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Analysis of Characteristics of the Combined Cooling Heating and Power System under Multiple Operation Modes

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Abstract: The Combined Cooling Heating and Power System (CCHP) system can achieve highly efficiency by energy cascade utilization, which is one of the core units of the integrated energy system in the future, with great development potential. Aiming at the complicated operation performance of the CCHP system, an operation characteristic analysis method is studied under multiple modes. Firstly, a typical simulation model of the CCHP system is established, while the energy flow is analyzed. Secondly, an evaluation system considering multi-dimensional indicators such as energy consumption, comprehensive cost and pollution discharge of the system is built. According to the electric and thermal load of a building, the capacity of the main equipment of the system is designed. Furthermore, the energetic, economic and environmental performances under “following electric load” (FEL) mode and “following thermal load” (FTL) mode are quantitatively analyzed, comparing with the traditional separated providing system. The results show that this method reveals the advantages and disadvantages of the performances of the CCHP system under different operating modes, thus can provide a reasonable basis for the selection of operational strategies.

1. Introduction

As the growth of energy demand, the disadvantages of traditional energy supply methods, such as inefficiency and high pollution, are increasingly serious, which have become a key bottleneck impeding the sustainable development of social economy. Thus, it is imminent to build a new energy supply system that is efficient, reliable and environment-friendly [1-3]. The Combined Cooling Heating and Power (CCHP) system is an integrated energy system based on energy cascade utilization, which simultaneously generating electricity, cool and heat. The energy efficiency of the CCHP system can reach above 80% by recovering the waste heat [4-5], while reducing the emissions of harmful gases such as SO₂ and CO₂, which is acknowledged as an important way for scientific energy supply in the future.

However, as a multi-energy coupling system, the CCHP system involves a great variety of structures



and modes, the performance under every operating strategies are totally different. Currently, many scholars have carried out related research on the operating strategy of CCHP system, and proposed a series of optimized operation modes [6-10]. Although it has good theoretical effects, the application is more difficult. The traditional operation strategies such as Following Electric Load (FEL) mode and Following Thermal Load (FTL) mode are still the primary choices for most CCHP projects nowadays. Thus it is necessary to thoroughly study the evaluation method of the operating characteristics of the CCHP system under the traditional operation mode, and analyze the social and economic benefits of the system.

In order to reveal and evaluate the characteristics of CCHP system under different modes, a typical CCHP system simulation model was established, while an evaluation system including energy consumption, energy efficiency, comprehensive cost, pollution discharge and other indicators was constructed. Based on the energy demand of a building, the CCHP system is configured by a conventional design method, and the separated providing (SP) system is taken as the reference object. The characteristics of energy conservation, economy and emission reduction under FEL mode and FTL mode are analyzed, which could provide a theoretical basis for choosing a reasonable operation strategy.

2. CCHP system model

2.1. Typical system structure

In general, a typical CCHP system includes the power generation unit, heating system, refrigeration system and the management system. Each subsystem connects appropriately with each other forming an organic system, thereby achieving efficient cascade utilization of energy. Except the above mandatory units, the system is additionally equipped with other auxiliary equipment sometime, such as electric chillers, gas boilers and energy storage units, which can further improve energy efficiency and reliability. The typical CCHP system configuration is shown as Fig.1.

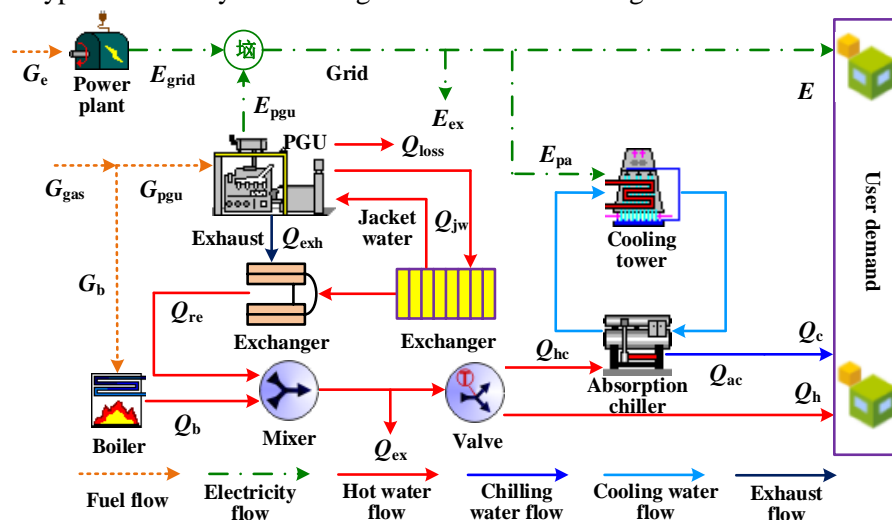


Figure 1. The typical configuration of a CCHP system

As shown in Fig.1, The power generation unit (PGU), choosing internal combustion engine, generates electricity for users and other equipment. And the shortfall power can be supplemented by the power grid (PG), while the benefits of selling the redundant power are not considering in this paper. In addition, the waste heat produced by the PGU, including the jacket water heat and the exhaust heat, is recovered through a water-cycle subsystem, which can be used either for heat or to drive the absorption chiller according to seasonal conditions. And the gas boiler is equipped for auxiliary.

2.2. Off-design Performance of the PGU

As the core unit of the CCHP system, the off-design performance of PGU have important influence on the equipment capacity and key parameters. Herein the ASHRAE naturally aspirated internal combustion engine data are adopted to simulate the off-design performance[11], as shown in Tab.1.

Table 1. Performance factors of small naturally aspirated internal combustion engine

PLR	η_m	η_p	f_j	f_e	f_s
0.0000	0.0000	0.0000	0.5628	0.2764	0.1608
0.1000	0.1020	0.7700	0.5227	0.2955	0.1818
0.2000	0.1809	0.7800	0.5031	0.3006	0.1963
0.3000	0.2250	0.8200	0.4903	0.3097	0.2000
0.4000	0.2637	0.8400	0.4865	0.3108	0.2027
0.5000	0.2871	0.8600	0.4861	0.3125	0.2014
0.6000	0.3085	0.8750	0.4892	0.3237	0.1870
0.7000	0.3184	0.8850	0.4818	0.3285	0.1898
0.8000	0.3184	0.9000	0.4745	0.3285	0.1971
0.9000	0.3039	0.9100	0.4507	0.3169	0.2324
1.0000	0.2886	0.9200	0.4336	0.3147	0.2517

It can be seen from the Tab.1 that the PGU efficiency drops significantly when the PLR is low, which will seriously affect the overall system performance. Therefore, light-load operation should be avoided. f_j, f_e, f_s are the coefficients corresponding to jacket water heat Q_{jw} , exhaust heat Q_{exh} and heat loss Q_{loss} , respectively, which satisfy the following relationship:

$$f_j + f_e + f_s = 1 \quad (1)$$

The variation curves of the parameters over the full range of operating conditions are fitted by a cubic spline interpolation method. Thus, the generated waste heat at different times can be calculated.

2.3. Energy flow

The energy flow of this CCHP system should be initially analyzed to study the optimal configuration. In Fig.1, E_{pgu} is the electricity generated by PGU; E_{grid} represents the purchased electricity from the grid; E_{pa} is the consumption of other equipments; E is the user demand for electricity; E_{ex} is redundant power. The electricity energy balance in the CCHP system at period t ($t = 1, 2, \dots, T$) is expressed as:

$$E_{pgu}(t) + E_{grid}(t) = E(t) + E_{ec}(t) + E_{ex}(t) \quad (2)$$

While E_{grid} can be converted into the primary energy consumption:

$$G_e(t) = \frac{E_{grid}(t)}{\eta_e \eta_d} \quad (3)$$

Where η_e is the power generation efficiency of PG, η_d is the transmission efficiency of the distribution network; $G_e(t)$ represents the energy consumed by power generation from PG in period t .

Meanwhile the PLR in period t , $r(t)$, can be calculated as:

$$r(t) = \frac{E_{pgu}(t)}{E_{max}} \quad (4)$$

Where E_{max} is the power of the PGU in rated condition.

The energy consumption of the PGU G_{pgu} in period t is:

$$G_{pgu}(t) = \frac{E_{pgu}(t)}{\eta_p(t) \eta_m(t)} \quad (5)$$

Where η_p and η_m are the electrical efficiency and thermal efficiency of the PGU, respectively.

Furthermore, the jacket water heat Q_{jw} , the exhaust heat Q_{exh} in period t can be expressed as:

$$Q_{jw}(t) = G_{pgu}(t)(1 - \eta_m(t)\eta_p(t))f_j \quad (6)$$

$$Q_{exh}(t) = G_{pgu}(t)(1 - \eta_m(t)\eta_p(t))f_c \quad (7)$$

Thus, the recovered waste heat in period t is:

$$Q_{re}(t) = (Q_{jw}(t) + Q_{exh}(t))\eta_r \quad (8)$$

Where Q_{re} represents the total recovered waste heat; η_r is the efficiency of the heat exchangers.

According to the system structure, the heat energy balance in the CCHP system is expressed as:

$$Q_{re}(t) + Q_b(t) = U_s Q_{hc}(t) + (1 - U_s)Q_h(t) + Q_{ex}(t) \quad (9)$$

As Eq. (7) shows, $Q_b(t)$, $Q_{hc}(t)$, $Q_{ex}(t)$ and $Q_h(t)$ are the heating power from the auxiliary boiler, the required heat input of the absorption chiller, the extra heat and the heating load demand in period t ; While U_s is the binary variable, which is 1 in summer and 0 in winter.

The consumption of the gas boiler, G_b , is:

$$G_b(t) = \frac{Q_b(t)}{\eta_b} \quad (10)$$

Besides, the power of the absorption chiller in period t , Q_{ac} , can be expressed as:

$$Q_{ac}(t) = \frac{Q_{hc}(t)}{I_{COP_{ac}}} \quad (11)$$

Where $I_{COP_{ac}}$ represents coefficient of performance (COP) of the absorption chiller.

Therefore, the total gas consumption of the CCHP system G_{gas} can be expressed as:

$$G_{gas}(t) = G_{pgu}(t) + G_b(t) \quad (12)$$

The total primary energy consumption of the CCHP system, G_{CCHP} , can be calculated to:

$$G_{CCHP}(t) = G_{gas}(t) + G_e(t) \quad (13)$$

The units of energy in this paper are all in kWh.

3. CCHP system operation and evaluation

3.1. Basic operation modes

The basic operation modes of CCHP system are mainly divided into FEL mode and FTL mode. And there is also a hybrid mode combining these two [12].

In addition, the CCHP system must be able to operation independently to meet the user's maximum demand in some areas where are still not connected to the grid, However, in this case, more energy storage devices and peak shaving units need to be configured, thereby the initial investment requirements for the system are higher.

In terms of the above basic operation mode, the FTL mode can maximize the recovery of the waste heat, so that the system can achieve better energy saving and emission reduction. However, it is inevitable that redundant electrical energy will be generated in FTL mode. Meanwhile, the electrical energy storage device is generally not considered in the CCHP system due to the high cost. Therefore, once the redundant electricity is unable to feedback to the grid, it will inevitably lead to energy waste. Therefore, most CCHP systems operate mainly in FEL mode, while using the heat storage devices to achieve redundant heat adjustment, thus improving the energy efficiency.

3.2. Evaluation criteria

The energetic, economic and environmental objectives are chosen as the evaluation objectives, thus studying the system performance under different operation mode [13].

(1) Energetic criteria

The primary energy utilization rate (PER) is the most common energetic criteria, which is defined as the ratio of the total output of the system electricity, heat (cool) and primary energy consumption. Therefore, larger PER represents the better the energy cascade utilization effect of the CCHP system.

According to the system configuration in Fig.1, the PER of the CCHP system and the SP system are expressed as:

$$F_{\text{PER}} = \frac{\sum_{t=1}^{8760} (E(t) + Q_c(t) + Q_h(t))}{\sum_{t=1}^{8760} G_{\text{CCHP}}(t)} \quad (14)$$

$$F_{\text{PER}} = \frac{\sum_{t=1}^{8760} (E(t) + Q_c(t) + Q_h(t))}{\sum_{t=1}^{8760} G_{\text{CCHP}}(t)} \quad (15)$$

Where F_{PER} is the PER of the CCHP system; $F_{\text{PER_SP}}$ is the PER of the SP system.

However, high energy efficiency doesn't mean the good energy efficiency. To further assess the energy-saving potential of the CCHP system, the Primary Energy Saving Ratio (PESR) is proposed, defined as the ratio of the energy-saving of the CCHP system compared to a separation production (SP) system, which can be expressed as:

$$F_{\text{PESR}} = \frac{\sum_{t=1}^{8760} G_{\text{SP}}(t) - \sum_{t=1}^{8760} G_{\text{CCHP}}(t)}{\sum_{t=1}^{8760} G_{\text{SP}}(t)} \quad (16)$$

Where F_{PESR} represents the PESR; G_{SP} is the energy consumption of the SP system.

(2) Economic criteria

Compared with the SP system, the CCHP system increases the initial investment cost, but reduces the energy costs. Therefore, the Annual Cost Saving Rate (ACSR) is used to measure the economics of the CCHP system. And the annual cost of equipment C_p , energy cost C_g and maintenance cost C_m are expressed as [14]:

$$C_p = \frac{q(1+q)^n}{(1+q)^n - 1} \sum_{i=1}^k C_i N_i \quad (17)$$

$$C_g = \sum_{t=1}^{8760} (E_{\text{grid}}(t) p_e(t) + G_{\text{gas}}(t) p_g(t)) \quad (18)$$

$$C_m = \delta \sum_{i=1}^k C_i N_i \quad (19)$$

In Eq.(17)-Eq.(19), q is the annual interest rate, 6.21%; n represents the life cycle of the equipment, 10 years; C_i is the unit cost of investment of the equipment i , yuan/kWh; while k is the quantity of the equipment; N_i represents the capacity of equipment i , kW; Where p_g and p_e are the electricity price and gas price in t period, respectively, yuan/kWh; δ is annual maintenance coefficient of the equipment, 2.5%. Thus, the total annual cost of the CCHP system C_{CCHP} is:

$$C_{\text{CCHP}} = C_p + C_g + C_m \quad (20)$$

Similarly, the total annual cost of the SP system, C_{SP} , can be calculated. And the ACSR, F_{ACSR} , is expressed as:

$$F_{ACSR} = \frac{C_{SP} - C_{CCHP}}{C_{SP}} \quad (21)$$

(3) Environmental criteria

The CCHP system achieves energy conservation through energy cascade utilization, which also effectively reduce CO₂ emissions and plays an important role in mitigating the greenhouse effect. The total annual CO₂ emissions, CO₂E_{CCHP} of the CCHP system can be expressed as:

$$CO_2 E_{CCHP} = \sum_{t=1}^{8760} (\omega_g G_{gas}(t) + \omega_e G_{ec}(t)) \quad (22)$$

Where ω_g and ω_e are the CO₂ emission coefficient of gas and power from the grid, which are set to 203.74g/kWh and 326.37g/kWh respectively.

According to Eq.(22), the total CO₂ emission of the SP system, CO₂E_{SP}, can also be calculated. Thus, the CO₂ Emission Reduction Ratio (CO₂ERR) of the CCHP system comparing to the SP system can be represented as:

$$F_{CO_2ERR} = \frac{CO_2 E_{SP} - CO_2 E_{CCHP}}{CO_2 E_{SP}} \quad (23)$$

Furthermore, the reduction ratio of SO₂ and NO_x of the CCHP system can be obtained.

4. Case study

According to the typical structure of the CCHP system, an office building is taken as an object to analyze the characteristics of the CCHP system under different operating modes. The building's annual load data is shown in Fig.2.

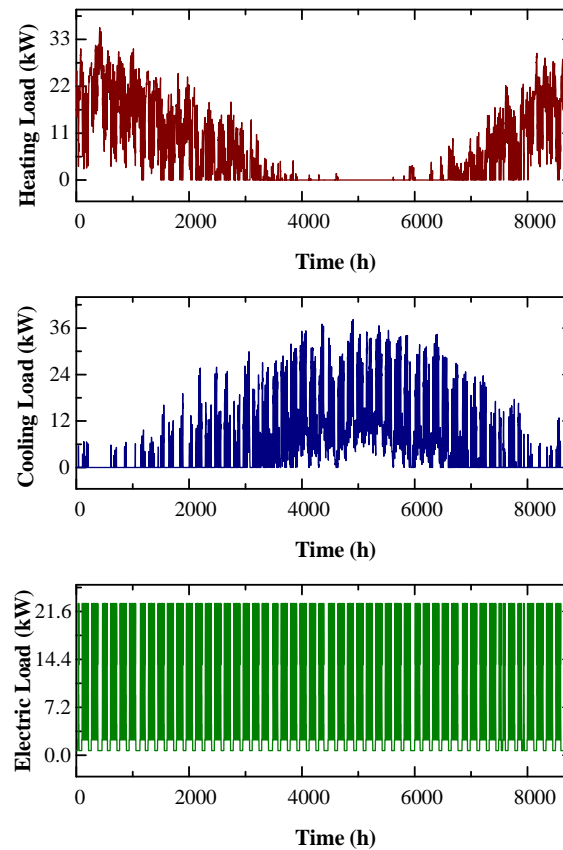


Figure 2. The annual load demand of a simulation building

As shown in Fig.2, the variation of electric load is more regular, the electricity consumption during working days is larger than holidays. On the other hand, the heating load is concentrated from November to February (7296-8760 hours, 1-161 hours), while the peak of the cooling load occurs between May and September (2880-6552 hours).

Based on the load of the building shown in Fig.3, the main equipment capacity of the CCHP system is configured, as shown in Tab.2.

Table 2. Configurations of the CCHP system under different operation mode

Mode	PGU	Absorption chiller	Boiler
FTL	13kW	38 kW	21 kW
FEL	22 kW	38 kW	19 kW

On this basis, the energetic, economic and environmental performances under the FEL mode and FTL mode are analyzed. According to the climate characteristics and energy supply habits of Shandong Province, the heating season is set from November to March, when the absorption chiller does not work. The rest of the time is the cooling season, the heating load is negligible, while the absorption chiller is driven by the waste heat of the PGU to meet the user's cooling load demand.

The annual energy consumption of the SP system and the CCHP system under FEL mode and FTL mode are shown in Fig. 3.

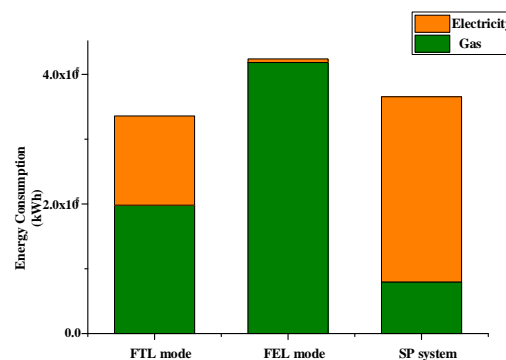


Figure 3. The annual energy consumption of the SP system and the CCHP system

The energy consumption of the CCHP system when connected to the grid includes the gas consumption and purchased electricity. It can be seen from Fig. 3 that when the CCHP system operates in FTL mode, the total energy consumption is reduced compared with the SP system. Whereas the CCHP system not only failed to save energy, but also caused a significant increase in total energy consumption under the FEL mode, which also confirmed the limitations of the traditional operating strategy. Each energy consumption of the system is shown in Tab.3.

Table 3. The comparison of energy consumption between the CCHP system and the SP system

Mode	Gas /(kWh)	Electricity/(kWh)	Total /(kWh)
FTL	198130	137730	335860
FEL	418350	5612.4	423962.4
SP	79648	285780	365428

Tab.3 shows that the purchased electricity of the CCHP system under the FEL mode and FTL mode reduce by 98% and 51.8%, respectively, caused by the energy cascade utilization. However, due to the long-term operation of the PGU, the gas consumption is increased by 4.25 times in FEL mode, while 1.5 times in FTL mode compared with the SP system.

In addition, the economics of the CCHP system are analyzed. Herein, the annual cost of the CCHP system is divided into three categories: equipment cost, gas cost and purchased electricity cost, which are shown in Fig.4.

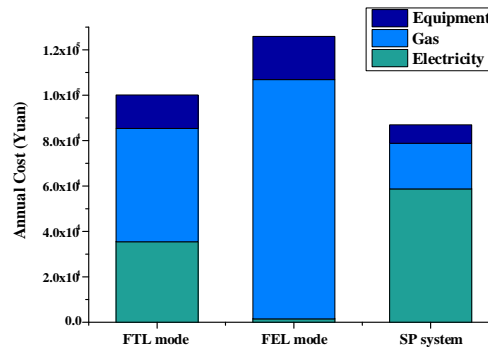


Figure 4. The annual cost of the SP system and the CCHP system

As shown in Fig. 4, the annual cost of the CCHP system is higher than the SP system in any mode, while the economics under FEL mode is the worst. In fact, since the CCHP system adds equipment such as PGU and absorption chillers, it will inevitably lead to an increase in equipment investment costs. In addition, as seen in Fig.4, the CCHP system also increases the gas consumption cost while reducing the cost of purchased electricity from the grid. Each cost of the CCHP system is shown in Tab.4.

Table 4. The comparison of annual cost between the CCHP system and the SP system

Mode	Equipment /(Yuan)	Gas /(Yuan)	Electricity /(Yuan)	Total /(Yuan)
FTL	14737.2	49928.8	35444	100110
FEL	19013.5	105424.2	1472.3	125910
SP	8143.7	20071.3	58746	86961

It can be seen from Tab.4 that the annual cost of the CCHP system is 15% and 45% higher than the SP system in FTL mode and FEL mode respectively. In addition, the increase of annual equipment cost of the CCHP system reaches 81% and 133% respectively. Overall, the annual cost of the CCHP system is still dominated by energy costs. The equipment cost for the two operating modes accounts for only about 15% of the total annual cost. However, this does not mean that reducing energy consumption can fundamentally improve the economics of the CCHP system, which still involves many factors such as equipment configuration, operation mode and energy policy.

Moreover, the environmental performance of the CCHP system is evaluated based on annual CO₂ emissions and SO₂ emissions, as shown in Fig.5 and Fig.6, respectively.

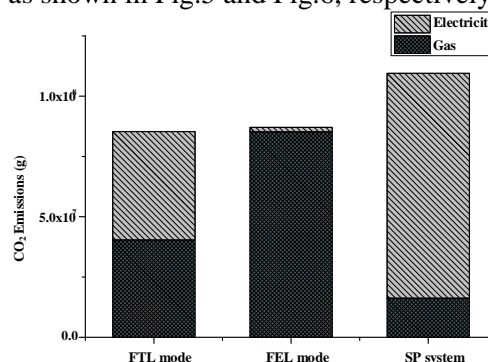


Figure 5. The annual CO₂ emission of the SP system and the CCHP system

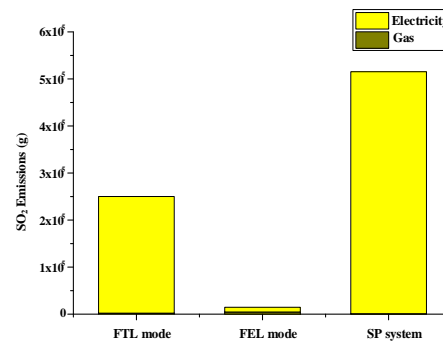


Figure 6. The annual SO₂ emission of the SP system and the CCHP system

Nowadays, coal is still the important energy source in China. Obviously, the amount of harmful gases generated by coal combustion process is much higher than other energy sources, which have caused long-lasting damage to the ecological environment. However, as seen in Fig.5 and Fig.6, the CCHP system get rid of the dependence on traditional power generation by reuse of waste heat, greatly reducing the electricity purchased of the grid, thereby significantly reducing the emissions of harmful gases such as CO₂ and SO₂. The emissions of the CCHP system under different operating modes are shown in Tab.5.

Table 5. The comparison of annual emission of the CCHP system and the SP system

Mode	CO ₂ Emission/kg			SO ₂ Emission/kg		
	Gas	Electricity	Total	Gas	Electricity	Total
FTL	40367.01	44950.94	85317.95	2.18	247.91	250.09
FEL	85234.63	1831.72	87066.35	4.60	10.10	14.70
SP	16227.48	93270.02	109497.50	0.88	514.40	515.28

It can be seen from Table 5 that CO₂ is the main emission product of the CCHP system, while the amount of SO₂ emissions is even less than 1% compared with the CO₂ emissions. Overall, the CO₂ emission reduction of the CCHP system in FTL mode and FEL mode both exceeds 20 tons, which contributes to greatly alleviating the greenhouse effect. On the other hand, since the CCHP system basically does not need to purchase electricity from the grid in FEL mode, thus the SO₂ emission reduction is quite obvious, the annual discharge is only about 14 kg, which can be negligible. Meanwhile, the annual SO₂ emission reduction rate under the FTL mode has also reached more than 50%. However, CO₂ emissions are still much larger than SO₂ emissions, thus should be a priority in system design and operation.

Therefore, the energetic, economic and environmental evaluation criteria of the CCHP system under FEL mode and FTL mode is shown in Tab.6.

Table 6. The evaluation criteria of the CCHP system

Evaluation Criteria		FEL mode	FTL mode
Energy	$F_{PER}/\%$	69.24	70.34
	$F_{PESR}/\%$	-16.02	8.09
Economy	$F_{ACSR}/\%$	-44.79	-15.12
	$F_{CO2ERR}/\%$	20.49	22.08
Environment	$F_{SO2ERR}/\%$	97.15	51.46

It can be seen in Tab.6, the performance in FTL mode is better than FEL mode except the SO₂ emission reduction rate. Especially the energy consumption in FEL mode is even more than the SP system. In addition, the ACSR in both modes is negative, indicating the poor economy of the CCHP system, which is a key bottleneck that hinder its development and promotion.

Nevertheless, the CCHP system has significant advantages in improving the environment.

Regardless of operation mode, the CO₂ emission reduction rate is greater than 20%, and the SO₂ emission reduction effect is more obvious. At the same time, the PER of the CCHP system in both operating modes is about 70%, while the PER of the SP system is only 51.2%, which means that the CCHP system actually improves the energy utilization efficiency through waste heat recovery. However, the conventional design method and the basic operation mode are far from the huge potential of energy saving and emission reduction of the CCHP system. The optimization methods are necessary for system design and operation.

5. Conclusion

This paper introduces a typical CCHP system configuration. The energy flow of the CCHP system are analyzed based on the off-design characteristics of the PGU, and the basic operation modes are also described. Furthermore, the basic CCHP system under the FEL mode and FTL mode were evaluated based on the criteria of energy, economy and environment.

The results show that the performance of the system in the FTL mode is better than that in the FEL mode. The energy consumption of the CCHP system is much more than the SP system when operating in FEL mode. However, the ACSR is negative in both modes, indicating that the CCHP system is less economical. In comparison, the CCHP system has significant emission reduction characteristics for pollutants. The CO₂ emission reduction rate under both operation modes exceeds 20%, and the SO₂ emission reduction rate under the FEL mode is more than 90%.

It can be seen that the social and economic benefits of the CCHP system are difficult to achieve simultaneously. Energy-saving and emission reduction often require a large economic cost by conventional methods, resulting in an imbalance of interests, which hinders the popularization and application of the CCHP system. Therefore, it is necessary to improve the comprehensive performance of the CCHP system by optimization methods, thereby fundamentally promoting the development of the CCHP system.

Acknowledgments

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