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# Study on The Thermal Characteristics of Solar Assisted Oxygen Enriched High Back Pressure Heating Units

Zhiyu Zhang [1, a] , Long Qin [1, b] *

[1] School of Energy and Environment, Inner Mongolia University of Science and Technology, Baotou 014010, China

[a] zzy0021@126.com, [b] 19834046897@163.com

**Abstract.** Establish a model of a solar-assisted oxygen-enriched high backpressure heating unit. Adopt the method of process simulation to explore the impacts of different solar energy coupling schemes on the power supply coal consumption rate, heating coal consumption rate of the unit, as well as the solar energy conversion efficiency and exergy efficiency. Additionally, conduct exergy analysis and economic analysis for different schemes. The research findings show that after adopting the optimal scheme, the power supply coal consumption rate of the unit is reduced by 11.64 g/(kW·h), the standard heating coal consumption rate is reduced by 0.238 kg/GJ, and the solar energy conversion efficiency and exergy efficiency are 41.84% and 22.49% respectively. The total exergy efficiency of the unit is the highest.

**Keywords:** solar energy; oxygen enriched; high backpressure; thermal characteristics.

## 1. Introduction

Among the numerous clean energy sources in our country, solar energy, as one of them, has extremely remarkable advantages and broad development prospects. Introducing solar energy into the oxygen-enriched high backpressure heating unit can not only reduce coal consumption but also increase the output power of the unit.

literature [1] analyzed the impacts of the changes in the normal direct solar irradiance on indicators such as the solar power generation, photoelectric conversion efficiency, and standard coal consumption rate of different schemes, aiming at different integration schemes of solar energy and coal-fired units. literature [2], based on the actual operation conditions of the heating units with two units running simultaneously, analyzed the coupling mode of the solar-assisted cogeneration units with two units under the premise of ensuring the heating load, and compared the peak regulation performance of the two units before and after coupling. literature [3] utilized solar energy before the boiler, that is, after the first high-pressure feed water heater of the solar preheater (water/heat exchanger). The results showed that the annual output of solar energy was 208 GWh, and the contribution rate of solar energy in power production was approximately 15%. The CO2 emissions were reduced by about 381,358 tons per year. literature [4] proposed a new type of tower solar-assisted coal-fired power generation system with thermal energy storage. This system used high-temperature solar energy to heat the primary and secondary reheated steam extracted from the boiler, while low-temperature solar energy was used to heat the boiler feed water. They obtained the maximum steam extraction mass flow rate of the boiler under different load rates and analyzed the thermodynamic performance. literature [5] respectively connected the solar collectors in parallel to the regenerative system, high-pressure heater, and low-pressure heater of the unit, and conducted an analysis based on the operation parameters of a 600 MW supercritical thermal power unit under the design operating conditions. The results showed that all three schemes could improve the thermal economy of the unit, reduce the coal consumption, and lower the $CO_2$ emissions. Among them, the levelized energy cost (LEC) of the second scheme was much lower than the cost of pure solar thermal power generation, showing higher economic efficiency.

This paper takes a 300 MW coal-fired power generation unit as the reference unit. By constructing a model of a solar-assisted oxygen-enriched high backpressure heating unit, it aims to study the impacts of different coupling schemes on the overall performance of the unit. Based on this, the power supply costs of different coupling schemes are analyzed. This research provides

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valuable references for the future development of solar-assisted oxygen-enriched high backpressure heating units.

## 2. Integration Scheme

This paper selects a 300 MW unit in Inner Mongolia with primary reheating and a natural circulation drum boiler. The boiler model is DG1065/18.2-II6, and the steam turbine model is CZK300/248-16.7/0.4/538/538. It adopts direct air cooling, and the regenerative system is composed of three stage high pressure heaters, three stage low pressure heaters, and one deaerator. The comparison results between the design parameters and simulation parameters of the unit are shown in Table 1.

Table 1 Comparison of main parameters between the design values and simulation values of conventional and oxygen enriched power generation units

| Parameter | Design value of the conventional unit | Simulation value of the conventional unit | Simulation value of the oxygen-enriched unit |
|---|---|---|---|
| Generating power/MW | 300 | 300 | 300 |
| Main steam temperature/℃ | 538 | 538 | 538 |
| Main steam flow rate/(t·h$^{-1}$) | 946.35 | 946.35 | 946.35 |
| Reheated steam temperature/℃ | 538 | 538 | 538 |
| Air supply volume /(Nm$^3$·h$^{-1}$) | 976407.27 | 976407.27 | amount of oxygen 159400.57 Circulating air volume 366853.27 |
| Boiler flue gas exhaust temperature/℃ | 127 | 127.02 | 218.91 |
| Coal consumption/(t·h$^{-1}$) | 141.87 | 141.87 | 139.09 |

### 2.1 Solar Energy Is Connected In Parallel With The Heating Network Heater (Scheme 1)

In Scheme 1, the solar collector is connected in parallel with the heating network heater. Part of the heating network water that has been heated by the heating network condenser is led into the solar energy collection field, and the remaining part flows into the heating network heater to be heated. The two parts of the working medium are heated to the same parameters, converge, and then are sent to the users. As shown in Figure 1.

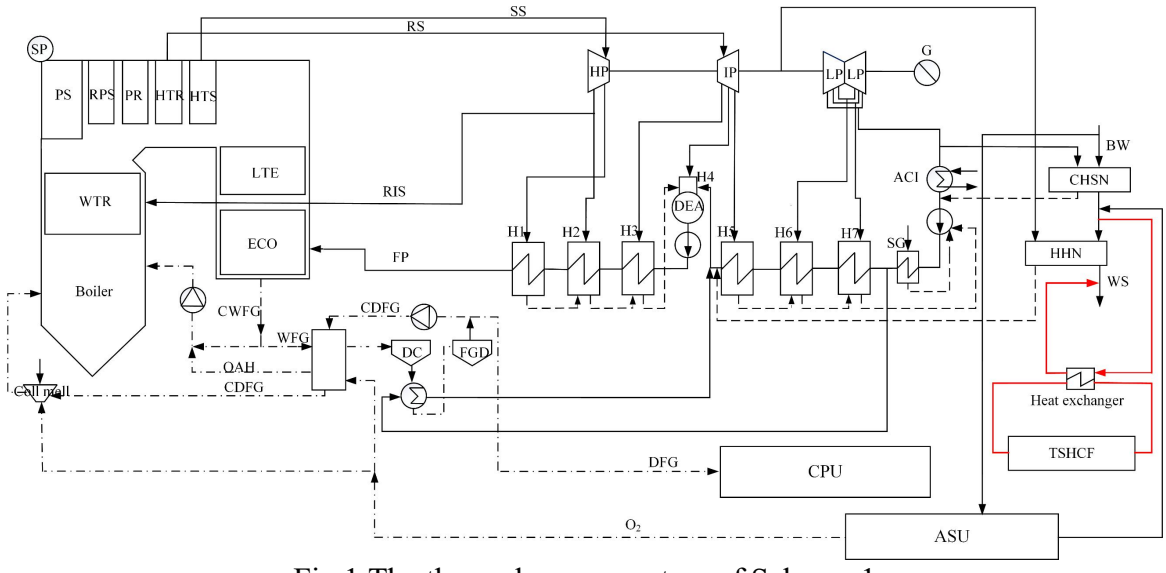


Fig.1 The thermal power system of Scheme 1

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## 2.2 Solar Energy Is Connected In Parallel With The High-Pressure Heater (Scheme 2)

In Scheme 2, the solar collector is connected in parallel with High-pressure Heaters No. 1 to No. 3. Part of the working medium is led into the solar energy collection field from the outlet of the feed water pump, and the remaining part continues to enter the regenerative heating system for heating. After the two parts of the working medium are heated to the same parameters, they are combined and conveyed to the boiler. The entire system is shown in Figure 2.

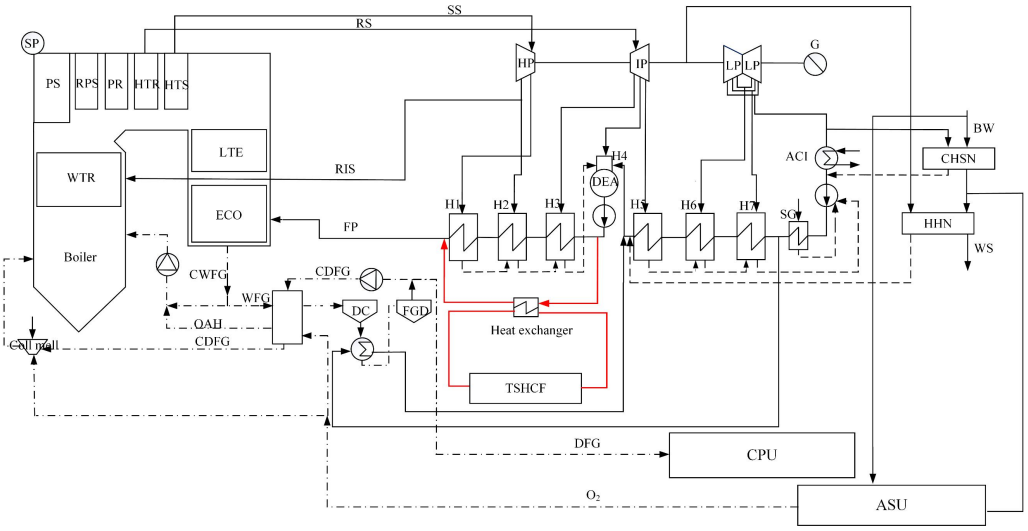



Fig.2 The thermal power system of Scheme 2

## 2.3 Solar Energy Is Connected In Parallel With Both The High-Pressure Heater And The Heating Network Heater (Scheme 3)

In Scheme 3, the solar collector is connected in parallel with high pressure Heaters No. 1 to No. 3 and the heating network heater respectively. Part of the working medium is led from the outlet of the feed water pump into the oil-water heat exchanger 1, and the remaining part continues to enter the regenerative heating system for heating. After the two parts of the working medium are heated to the same parameters, they are combined and conveyed to the boiler. Part of the heating network water is led from the outlet of the heating network condenser into the oil-water heat exchanger 2, and the remaining part enters the heating network heater for heating. After the two parts of the heating network water are heated to the same parameters, they are combined and sent to the users. The entire system is shown in Figure 3.

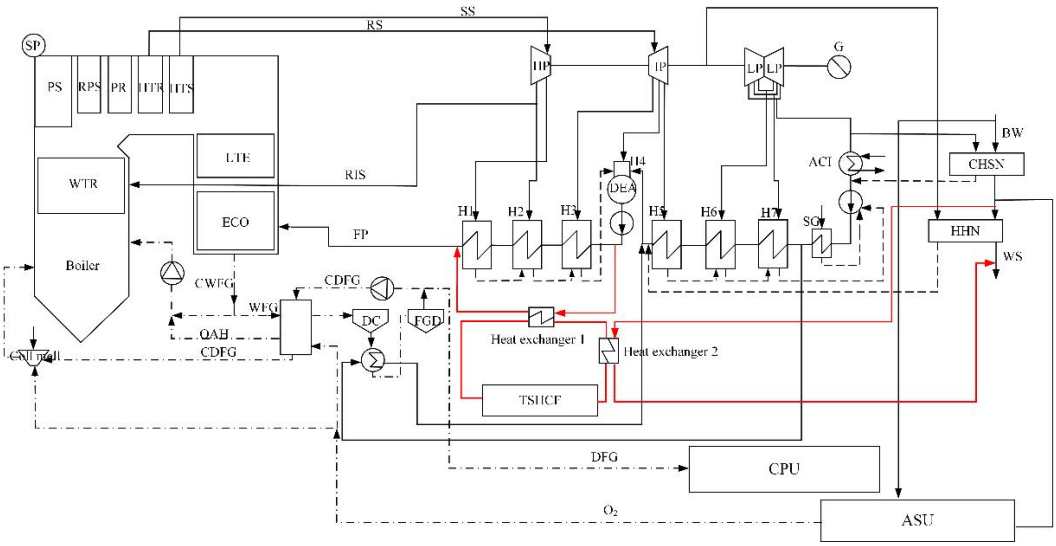



Fig.3 The thermal power system of Scheme 3

ISSN: 3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.4.1.P119

# 3. Evaluation Index

## 3.1 Standard Coal Consumption Rate For Power Supply

The calculation formula for the total energy consumption of the unit is as follows:

$$E_s = E_{ASU} + E_{CPU} + E_{FEC} \tag{1}$$

In the formula: $E_s$ is the total energy consumption during the unit operation,MW; $E_{ASU}$ is the energy consumption of the air separation unit,MW; $E_{CPU}$ is the energy consumption for flue gas compression and purification,MW; $E_{FEC}$ is the energy consumption of the electrical equipment in the power plant,MW.

The calculation formula for the total heat consumption of the thermal power plant is as follows:

$$Q_{tp} = \frac{B_{coal} Q_{net}}{3600} \tag{2}$$

In the formula: $Q_{tp}$ represents the total heat consumption of the thermal power plant,MW; $B_{coal}$ represents the total hourly fuel consumption of the thermal power plant,t/h; $Q_{net}$ represents the net calorific value of the fuel,kJ/kg.

The calculation formula for the power supply capacity is as follows:

$$W_{ps} = W_f - E_s \tag{3}$$

In the formula: $W_{ps}$ is the power supply capacity of the unit,MW; $W_f$ is the power generation capacity of the unit, in MW.

The calculation formulas for the thermal efficiency in terms of power supply and the standard coal consumption rate for power supply are as follows:

$$Q_{tp,f} = Q_{tp} - Q_{tp,h} \tag{4}$$

$$\eta_{tp,ps} = \frac{W_{ps}}{Q_{tp,f}} \tag{5}$$

$$b_g = \frac{123}{\eta_{tp,ps}} \tag{6}$$

In the formula: $Q_{tp,f}$、$Q_{tp,h}$ are respectively the heat consumption in power generation and the heat consumption in heat supply,MW; $\eta_{tp,ps}$ is the thermal efficiency of power supply,%; $b_g$ is the standard coal consumption rate for the power supply of the unit,g/(kW·h).

## 3.2 Standard Coal Consumption Rate For Heat Supply

$$\beta_h = \frac{E_h}{E_h + W_f} \tag{7}$$

$$b_h = \frac{1000 \beta_h B}{Q_h} \tag{8}$$

In the formula: $\beta_h$ is the exergy ratio of heat supply,%; $b_h$ is the standard coal consumption rate for heat supply,kg/GJ; $B$ is the standard coal consumption for power generation,kg/s; $Q_h$ is the heat supply capacity of the unit,MW.

## 3.3 Solar Energy Conversion Efficiency And Exergy Efficiency

$$\eta_s = \frac{Q_{h,s} + P_{e,s}}{Q_s} \tag{9}$$

$$\eta_{s,s} = \frac{E_{h,s} + p_{e,s}}{E_s} \tag{10}$$

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In the formula: $\eta_s$ is the solar energy conversion efficiency,%; $Q_{h,s}$ is the solar heat supply power, MW; $p_{e,s}$ is the difference in the power generation capacity of the unit before and after integrating solar energy,MW; $Q_s$ is the solar input power,MW; $\eta_{s,s}$ is the solar exergy efficiency, %; $E_{h,s}$ is the solar thermal exergy output by the system,MW; $E_s$ is the solar input exergy,MW.

## 4. Performance Analysis of Different Coupling Methods

### 4.1 Comparison Between The Standard Coal Consumption Rate For Power Supply And The Standard Coal Consumption Rate For Heat Supply

Different coupling schemes will have an impact on the thermal indicators of the unit, such as the standard coal consumption rate for power supply, the standard coal consumption rate for heat supply, the solar energy conversion efficiency, and the exergy efficiency. See Figures 4 and 5.

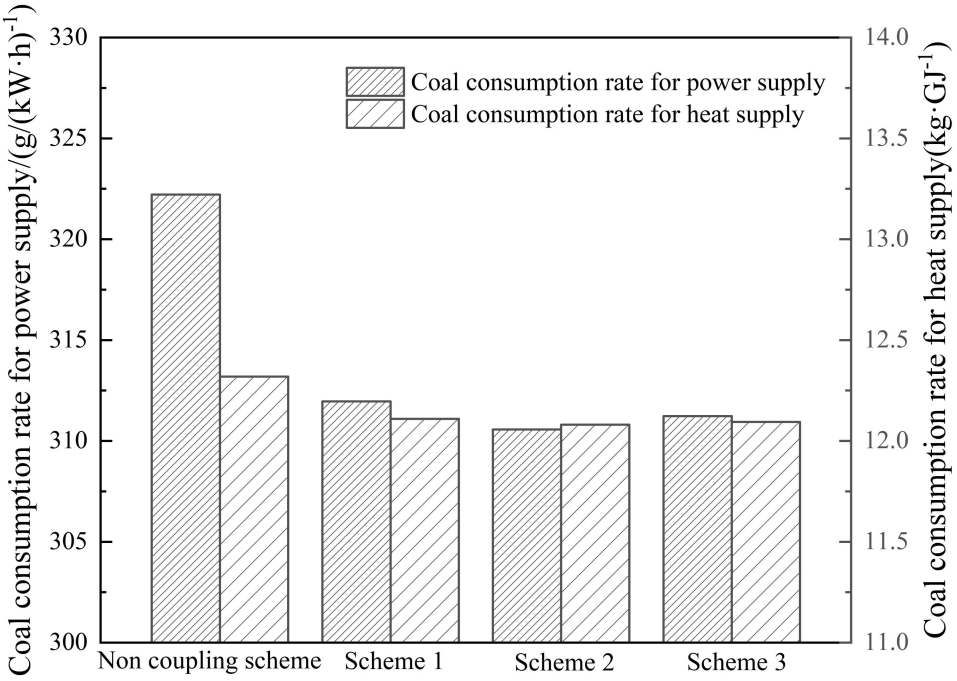



Figure 4: Comparison Chart of the Standard Coal Consumption Rate for Power Supply and the Standard Coal Consumption Rate for Heat Supply under Different Schemes

Figure 4 shows the comparison of the standard coal consumption rate for power supply and the standard coal consumption rate for heat supply under different coupling schemes. The standard coal consumption rates for power supply of the four schemes are 322.21 g/(kW·h), 311.96 g/(kW·h), 310.57 g/(kW·h), and 311.23 g/(kW·h) respectively. The standard coal consumption rates for heat supply of the four schemes are 12.32 kg/GJ, 12.11 kg/GJ, 12.08 kg/GJ, and 12.09 kg/GJ respectively. It can be seen that compared with the non-coupling scheme, the standard coal consumption rates for power supply and heat supply of the three coupling schemes are all reduced, and Scheme 2 has the lowest values.

Due to the incorporation of solar energy, when the heat supply load remains unchanged, solar energy replaces a part of the extracted steam, resulting in a reduction in the extracted steam volume of the unit. The steam flow rate inside the steam turbine increases, and more steam enters the turbine to do work. The generating power of the units in Scheme 1 to Scheme 3 increases. With the total energy consumption remaining the same, the power supply capacity of the unit increases, the power supply thermal efficiency increases, and the standard coal consumption rate for power supply decreases. The exergy ratio of heat supply decreases, and thus the standard coal consumption rate for heat supply decreases. After integrating solar energy in Scheme 2, the flow rate of high

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temperature heat supply extracted steam of the unit increases. The steam after heat exchange in the heat network heater enters the outlet of the fifth-stage heat exchanger. Compared with Scheme 1 and Scheme 3, the flow rate of low-pressure regenerative extracted steam in Scheme 2 is smaller, and the reduction range of the standard coal consumption rates for both power supply and heat supply of the unit is the largest.

### 4.2 Comparison Between The Solar Energy Conversion Efficiency And The Exergy Efficiency

Figure 5 shows the comparison of the solar energy conversion efficiency and the solar exergy efficiency under different coupling schemes. The solar energy conversion efficiencies of Scheme 1 to Scheme 3 are 41%, 41.84%, and 41.44% respectively, and the solar exergy efficiencies of Scheme 1 to Scheme 3 are 12.85%, 22.49%, and 18.52% respectively. It can be seen that compared with the non - coupling scheme, both the solar energy conversion efficiency and the exergy efficiency of the three coupling schemes are reduced, and Scheme 2 has the lowest values.

When the solar energy system absorbs the same amount of heat, in Scheme 2, the generating power of the unit is greater than that in Scheme 1 and Scheme 3. The sum of the generating power and the heat - supply power in terms of solar energy is the largest among the three schemes, and the solar energy conversion efficiency is the highest. In Scheme 2, the sum of the generating power and the heat supply exergy in terms of solar energy is greater than that in Scheme 1 and Scheme 3, and the solar exergy efficiency is the highest.

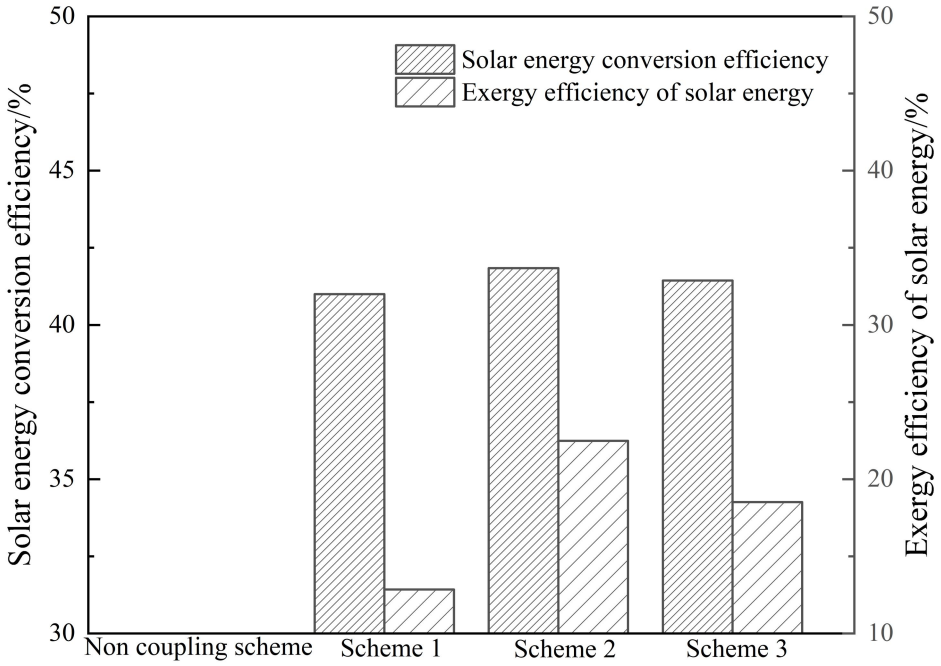


Figure 5: Comparison chart of solar energy conversion efficiency and solar exergy efficiency under different schemes

### 4.3 Exergy Analysis Of Different Coupling Methods

An exergy analysis was conducted on different coupling schemes of the solar-assisted high-back-pressure heating unit, and the results are presented in Table 2. After integration, the input exergy of the boiler and the input exergy of the air separation unit remain the same, and the input exergy of

solar energy is 13.19 MW. Through comparison, it is found that in Scheme 2, as solar energy replaces part of the extraction steam for the high-pressure heater, the exergy loss of the high-pressure

Table 2 Comparison of exergy parameters of various coupling schemes

| Parameter | Scheme 1 | Scheme 2 | Scheme 3 |
|---|---|---|---|

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| | | | |
|---|---|---|---|
| Input exergy of the boiler/MW | 737.46 | 737.46 | 737.46 |
| Input exergy of solar energy/MW | 13.19 | 13.19 | 13.19 |
| Input exergy of the air separation unit /MW | 5.86 | 5.86 | 5.86 |
| Exergy of power generation output /MW | 263.895 | 264.615 | 264.313 |
| Exergy of heat supply output /MW | 45.03 | 45.03 | 45.03 |
| Exergy loss of the boiler /MW | 346.14 | 346.14 | 346.14 |
| Exergy loss of the generator /MW | 3.855 | 3.866 | 3.861 |
| Exergy loss of the steam turbine /MW | 25.01 | 28.06 | 27.66 |
| Exergy loss of the regenerator /MW | 4.79 | 4.09 | 4.38 |
| Exergy loss of the condenser /MW | 31.518 | 31.416 | 31.457 |
| Exergy loss of the heat network /MW | 23.682 | 20.7 | 21.079 |
| Plant electricity consumption /MW | 12.59 | 12.59 | 12.59 |
| Energy consumption of the air separation unit /MW | 58.37 | 58.37 | 58.37 |
| Energy consumption of flue gas compression /MW | 31.59 | 31.59 | 31.59 |
| Total exergy loss /MW | 447.59 | 446.87 | 447.17 |

heater regenerator decreases. In Scheme 2, since solar energy is used to heat the feed water, the direct heat exchange temperature difference between more heat network water and steam in the heat network heater is reduced. Compared with heating the heat network water with solar energy, the energy transfer method is more reasonable. Therefore, the exergy loss of the heat network part is lower than that of Scheme 1 and Scheme 3.

In Scheme 1 and Scheme 3, as solar energy is used to heat part of the heat network water, the exhaust steam increases with the decrease of the extraction steam for heating, resulting in an increase in the exergy loss of the condenser. Therefore, the total exergy loss of the unit is greater than that of Scheme 2. Scheme 2 has the minimum total exergy loss and the highest total exergy conversion efficiency.

## 5. Summary

(1) Scheme 2, which involves the parallel connection of solar energy and the high-pressure heater, is the optimal solar energy coupling scheme.

(2) When the optimal coupling scheme is adopted, the power supply coal consumption rate of the unit is reduced by 11.64 g/(kW·h), the heating standard coal consumption rate is decreased by 0.238 kg/GJ, and the solar energy conversion efficiency and exergy efficiency are 41.84% and 22.49% respectively.

(3) Exergy losses of different coupling schemes occur at different positions of the unit, and the unit in Scheme 2 has the highest total exergy efficiency.

(4) Compared with the conventional extraction steam heating unit, Scheme 2 has the lowest power supply and heating costs.

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