the energy efficiency of the CHP plant, which also has excellent compatibility with the low-temperature grid in 4th generation DH technology [14].

The evaluation method which guides the development of the CHP system, is also an essential part of the CHP research. Efficiencies and indicators for the CHP plant are typically based on the first law and second law of thermodynamics, which are also defined as energy-based and exergy-based methods [15]. Wang et al. performed a techno-economic analysis of the CHP system, which is the extension of the energy-based evaluation with the consideration of the feasibility and economic performance [16]. Yannay et al. studied the performance of the CHP system through the integration of thermodynamics with economic criteria [17]. From the aspect of the environmental emissions, Pouria et al. provided a thermo-environmental modeling for the CHP system, in which environmental emissions of CO, CO₂ and NO_x were considered [18]. Emin et al. applied the advanced exergy analysis to the trigeneration system to reveal the potential for improvement of the components in the system [19]. Duccio et al. analyzed a micro CHP system fueled by solar and geothermal by thermo-economic analysis which combined exergy analysis and economic principles [20]. Besides, the “green heating (GH)” theory proposed by Yang et al. is also supplementary to the existing evaluation system [21], in which the theoretical minimum specific fuel consumption is introduced and taken as the basic of GH index.

The traditional exergy-based evaluation method usually concerns the resources and products and their energy levels, but not the process. That means that the result is firmly based on the temperatures of the environment and different cold-ends. On the other hand, it also ignores the energy level difference between different types of CHP systems. It makes the exergy-based analysis of the CHP system complex, especially in the comparison of different CHP technologies. Thus, the innovation of CHP technology also calls for the development of the evaluation method.

Hence, this paper provides a novel exergy-based evaluation method, in which the heating process of the CHP system is well concerned. Due to the remove of the exergy consumption for heating from the total exergy input, this method can be used in not only the comparison among CHP systems with different heating sources, but also among the CHP systems and systems that only generate power.

In this research, a comprehensive thermodynamic analysis of the HBP system was conducted in both design and off-design conditions. By comparing it with the traditional CHP system, limitations of the conventional evaluation methods are discussed. Then, a novel exergy-based evaluation method is proposed, and it was applied to compare the different CHP systems.

2. System Description

2.1. Traditional CHP System

In traditional coal-fired CHP plant, the live steam, which is generated directly from the boiler, is usually expanded in the high-pressure turbine (HPT) and medium-pressure turbine (MPT) first. Then, part of the steam will be extracted to heat the water through the thermal network heater (TNH), while the rest is sent to the low-pressure turbine (LPT). This mode is also called the “extraction condensing (EC) system.” By the cascade utilization of the steam and the decrease of the exhaust steam loss, the CHP system shows great advantages in energy conservation over the system that generates electricity only (power-only system). In this research, a 300 MW coal-fired subcritical single-reheat power plant was selected as the reference system, which has three high-pressure regenerative heaters, three low-pressure regenerative heaters and one deaerator, as shown in Figure 1.

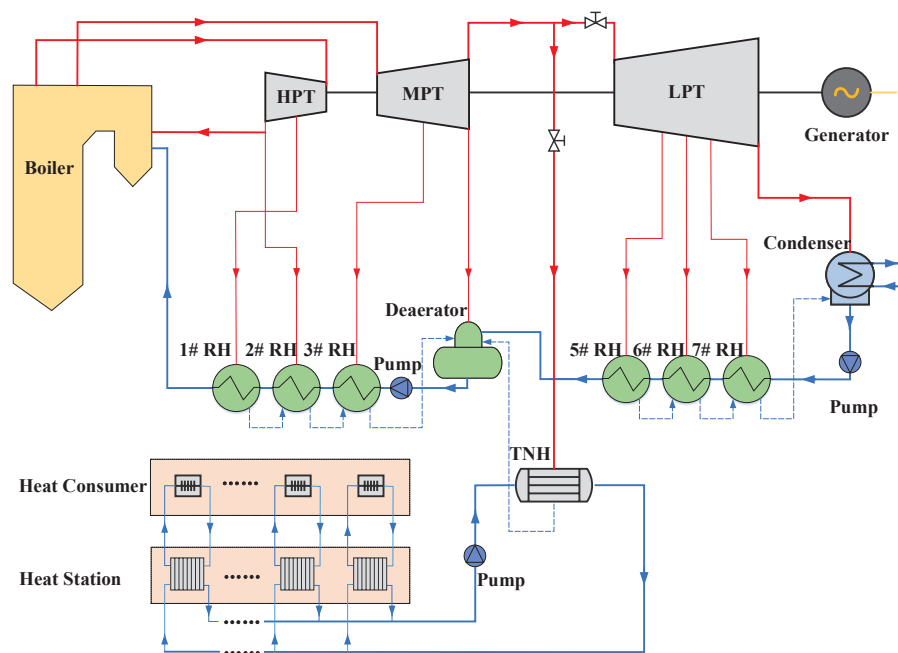


Figure 1. Schematic of the traditional coal-fired CHP-EC system.

The pressure of the extracted steam for heating is 0.4 MPa. After the thermal network heater, the steam is cooled as the drain water of 104 °C and sent to the deaerator. The maximum mass flow of the extraction steam is 500 t/h. Tables 1 and 2 give the main technical parameters and the steam parameters of the reference system under the turbine maximum continuous rating (TMCR) conditions, respectively. Generally, the turbine heat acceptance (THA) is the normal condition for generation given by the manual of the steam turbine, while the TMCR is the base condition for the CHP process. Table 3 gives the elemental analysis of the selection coal, in which q_{LHV} , A_{ar} , M_{ar} and V_{ar} denote the lower heating value, ash, moisture and volatile contents of the coal as-received, respectively.

However, there are still improvements in the traditional CHP plant: (1) Considering the safety of the LPT, not all the steam can be extracted for heating, which means the exhaust steam loss in the condenser is inevitable. In fact, the volumetric flow rate of the steam in the LPT is usually no less than 1/3 of the designed value. (2) Besides, the energy level of the extracted steam is much higher than that of the thermal network water, which restricts the possibly performance improvement of the traditional CHP plant.

Table 1. Main technical parameters of the reference power plant.

Item	Unit	Value
Gross power output (In THA condition)	MW	300
Gross power output (In TMCR condition)	MW	322.20
Net power output (In TMCR condition)	MW	313.42
Mass flow of the coal	t/h	96.43
Efficiencies		
Boiler	%	93
Pipeline	%	99
Mechanical	%	99
Generator	%	99
Pump	%	83
Pressure losses		
Live steam	%	2
Reheat steam	%	10
Pipeline from MPT to LPT	%	4.5
High-pressure regenerative heater	%	3
Low-pressure regenerative heater	%	5

Table 2. Steam parameters of the power plant in turbine maximum continuous rating (TMCR) conditions.

Item	Pressure (MPa)	Temperature (°C)	Specific Enthalpy (kJ/kg)	Mass Flow Rate (t/h)
Live steam	16.67	538	3397.3	1017.92
Reheat steam	3.58	538	3535.4	846.91
Exhaust steam	0.014	52.57	2429.3	666.63
1# RH	6.20	390.4	3151.5	69.41
2# RH	3.98	332.6	3051.3	60.00
3# RH	1.90	442.7	3343.3	33.66
Deaerator	0.98	355.9	3170.5	29.60
5# RH	0.63	295.4	3049.9	43.69
6# RH	0.26	128.56	2868.2	41.50
7# RH	0.89	96.32	2677.8	47.60

Table 3. Elemental analysis of the selected coal.

Items	C_{ar} (%)	H_{ar} (%)	O_{ar} (%)	N_{ar} (%)	S_{ar} (%)	A_{ar} (%)	M_{ar} (%)	V_{ar} (%)	q_{LHV} (kJ/kg)
Value	73.69	4.29	2.51	2.45	1.05	6.26	9.75	23.98	29,686

2.2. CHP System with a High Back-Pressure Turbine

CHP-HBP is a novel process for the coal-fired power plant, also known as the low vacuum system, as shown in Figure 2 [7]. In the HBP system, the back-pressure of the LPT is increased to improve the energy level of the exhaust steam. Then, the waste heat of the exhaust steam can be recovered to heat the thermal network water. By doing this, the loss of exhaust steam is eliminated and nearly zero loss of the turbine side can be achieved. Thus, the HBP system could significantly improve the heating capacity and efficiency of the power plant [22].

In this research, the back-pressure of the LPT was set as 54 kPa with the saturation temperature of 83.27 °C, by removing the last two stages of blades [23]. Compared with the traditional CHP system, the temperature of the heating steam in the HBP system is much lower. This could reduce the exergy loss between the steam and thermal network water, but make it worse in the adaption to a high-temperature thermal network. However, such characteristics cannot be reflected in the existing energy- and exergy-based evaluation method, because they are all based on the product only and care little about the energy level of the heating steam. In the following part, thermodynamic performances of the two system based on the existing evaluation methods are compared and the limitations are discussed.

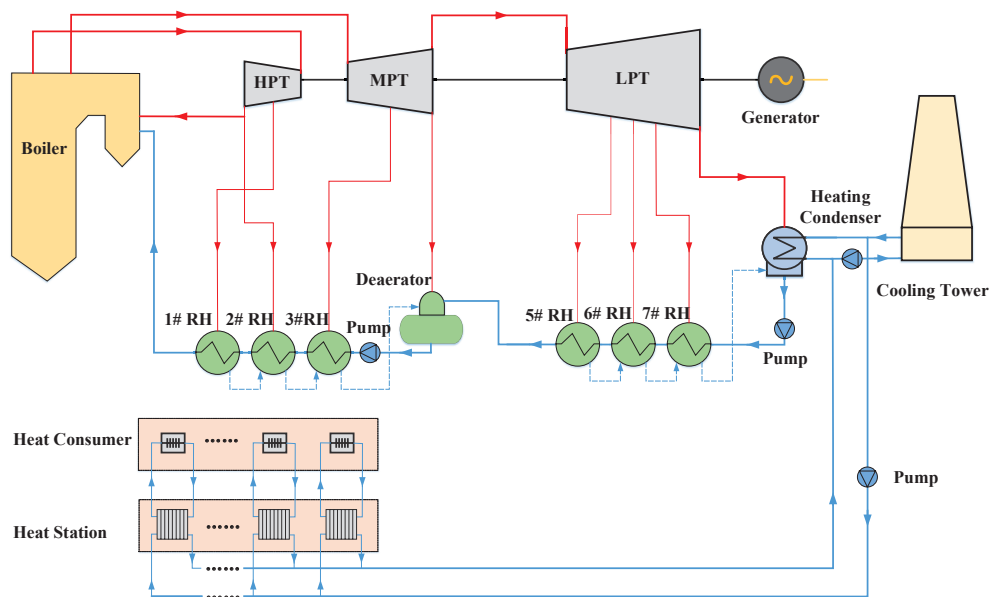


Figure 2. Schematic of the coal-fired CHP-HBP system.

3. Modeling and Evaluation Criterion

3.1. Modeling Method

In this research, EBSILON Professional was used to building the mathematical model, which is widely used in the design, optimization and evaluation of the general thermal process and has proved to be a reliable tool in modeling process [24,25]. Model details of the main components are listed in Table 4, and the model of the reference system in EBSILON is shown in Figure 3. In the modeling process, the shaft-packing leakage of the turbine is also considered to improve the accuracy. Some of the leakages are recovered to the gland heater (GH), while the others are sent to the seal system of the LPT. Detailed sources and destinations of the leakages can be seen in Figure 3.

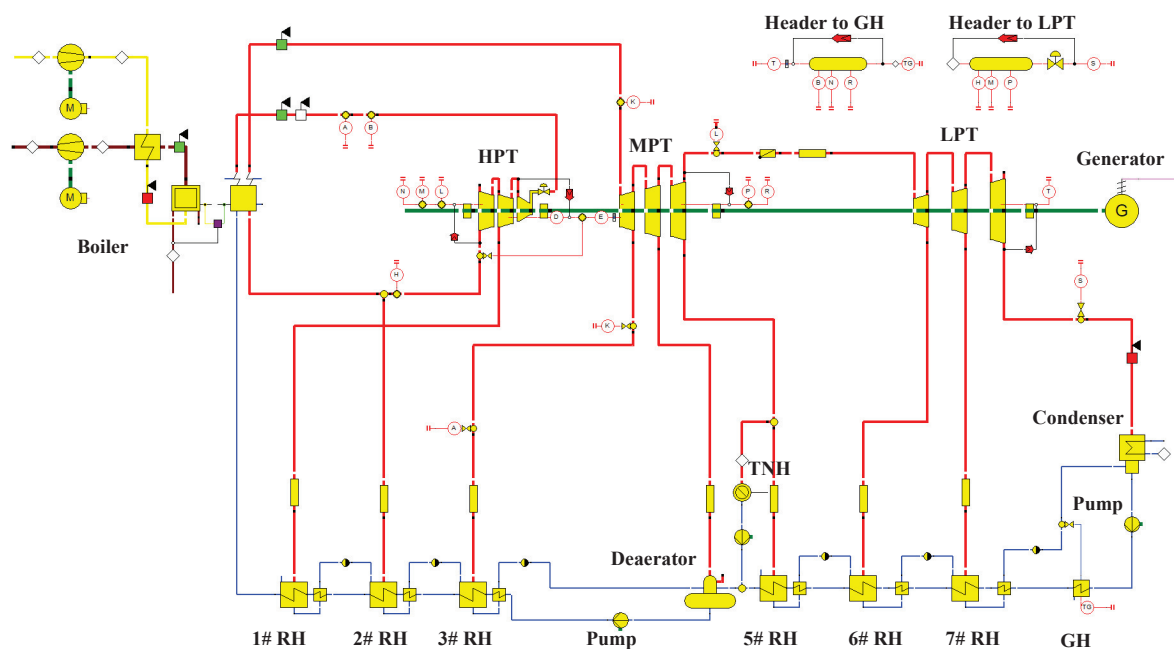


Figure 3. Model of the CHP-EC system in EBSILON Professional.

Table 4. Model details of the main components in EBSILON Professional.

Component	Module Type	Parameters
Boiler	NO. 5	Reheat steam temperature = 538 °C; Live steam pressure = 16.67 MPa; Live steam pressure loss = 14%; Reheat steam pressure loss = 10%
Turbines	NO. 122	Isentropic Efficiency = 83.53–93.56%; Mechanical Efficiency = 99.8%; Heat loss = 0
Generator	NO. 11	Electrical efficiency = 99%
Condenser	NO. 7	Upper temperature difference = 1 °C; Pressure drop = 5 kPa
Pump	NO. 8	Isentropic Efficiency = 83%; Mechanical Efficiency = 99.80%
Thermal network heater	NO. 35	Maximum mass flow = 500 t/h; Dain water temperature = 104 °C
Pressure-control	NO. 59	Pressure for DH system \geq 0.4 MPa
Pressure losses	NO. 13	High-pressure regenerative heater = 3%; Low-pressure regenerative heater = 5%; Pipeline from MPT to LPT = 4.5%
Feed water preheater	NO. 10	Pressure loss of feed water = 5 kPa; Upper temperature difference: 1# = −1.7 °C, 2#/3# = 0 °C, 5# 7# = 2.8 °C
After cooler	NO. 27	Lower temperature difference = 5.6 °C

In the off-designed simulation of the turbine, there are two parameters that have substantial influences on the power output: (1) the inlet and outlet pressures and (2) the isentropic efficiency.

In EBSILON professional, the pressures can be deduced by Stodola's law [26]:

$$Const = G \sqrt{\frac{v}{p}} \quad (1)$$

where G is the mass flow rate the steam, kg/h; p is the inlet pressure, MPa; v denotes the specific volume, m^3/kg .

The output of the turbine stage (P_s) can be calculated as:

$$P_s = G (h_1 - h_{2,is}) \eta_{is} \eta_{s,m} \quad (2)$$

where h_1 and $h_{2,is}$ are the enthalpies of the inlet steam and outlet steam in isentropic process, kJ/kg; η_{is} and $\eta_{s,m}$ denote the isentropic efficiency and mechanical efficiency, which are obtained in the manual of the steam turbine, %.

Figure 4 gives the accuracy validation of the model, which compares the simulation results of the model with design data of the turbine manual in both power-only and CHP conditions. The maximum relative error(RE) is −0.39% in 75% THA condition, which proves that the model has high precision and can be used in the following discussion.

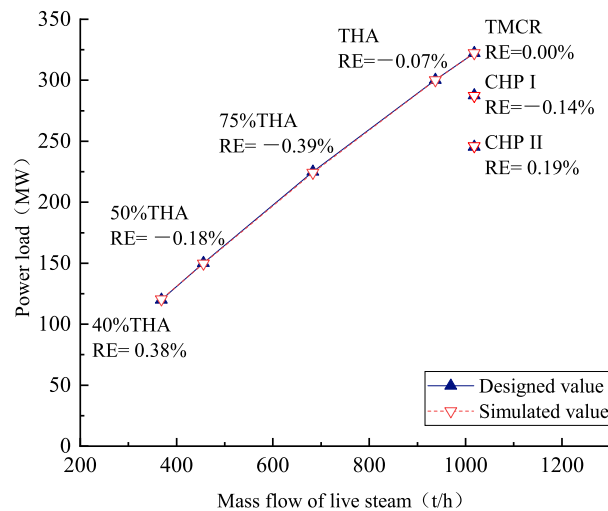


Figure 4. Comparison between simulation results and design data.

3.2. Evaluation Criterion

3.2.1. Energy-Based Evaluation

The most commonly used evaluation method of the CHP system is based on the first law of thermodynamics, called the energy-based evaluation [27]. This method mainly follows the mass and energy balances and can obtain primary energy savings. The typical indicators are given below.

The gross thermal efficiency ($\eta_{g,CHP}$):

$$\eta_{g,CHP} = \frac{P + Q_H}{Bq_{LHV}/3600} \times 100\% \quad (3)$$

where P and Q_H are the power and heat loads of the CHP system, respectively, MW; B is the coal consumption rate of the boiler, t/h.

The heating efficiency ($\eta_{h,CHP}$):

$$\eta_{h,CHP} = \eta_{b,CHP}\eta_{p,CHP} \quad (4)$$

where $\eta_{b,CHP}$ and $\eta_{p,CHP}$ are the efficiencies of the boiler and pipe, %.

The generation efficiency ($\eta_{e,CHP}$):

$$\eta_{e,CHP} = \frac{P}{Bq_{LHV} - Q_H/\eta_{h,CHP}} \times 100\% \quad (5)$$

The standard coal consumption rate of generation ($b_{e,CHP}$):

$$b_{e,CHP} = \frac{122.8}{\eta_{e,CHP}} \quad (6)$$

The standard coal consumption rate of heating ($b_{h,CHP}$):

$$b_{h,CHP} = \frac{34.1}{\eta_{h,CHP}} \quad (7)$$

3.2.2. Conventional Exergy-Based Evaluation

The energy-based evaluation presents the energy utilization condition from the quantity aspect, but ignores the energy level differences of the sources and products. By contrast, the exergy is a conception based on the second law of thermodynamics. It represents the maximum useful work the

energy can generate with its environment during a reversible process, and is the measure of the energy quality. The exergy efficiency can be usually defined as the ratio of useful exergy output to the total exergy input. Hence, exergy-based evaluation covers not only the quantity but also the quality of the energy and is considered as a more objective criterion than the energy-based method [28].

The traditional exergy efficiency of the CHP system can be given as:

$$\eta_{g,CHP}^{ex} = \frac{P + E_H}{Bq_{LHV}\xi} \times 100\% = \frac{P + Q_H\eta_{DH}^{ex}}{Bq_{LHV}\xi} \times 100\% \quad (8)$$

where E_H is the output exergy for heating, MW; ξ is the ratio of the exergy of the coal to its q_{LHV} ; η_{DH}^{ex} is the exergy efficiency of the DH system, %.

ξ can be calculated as [29]:

$$\xi = 1.009 + \frac{0.131O_{ar} + 0.16M_{ar}}{1 - (A_{ar} + M_{ar})} \quad (9)$$

The η_{DH}^{ex} can be calculated as:

$$\eta_{DH}^{ex} = 1 - \frac{T_0 + 273.15}{T_C + 273.15} \times 100\% \quad (10)$$

where T_0 and T_C are the temperatures of the environment and the cold-end, °C. In this study, the temperature of the environment was set as 0 °C. In traditional exergy-based evaluation, the cold-end has different definitions. Usually, the object of the cold-end could be the heat consumer or the heat station. In this research, T_C of the former was constant as 20 °C while T_C of the latter was the mean temperature of the supplied- and returned-water, °C.

4. Results and Discussion

4.1. Traditional Energy-Based and Exergy-Based Evaluations

4.1.1. Thermodynamic Performance in Design Conditions

Figure 5 gives the energy flow diagram of the two systems in the maximum heating condition. The energy from the boiler of the HBP system is 1.87 MW lower than the EC system when the mass flow of the main steam remains the same. The main losses of the EC system from the condenser, boiler, pipes and others, account for 17.72%, 7%, 1.35% and 0.35% of the input energy, respectively. Moreover, the output heating and power occupy 43.83% and 29.74%, respectively. Compared with the EC system, the HBP system has a similar energy loss distribution except for the exhaust steam loss, which is 0 in the HBP system. The output heating and power of the HBP system account for 55.61% and 35.63%, 11.78% and 5.89% higher values than those of the EC system.

Table 5 gives the energy-based comparison of the two CHP modes in design conditions. The HBP system has higher heating capacity, power output, generation efficiency and exergy efficiency than the EC system. In detailed, the gross efficiencies of the HBP system reach 91.24% and 17.67% higher than the EC system. Moreover, the heating capacity of the HBP system also has a 26.58% (92.89 MW) improvement over that of the EC system. In the meantime, the power generated by the HBP system is also 46.29 MW higher. Overall, the generation efficiency of the HBP system reaches 89.98% with the standard coal consumption rate of 136.47 g/kWh, 79.84 g/kWh lower than that of the EC system. When the temperature of the cold end is set as the heat user ($T_C = 20$ °C), the exergy efficiency of the HBP system is 6.52% higher than that of the EC system.

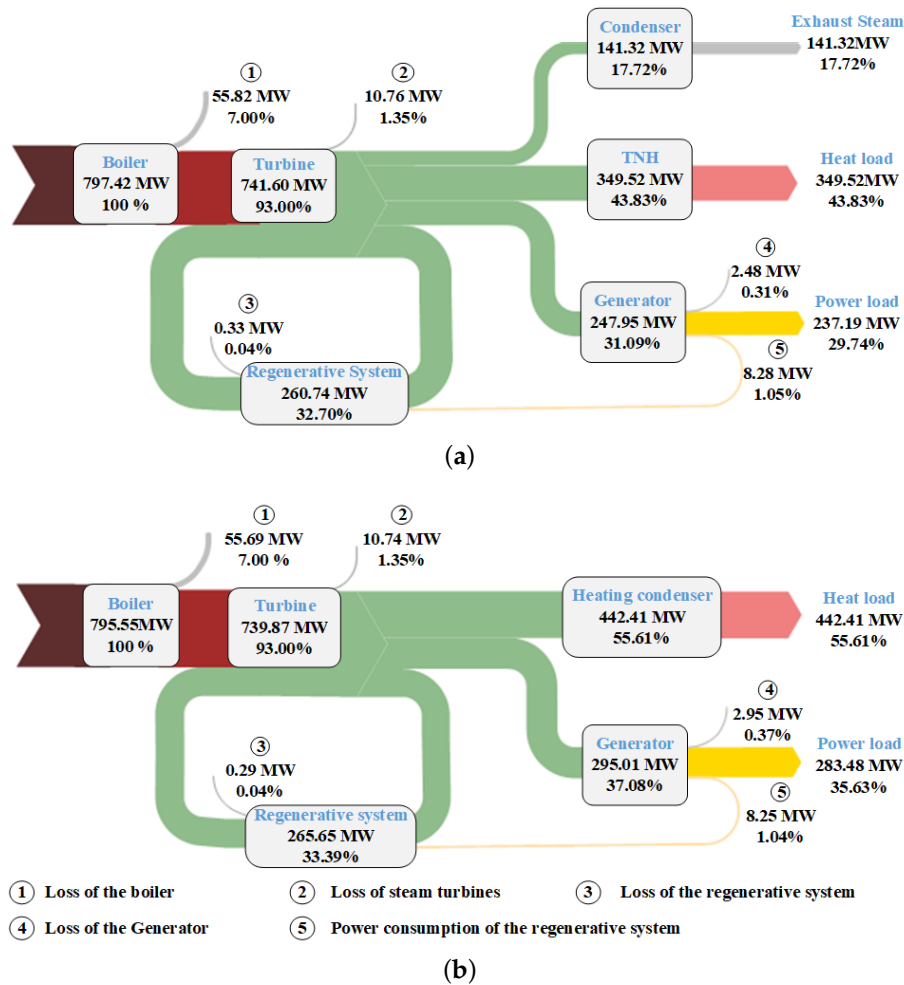


Figure 5. Energy flow of the CHP systems: (a) EC system; (b) HBP system.

Table 5. Thermodynamic performances of the two CHP systems in design conditions.

Items	Unit	EC System	HBP System	Differences
Energy of the coal	MW	797.42	795.55	–
Pressure of the heating steam	kPa	400	54	–
Mass flow of the heating steam	t/h	500	703.78	–
Temperature of the heating steam	°C	145.87	83.27	–
Heating capacity	MW	349.52	442.41	92.89
Generation power	MW	237.19	283.48	46.29
Generation efficiency ($\eta_{e,CHP}$)	%	56.77	89.98	33.21
Coal consumption rate for generation ($b_{e,CHP}$)	g/kWh	216.30	136.47	–79.84
Heating efficiency ($\eta_{h,CHP}$)	%	92.07	92.07	0.00
Coal consumption rate for heating ($b_{h,CHP}$)	kg/GJ	37.04	37.04	0.00
Gross thermal efficiency ($\eta_{g,CHP}$)	%	73.58	91.24	17.67
Exergy efficiency of DH system (η_{DH}^{ex}) ($T_C = 20\text{ °C}$)	%	6.82	6.82	0.00
Exergy efficiency ($\eta_{g,CHP}^{ex}$) ($T_C = 20\text{ °C}$)	%	31.89	38.41	6.52

4.1.2. Efficiencies under the Off-Design Conditions

Figure 6 shows the gross thermal efficiencies, generation efficiencies and exergy efficiencies of the two systems in the whole feasible operational range. It can be seen that the energy-based evaluation methods ($\eta_{g,CHP}$ and $\eta_{e,CHP}$) show similar trends, which are that $\eta_{g,CHP}$ and $\eta_{e,CHP}$ will increase with the increment of the heat load when the live steam remains the same. With the maximum mass flow of live steam, when the heat load of the EC system changes from 0 to 249.52 MW, $\eta_{g,CHP}$ and $\eta_{e,CHP}$ are

increased from 39.83% to 73.58% and from 39.83% to 56.77%, respectively. By contrast, when the heat load of the HBP system changes from 0 to 442.41 MW, $\eta_{g,CHP}$ and $\eta_{e,CHP}$ are increased from 35.70% to 91.24% and from 35.70% to 89.98%, respectively. This trend also reflects the advantage of the CHP system over the power-only system. However, a different trend is achieved when it comes to $\eta_{g,CHP}^{ex}$. The rise of the heat load could decrease $\eta_{g,CHP}^{ex}$ of the EC system but increase $\eta_{g,CHP}^{ex}$ of the HBP system. When the heat load changes from 0 to the maximum, $\eta_{g,CHP}^{ex}$ of the EC system decreases from 38.81% to 31.89% when $\eta_{g,CHP}^{ex}$ of the HBP system increases from 34.78% to 38.41%. Furthermore, results in Figure 6c,f also are affected by the cold-end temperature, which brings about some limitations which are discussed in Sections 4.1.3 and 4.2.

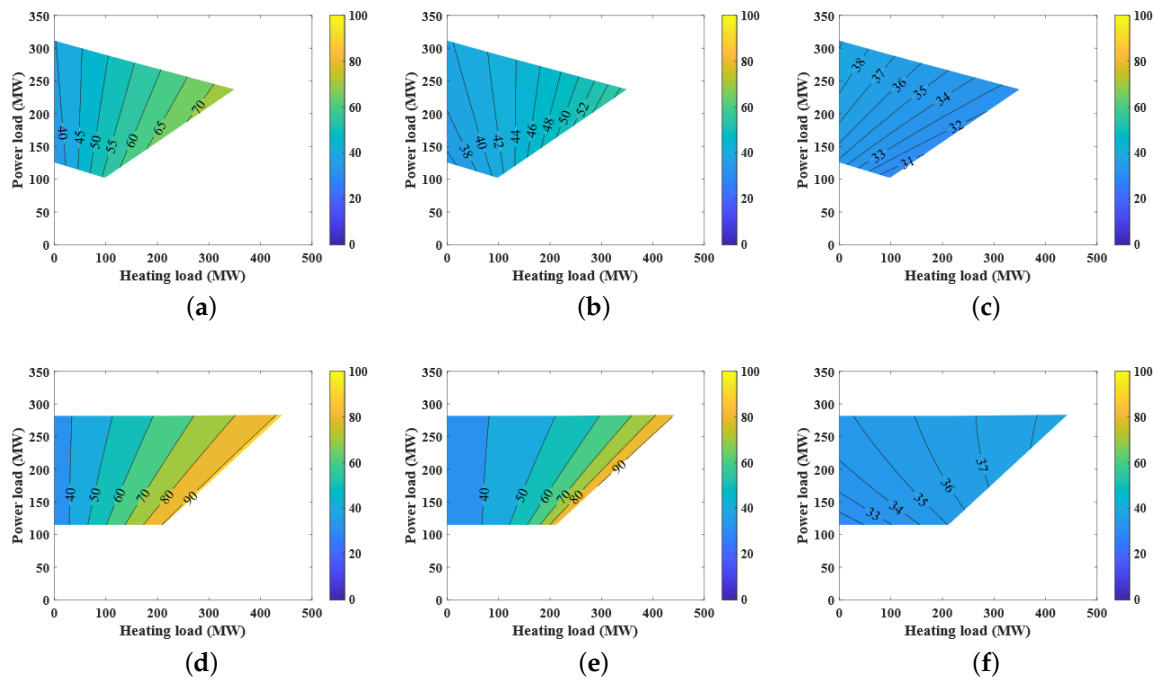


Figure 6. Efficiencies in the feasible operational region: (a) $\eta_{g,CHP}$ of EC system; (b) $\eta_{e,CHP}$ of EC system; (c) $\eta_{g,CHP}^{ex}$ of EC system ($T_C = 20\text{ }^\circ\text{C}$); (d) $\eta_{g,CHP}$ of HBP system; (e) $\eta_{e,CHP}$ of HBP system; (f) $\eta_{g,CHP}^{ex}$ of HBP system ($T_C = 20\text{ }^\circ\text{C}$).

4.1.3. Exergy Analysis with Different Cold-End Temperatures

According to Equation (10), the conventional exergy-based evaluation is based not only on the CHP system but also on the temperature of the cold end. In the above section, the cold end is set as the heat user ($T_C = 20\text{ }^\circ\text{C}$). In this section, the cold end is the water in the DH system. Moreover, the temperatures of the returned- and supplied-water could influence the exergy-based performance. Figure 7 shows the influences of returned- and supplied-water temperatures on η_{DH}^{ex} . In the application, the temperatures of returned- and supplied-water are usually no more than 70/130 $^\circ\text{C}$. Temperatures higher than these are for the theoretical analysis only and are presented as empty circles in the figure.

With the increment of the returned- and supplied-water temperatures, the exergy of the DH system increases. With the mean temperature of the water increases from 35 $^\circ\text{C}$ to 125 $^\circ\text{C}$, η_{DH}^{ex} is raised from 11.36% to 31.40%, which means every 10 $^\circ\text{C}$ improvement of the mean temperature could bring about 2.23% increment of η_{DH}^{ex} in the given temperature range. With the returned- and supplied-water temperatures of 70/130 $^\circ\text{C}$, η_{DH}^{ex} could reach 26.80%.

Based on η_{DH}^{ex} given in Figure 7, Figure 8 gives the exergy efficiencies of the two systems with different returned- and supplied-water temperatures. The exergy efficiency has a similar trend as η_{DH}^{ex} , and increases with the improvement of the mean temperature of the thermal network water. Every 10 $^\circ\text{C}$ improvement of the mean temperature could bring about 1.38% increment of the exergy efficiency of the

HBP system, which is 0.95% of the EC system. Compared with the EC system, the exergy efficiency of the HBP system is 7.04–8.21% higher with the same cold-end temperature.

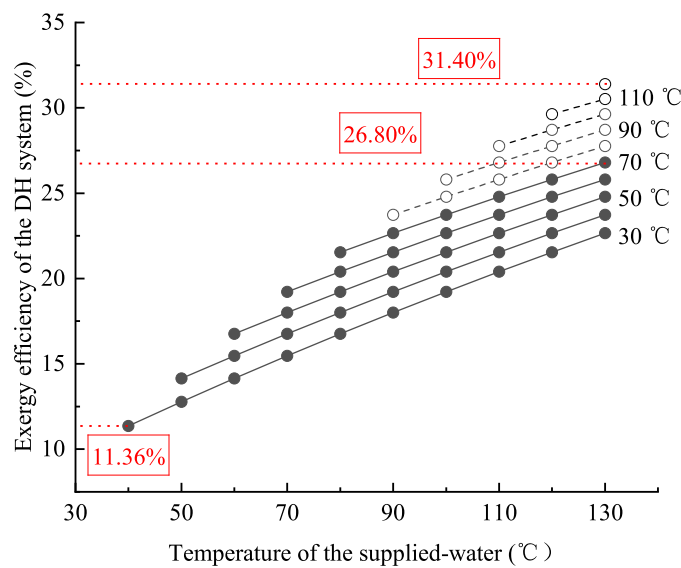


Figure 7. Influences of returned- and supplied-water temperatures on η_{DH}^{ex} .

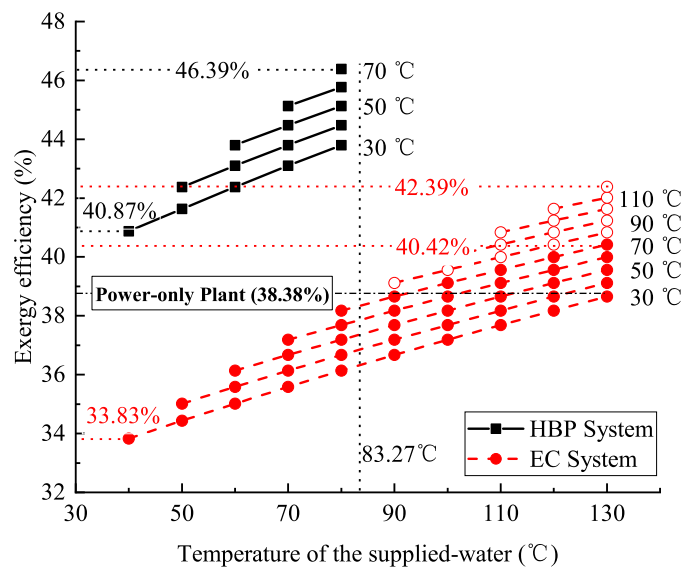


Figure 8. Influences of returned- and supplied-water temperatures on $\eta_{g,CHP}^{ex}$.

4.2. Novel Exergy-Based Evaluation

4.2.1. Limitations of the Traditional Evaluations

Results above show some limitations of the traditional exergy-based evaluation:

1. The conventional exergy-based evaluation of the CHP system strongly relies on the temperatures of the cold-end and the environment, which increases the complexity of further exergy-based research. For example, each cold-end temperature will need a unique diagram to show the exergy efficiencies in the feasible operational region (Figure 6c,f).
2. The conventional exergy-based evaluation only concerns the product but ignores the heat sources. For example, the HBP system shows great advantages over the EC system under both the energy-based and the conventional exergy-based evaluations. However, the heating steam of

- the EC system has a higher level, which is hard to be displayed in these evaluations. Thus, these evaluation methods have limitations when used to compare different types of CHP systems.
- Results based on conventional exergy-based evaluation could also lead in the wrong directions. For example, according to the results in Figures 7 and 8, the increment of the cold-end temperature could increase the exergy efficiency of the CHP system. However, this may raise the bar to recover the low-level waste heat and is opposite to the DH system in the future [30].

4.2.2. Proposal of the Novel Exergy-Based Evaluation

The conventional exergy-based evaluation of the CHP system has some limitations and has difficulties in guiding the improvement of CHP technology. Considering that, a novel exergy-based evaluation is proposed in this research, which is based on the exergy consumption dispatch of the heat and power.

In the novel evaluation, the main objective is to separate the exergy consumption of heating from the gross consumption scientifically. After that, the exergy consumption of the generation can be obtained, as shown in Figure 9. The new evaluation concerns the heating steam and its exergy consumption of different CHP types, so the temperatures will not influence it. The following gives the main criterion of the novel evaluation method.

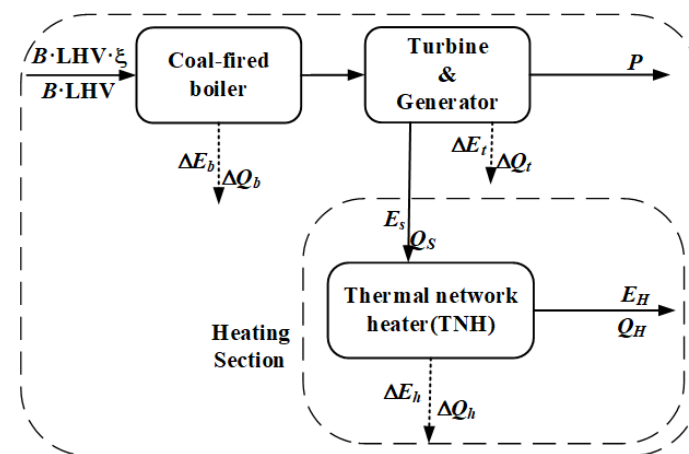


Figure 9. Diagram of energy and exergy flows of the CHP system.

For the thermal network heater (TNH), the exergy efficiency can be achieved as:

$$\eta_{TNH,CHP}^{ex} = \frac{E_H}{E_S} \times 100\% = \frac{1 - (T_0 + 273.15)/(T_C + 273.15)}{1 - (T_0 + 273.15)/(T_S + 273.15)} \times 100\% \quad (11)$$

where E_s and T_s are the exergy and mean temperature of the heating steam, respectively.

The exergy efficiency for heating ($\eta_{h,CHP}^{ex}$):

$$\eta_{h,CHP}^{ex} = \eta_{TNH,CHP}^{ex} \eta_{b,CHP}^{ex} \eta_{p,CHP}^{ex} \quad (12)$$

where $\eta_{p,CHP}^{ex}$ is the exergy efficiencies of the pipe, which is 97% in this study [31]; and $\eta_{b,CHP}^{ex}$ denotes the exergy efficiency of the boiler, which can be calculated as:

$$\eta_{b,CHP}^{ex} = \frac{D_0(e_0 - e_f) + D_r(e_{r,hot} - e_{r,cold})}{Bq_{LHV}\xi} \times 100\% \quad (13)$$

where D_0 and D_r are the mass flows of the live steam and reheat steam, t/h; e_0 , e_f , $e_{r,hot}$ and $e_{r,cold}$ are the specific exergies of the live steam, feed water, hot and cold sides of the reheat steam, respectively, kJ/kg.

Finally, the exergy efficiency for the generation ($\eta_{e,CHP}^{ex}$) of the EC system can be deduced:

$$\eta_{e,CHP}^{ex} = \frac{P}{Bq_{LHV}\xi - E_H/\eta_{h,CHP}^{ex}} \times 100\% \quad (14)$$

For the HBP system, the mass flow of the exhaust steam depends on the mass flow of live steam only. That means when the live steam is constant, the exergy consumption for heating should be the same no matter whether the waste heat of the exhaust steam is fully recovered. Here, τ is defined as the mass flow ratio of the exhaust steam recovered in the heating condenser. Then, the exergy consumption for heating should be $E_H/(\eta_{h,CHP}^{ex}\tau)$, and the $\eta_{e,CHP}^{ex}$ of the HBP system is deduced as:

$$\eta_{e,CHP}^{ex} = \frac{P}{Bq_{LHV}\xi - E_H/(\eta_{h,CHP}^{ex}\tau)} \times 100\% \quad (15)$$

4.2.3. Exergy Analysis under Design Conditions

To show the energy level differences between the heating steam in the two systems, Figure 10 gives the T - Q diagram of the heating steam in the two systems. The heating steam of the EC system goes through several states (superheated steam, saturated steam, wet steam, saturated water, unsaturated water) in the heating process with the mean temperature of 145.87 °C. By contrast, the heating steam of the HBP system is wet steam initially, and releases heat to the saturated water with a constant temperature of 83.27 °C. Thus, although the heating capacity of the HBP system is 72.89 MW higher, the energy level of the heating steam is lower than that of the EC system.

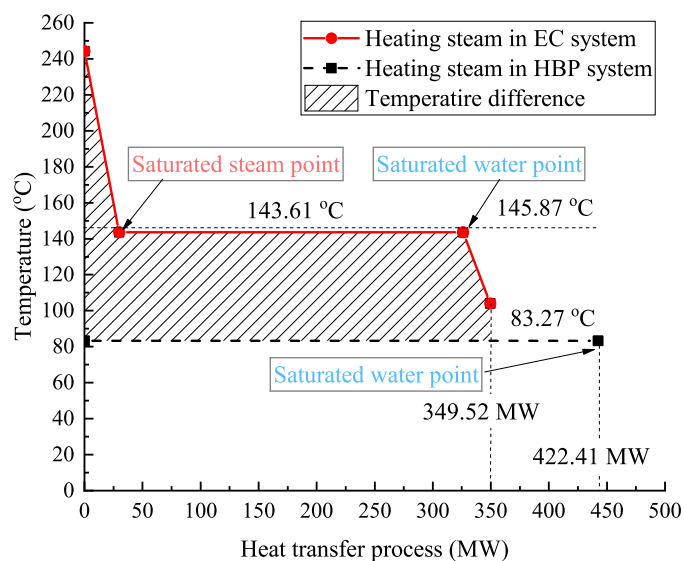


Figure 10. T - Q diagram of the heating steam.

Figure 11 gives the influences of the supplied- and returned water temperatures on the exergy efficiency of the TNH. Similar to the gross exergy efficiency shown in Figure 9, the improvement of the temperature of the thermal network water can increase $\eta_{TNH,CHP}^{ex}$ in both systems. With the same supplied- and returned water temperatures, the $\eta_{TNH,CHP}^{ex}$ of the HBP system is 16.00–30.32% higher than that of the EC system. Within the given range, the $\eta_{TNH,CHP}^{ex}$ of the HBP system can reach 92.21% (80/70 °C), which is 76.98% (130/70 °C) of the EC system.

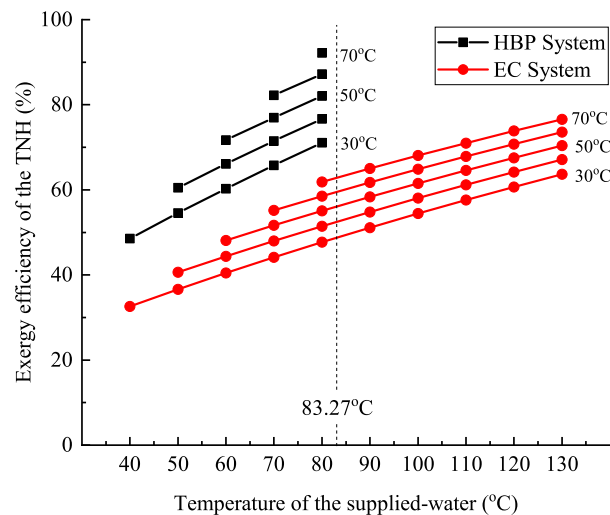


Figure 11. Influences of the returned- and supplied-water temperatures on $\eta_{TNH,CHP}^{ex}$.

Based on the results in Figure 11, Figure 12 shows the influence of the thermal network heater temperature on the exergy efficiency for heating ($\eta_{h,CHP}^{ex}$). The exergy efficiency of the boiler was calculated to be 51.14%, and the exergy efficiency of the pipes was set as 97%. With the returned-water temperature increasing from 30 °C to 70 °C, the $\eta_{h,CHP}^{ex}$ of the EC system changed from 32.71% to 38.70% with the supplied-water temperature of 130 °C; that of the HBP system changed from 36.06% to 46.35% with the supplied-water temperature of 80 °C.

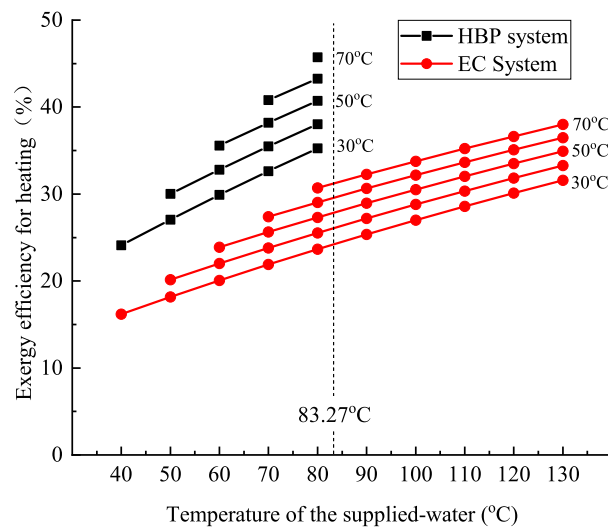


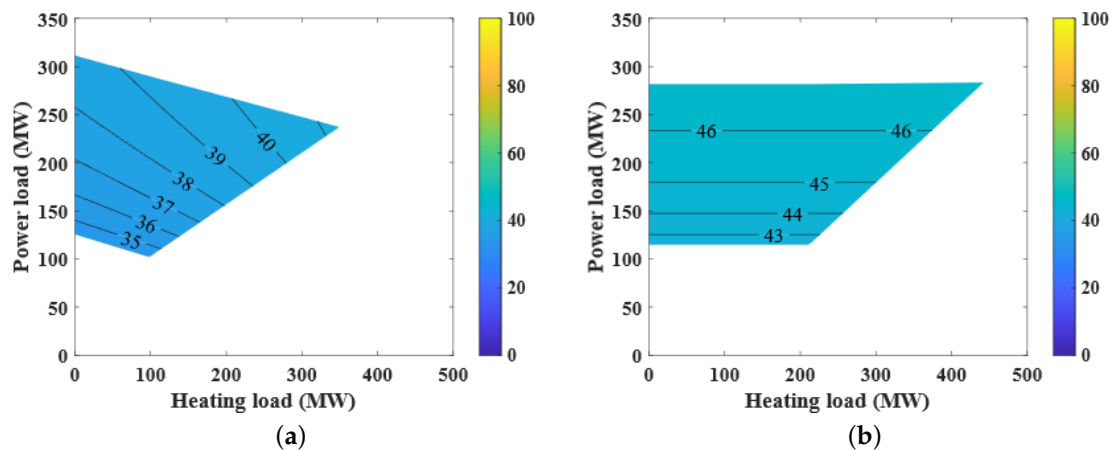
Figure 12. Influences of the returned- and supplied-water temperatures on $\eta_{h,CHP}^{ex}$.

Then the thermodynamic comparison based on the novel exergy analysis is shown in Table 6. According to the results before, the energy of the heating steam of the HBP system is 72.89 MW higher than that of the EC system. However, the exergy of the heating steam of the HBP system is 18.32 MW lower than that of the EC system, which is caused by the energy difference of the heating steam and also leads to a 33.30 MW decrement of the exergy consumption for heating. Finally, the exergy efficiencies for generation ($\eta_{e,CHP}^{ex}$) of the HBP system and EC system can be achieved, which are 46.48% and 41.22%, respectively. Compared with the power-only system, the $\eta_{e,CHP}^{ex}$ of the HBP system and EC system are 8.10% and 2.84% higher.

Table 6. Novel exergy analysis of the systems.

Items	Unit	Power-Only System	EC System	HBP System
Exergy of the coal	MW	816.64	818.48	816.55
Exergy to the live and reheat steam	MW	423.19	424.14	423.15
Exergy of the heating steam	MW	–	121.68	103.36
Exergy consumption for heating	MW	–	241.64	208.34
Net generation power	MW	313.42	237.19	283.48
Exergy efficiency for generation	%	38.38	41.22	46.48

Figure 13 gives the $\eta_{e,CHP}^{ex}$ in the feasible operational region of the EC system and HBP system. Then, three features of the novel exergy-based evaluation can be deduced by comparing with the results in Figure 6e,f: (1) $\eta_{e,CHP}^{ex}$ and $\eta_{g,CHP}^{ex}$ are the same when the heat load is 0. Since in this condition the CHP plant can be considered as the power-only system, $\eta_{e,CHP}^{ex}$ and $\eta_{g,CHP}^{ex}$ will be not influenced by the heating part. (2) With the increment of the heat load, different trends are achieved. For the EC system, with the live steam mass flow unchanged, the $\eta_{e,CHP}^{ex}$ is increased with the improvement of the heat load, when $\eta_{g,CHP}^{ex}$ is decreased in the same condition. For the HBP system, the $\eta_{e,CHP}^{ex}$ remains unchanged with the same mass flow of the live steam. In this condition, the change of the heat load only influences the heat dispatch of the heating condenser and cooling tower, not the coal consumption and generation characters. Thus, the trend of $\eta_{e,CHP}^{ex}$ can reflect the characters of the CHP system clearer than $\eta_{g,CHP}^{ex}$. (3) Since $\eta_{e,CHP}^{ex}$ is based on the exergy consumption dispatch of the heat and power concerning more regarding the CHP system itself, the cold-end temperature has no influence on the results in Figure 13. With these features, the novel exergy-based evaluation is supplementary to the existing evaluation system.

**Figure 13.** $\eta_{e,CHP}^{ex}$ in the feasible operational region: (a) EC system; (b) HBP system.

5. Conclusions

In this study, a comprehensive thermodynamic performance evaluation of the coal-fired CHP plant with a HBP turbine was performed based on both the energy- and exergy-based evaluation methods. Compared with the traditional CHP plant with EC mode, the thermodynamic characteristics of the HBP system under full operational conditions were obtained. Then, considering the energy level differences of the heating steam, a novel exergy-based evaluation method was proposed and applied to compare the performances of different CHP systems. The main results were as follows:

(1) In design conditions, both the heating capacity and power output of the HBP system were higher than those of the EC system, which led to 17.67% and 33.21% increments of the gross thermal efficiency and generation efficiency respectively, and a 79.84 g/kWh decrement of the standard coal

consumption rate. Compared with the EC system, the exergy efficiencies of the HBP system were 7.04–8.21% higher with the same cold end temperature.

(2) Efficiencies in the feasible operational region were also achieved and show that the energy-based evaluation methods ($\eta_{g,CHP}$ and $\eta_{e,CHP}$) show similar trends: $\eta_{g,CHP}$ and $\eta_{e,CHP}$ will increase with the increment of the heat load when the live steam remains the same, while $\eta_{g,CHP}$ will show the opposite trend.

(3) According to the novel exergy-based evaluation method, the exergy efficiencies for the generation ($\eta_{e,CHP}^{ex}$) of the HBP system and EC system were 46.48% and 41.22%, respectively—8.10% and 2.84% higher than those of the power-only system. $\eta_{e,CHP}^{ex}$ in the whole feasible operational region was obtained.

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

Funding: This research was funded by the Science and Technology Innovation Team of Henan Colleges (16IRTSTHN7) and Start-up Project for the High-level Researcher of North China University of Water Resources and Electric Power (400140837).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CHP	Combined Heat and Power
DH	District Heating
EC	Extraction Condensing
GH	Gland Heater
HBP	High Back-Pressure
HPT	High-Pressure Turbine
LPT	Low-Pressure Turbine
MPT	Medium-Pressure Turbine
RE	Relative Error
RH	Regenerative Heater
THA	Turbine Heat Acceptance
TMCR	Turbine Maximum Continuous Rating
TNH	Thermal Network Heater

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