Economic Benefit Evaluation of Waste Heat Recovery in Coal-fired CHP System Based on Exergoeconomic Analysis

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Abstract: As one of the main energy-saving measures and an important part of the power industry, CHP (combined heat and power) has achieved rapid development in recent years, which have the advantages of low heat loss, flexible operation mode, and cascade utilization of energy compared with heating boilers and traditional power plants. However, there is a lack of reasonable evaluation of CHP systems, due to the difference in energy quality of heat and electricity. It is urgent to establish considerable and reasonable evaluation indexes of CHP systems. In addition, in the actual operation of CHP plant, a large amount of waste heat is released into the environment, and there is still room for further improvement in the waste heat utilization. In this paper, an exergoeconomic analysis model of CHP system with circulating fluidized bed boiler is established, and the economic benefits of waste heat recovery in CHP systems are studied. After the application of waste heat recovery, the system exergy efficiency increased from 32.94% to 34.14%. The unit exergoeconomic cost of electricity and process steam did not change much, but the unit exergoeconomic cost of heating decreased by 17.1%, which indicates the economic benefits of waste heat recovery.

1. Introduction
With the in-depth development of haze control in China, CHP has gradually become one of the important measures to replace coal-fired boilers and solve the problem of loose coal pollution, and has been vigorously promoted by all sides. Due to the coal-based energy structure in China, the development trend of coal-fired CHP (combined heat and power) plant was accelerated in recent years, and the unit capacity has been increasing, which will be the main way of central heating in northern China in the future. Although the thermal efficiency of CHP is significantly improved compared to traditional power plants, in the operation of CHP plants, a large amount of waste heat is released into the environment, and there is still room for further improvement in the overall energy efficiency. The waste heat resources generated during the operation of CHP plants mainly include flue gases, boiler bottom ash, and exhaust steam, etc. The flue gases released from the boiler is generally between 120 °C - 150 °C. When the gas temperature is increased by 10 °C, the increased heat loss is close to 1%. Due to the ash content of coal and the insufficient combustion, there is a large amount of unused waste heat in the high temperature ash discharged from the boiler with high-grade temperature. For example, circulating fluidized bed boiler generally burns the lignite with poor quality and high ash content, and discharges large amount of ash. The hot ash discharged from the bottom of the boiler is usually around 950 °C. In addition, the heat of exhaust steam from the steam turbine in power plant accounts for about 35% - 60% [1] of the total input energy. This part of heat is finally discharged into the environment through the cooling tower.
The grade of the waste heat carried by the circulating cooling water of the cooling tower is low, but the total amount is large, and it can be extracted by heat pumps to preheat the return water and reduce steam extraction.

Due to the difference in energy quality of heat and electricity, the reasonable evaluation of CHP systems has become a difficult point, and it is urgent to establish a reasonable evaluation index of CHP systems. In addition, the improvement of overall exergy efficiency through waste heat recovery is based on the increase of investment, and it is necessary to consider both energy conversion efficiency and investment cost. Therefore, this paper conducts a comprehensive analysis of waste heat recovery of coal-fired CHP system based on exergoeconomic method, and provides a theoretical basis for the energy-saving reconstruction of power plants.

Table 1. Waste heat resources.

| Resources     | Initial temperature | Final temperature | Specific heat capacity | Mass flow rate | Heat flow |
|---------------|---------------------|-------------------|------------------------|----------------|-----------|
| Bottom ash    | 890 °C              | 150 °C            | 1.0421                 | 40.37 t/h      | 8.65 MW   |
| Flue gas      | 137 °C              | 97 °C             | 0.8556                 | 1335.86 t/h    | 12.70 MW  |
| Cooling water | 37.27 °C            | 28 °C             | -                      | 12000 t/h      | 129.13 MW |

Figure 1. Waste heat profile for the CHP system.

2. Waste Heat Resources and Potential of CHP systems

The summary of waste heat resources of the case plant is shown in Table 1. The heat flows of the three waste heat resources are 8.65 MW (boiler bottom ash), 12.7 MW (boiler flue gas) and 129.13 MW (circulating cooling water), respectively. In this case, the released flue gases are generally below 140 °C. Except the corrosion caused by the acidic compounds in the flue gases, the cold source temperature must be below the flue gas dew point temperature, so that the latent heat of the flue gas can be recovered. When the moisture content of the flue gas is high, the dew point temperature is very low (for example, when the humidity is 0.11 kg/kg, the dew point temperature is only 57.5 ° C), and the initial temperature of the cold source (such as heating return water) is generally above 50 ° C. In this case, there is little space for heat recovery. The waste heat profile [2,3] is obtained by plotting the data in Table 1. As shown in Figure 1, the horizontal axis represents the heat flows and the vertical axis represents the corresponding temperature range. It can be seen from the figure that the temperature of the boiler bottom ash is the highest among the three waste heat resources. Generally, the discharged ash of the circulating fluidized bed boiler can reach about 900 ° C, which can be cooled to below 150 ° C by the ash cooler. The outlet temperature of circulating cooling water from condenser is about 38 ° C, then it enters the cooling tower and is cooled to 27 ° C. About 129 MW of low temperature waste heat is released into the environment in this process, which is the largest among the three waste heat resources.
3. Waste Heat Recovery System Models of CHP Systems

The structure of the waste heat recovery in CHP system is shown in Figure 2, which uses rolling-cylinder ash cooler and absorption heat pump to recover the waste heat of the boiler bottom ash and exhaust steam, respectively. It is composed of 24 equipments: Boiler, high pressure cylinder (HPT), intermediate pressure cylinder (IPT), low pressure cylinder (LPT), boiler feed pump turbine (BFPT), condensate pump (CONP), gland condenser heater (GC), low pressure heater (LPH), deaerator (DEA), feed water pump (FWP), high pressure heater (HPH), steam user, absorption heat pump (AHP), steam to water heat exchanger (SWHE), rolling-cylinder ash cooler (RAC), generator (GEN), condenser (CON) and two dissipative units (Stack). The case plant has a 1025 t/h circulating fluidized bed boiler and a supporting 300 MW unit. The circulating fluidized bed boiler has a large amount of ash discharge with high temperature. The ash discharge at high temperature is not easy to handle and transport. Therefore, it is necessary to use the ash cooler to cool the hot ash, and the waste heat of the bottom ash can be recovered to increase the temperature of the feed water. In addition, the heating extraction temperature is relatively high (246.7 °C, 0.39 MPa), while the temperature of the return water from heating network is only 56.2 °C. There is a serious energy level mismatch, and the exergy loss is great during the heat exchange process, so it is necessary to preheat the return water to reduce the heat transfer temperature difference of the heat exchanger. A part of the heating steam is extracted to drive the absorption heat pump, and the heat of the circulating cooling water can be recovered to produce hot water at about 86 °C. In this case, the purpose of preheating the return water and reducing the heat transfer temperature difference of the heat exchanger is achieved.

![Figure 2. The integration of the RAC and AHP in the CHP system.](image)

3.1 Rolling-cylinder Ash Cooler (RAC)

Four sets of GTL15C-20*L rolling-cylinder ash coolers are used, which are composed of inner cylinder and outer cylinder. The single bottom ash processing capacity is 25 t/h, with a 15 kW motor. After the bottom ash of the boiler enters the ash cooler from the inlet, the spiral blade inside the cylinder is pushed towards the outlet. The bottom ash exchanges heat with the boiler feed water arranged in the counterflow in the outer cylinder during the moving process, thereby achieving the purpose of reducing the ash temperature and recovering the waste heat.

3.2 Absorption Heat Pump (AHP)

The circulating cooling water in the case plant has low temperature, large flow, and carries a large amount of low-grade waste heat, which can be recovered by the AHP to preheat return water. In this case, the steam extraction from the turbine can be reduced. This part of steam can continue to work in the steam turbine to increase the system power generation and improve the overall energy efficiency [4, 5].
The basic principle of the single-effect absorption heat pump is shown in Figure 3. It mainly includes five heat exchange units (generator, absorber, condenser, evaporator and solution heat exchanger, solution pump and throttle valve). In the case plant, a part of the heating steam is used as the heat source of the absorption heat pump, which absorbs the waste heat of circulating cooling water. The pressures of the evaporator and the condenser were 3.4 kPa and 53.4 kPa. The heat load of the generator is 99.09 MW, and the generation temperature is 141.8 °C. The LiBr solution (4) is heated in the generator to generate refrigerant vapor (8). The concentration of the remaining solution (7) is increased to 62.54%. After exchanging heat with the diluted solution (3), it enters the absorber to absorb the refrigerant vapor (1) from the evaporator, and the concentration is reduced to 58.61% with heat output. The released heat is used for the heating of the return water from heating network. The condensed water (9) is depressurized and then enters the evaporator. It is heated by the circulating cooling water to a saturated steam state (1), and then enters the absorber to complete the cycle. After being heated in the absorber and condenser, the temperature of the return water is raised from 56.2 °C to 86.16 °C, and then entered into the heat exchanger to be heated to the required temperature. The total investment cost of the heat pump system in the case plant is 78.2 million RMB.

![Figure 3. The schematic diagram of single-effect absorption heat pump.](image)

4. Exergoeconomic Analysis

4.1 Exergy Cost Formation

In order to allocate the waste heat cost to the final product, it is necessary to determine the source of the waste heat. After the fuel products of each equipment and the production structure of the system are determined, the external resources consumed in the production process and the cost of the waste generated are distributed to the final product according to the production structure. According to the literature [6-9], the exergy cost of the equipment product is equal to the exergy cost of the fuel plus the allocated waste cost, as shown in equation (1).

$$C_{P,i} = C_{F,i} + C_{R,i}$$

(1)

Where, \( C_{P,i} \), \( C_{F,i} \), and \( C_{R,i} \) represent the product cost, fuel cost, and allocated waste cost of equipment \( i \). The fuel cost can be divided into two parts, one is from the resources outside the system boundary, and the other is the product of other equipment (equipment \( j \)), which is represented by \( C_{e,i} \) and \( C_{j,i} \) in equation (2).

$$C_{F,i} = C_{e,i} + \sum_j C_{j,i} = C_{e,i} + \sum_j E_{j,i} \eta_{j,i} C_{P,j} = C_{e,i} + \sum_j \eta_{j,i} C_{P,j}$$

(2)

The allocation coefficient of the waste cost is defined as \( \psi_{i,r} \), which means the percentage of waste cost generated by the dissipative equipment \( r \) in the total cost of equipment \( r \), and the waste cost of equipment \( i \) is:

$$C_{R,i} = \sum_r C_{r,i} = \sum_r \psi_{i,r} C_{P,r}$$

(3)

Regarding the determination of the waste cost’s allocation coefficient \( \psi_{i,r} \), the method in Ref. [7] is
used in this paper. Then, the equations (2) and (3) are substituted into the equation (1) to obtain the exergy cost balance equation of the device \(i\).

\[
C_{P,i} - \sum_j \kappa_{ij} C_{P,j} - \sum_r \psi_{ir} C_{P,r} = C_{e,i}
\]

(4)

4.2 Exergy Cost Calculation in Matrix Mode

Applying the exergy balance equation from the previous section to each device in the system yields a series of linear equations that can be represented in matrix form, as shown in equations (5) and (6),

\[
(U_D - \langle KP \rangle - \langle KR \rangle C_p) = C_e
\]

(5)

\[
C_p = (U_D - \langle KP \rangle)^{-1} (C_e + \langle KR \rangle C_p)
\]

(6)

where \(U_D\) is a unit matrix, and both \(\langle KP \rangle\) and \(\langle KR \rangle\) are square matrices, the elements of which are the product cost allocation coefficient \(\kappa_{ij}\) and the waste cost allocation coefficient \(\psi_{ir}\). Then, the operator \(C_R = \langle KR \rangle C_p\) and \(\langle P^* \rangle = (U_D - \langle KR \rangle)^{-1}\) are defined to simplify the equation and get the equation (7).

\[
C_p = \langle P^* \rangle (C_e + C_R) = C_{pe} + C_{pR}
\]

(7)

It can be seen from the above formula that the product exergy cost in the system is divided into two parts: external resource exergy cost \((C_{pe})\) and waste cost \((C_{pR})\). Before establishing the economic analysis model, it is necessary to obtain the investment cost of the main equipment according to the cost estimation method and to annualize it, that is, to equalize the annual service life of the asset to the annual amount, as shown in equation (8) and (9), where \(Z_i\) is the annualized cost of equipment \(i\); \(CRF\) is the capital recovery coefficient, calculated by equipment life \(N\) and interest rate \(IR\); \(\phi\) is the system maintenance factor; \(num\) is the annual operation hours.

\[
Z_i = IC_i \cdot CRF \cdot \phi/(N \cdot num)
\]

(8)

\[
CRF = \frac{IR(1+IR)^N}{(1+IR)^N-1}
\]

(9)

The equipment annualized cost vector \(Z\) and the resource consumption cost vector \(C^*_e\) are brought into equation (7), and the exergoeconomic cost balance equation is shown in equation (10), where \(C^*_e\) is a vector, representing the exergoeconomic cost of each system equipment product; \(C^*_e\) represents the unit cost of external resources; \(C^*_r\) represents the unit cost unit of waste. In this paper, the flue gases treatment cost is included in the economic analysis category, which is included in equation (11). \[10^{11,12}\]

\[
C^*_p = \langle P^* \rangle (C^*_e + C^*_r + Z) = C^*_{pe} + C^*_{pR} + C^*_{pZ}
\]

(10)

\[
C^*_p = \langle P^* \rangle (C^*_e + C^*_r + Z + G) = C^*_{pe} + C^*_{pR} + C^*_{pZ} + C^*_{pG}
\]

(11)

5. Exergoeconomic Analysis Results

The exergoeconomic analysis results of the case plant with and without waste heat recovery are shown in Table 2. The second column in the table is the equipment investment cost \((Z)\), and the unit exergy cost of fuel and product are respectively represented by \(c_{r,i}\) and \(c_{r,i}^*\). \(f_i\) and \(r_i\) represent the exergoeconomic factors and relative cost differences\([13]\). It can be seen from the data that the relative cost difference of the boiler is the largest and has the greatest potential for improvement. In the case of no waste heat recovery, the relative cost difference \(r_i\) of the steam-water heat exchanger (SWHE) is 1.0871, which is only second to the boiler’s 1.4986. In the waste heat recovery case, the relative cost difference of SWHE is only 0.6774. In the case of that the investment cost is unchanged, this shows that the cost increase caused by the irreversibility inside the equipment is reduced, that is, the cost of the equipment to produce the same product (the irreversibility in the production process) is reduced. The reason is that the return water is preheated by the absorption heat pump and then enters the heat exchanger. In this case, the heat exchange temperature difference and exergy dissipation are reduced, and the performance of the heat exchanger is significantly improved. In addition, after the application of the ash cooler, the performance of LPH4 is also improved.
Table 2. Exergoeconomic analysis results.

|       | Base case |          |          | Recovery case |          |          |
|-------|-----------|----------|----------|---------------|----------|----------|
|       | $c_{p,i}$ | $f_i$    | $r_i$    | $c_{p,i}$    | $f_i$    | $r_i$    |
|       | RMB/h     | RMB/kWh  | RMB/kWh  | RMB/h        | RMB/kWh  | RMB/kWh  |
| Boiler| 0.2422    | 0.0746   | 0.1862   | 0.0067       | 1.4986   | 0.0746   |
| HPT   | 0.6085    | 0.1967   | 0.2304   | 0.0202       | 0.1708   | 0.1928   |
| IPT   | 0.8474    | 0.1967   | 0.2159   | 0.0379       | 0.0982   | 0.1928   |
| LPT   | 0.1720    | 0.1967   | 0.3255   | 0.0069       | 0.6552   | 0.1928   |
| BFT   | 0.974     | 0.1967   | 0.2436   | 0.0284       | 0.2387   | 0.1928   |
| CONP  | 0.17      | 0.2337   | 0.3142   | 0.0070       | 0.3436   | 0.2337   |
| GC    | 0.34      | 0.1967   | 0.3030   | 0.0075       | 0.5398   | 0.1928   |
| LPH1  | 0.91      | 0.1967   | 0.2462   | 0.0485       | 0.2528   | 0.1928   |
| LPH3  | 0.91      | 0.1967   | 0.2528   | 0.0242       | 0.2847   | 0.1928   |
| LPH2  | 0.91      | 0.1967   | 0.2654   | 0.0109       | 0.3473   | 0.1928   |
| LPH1  | 0.91      | 0.1967   | 0.2872   | 0.0016       | 0.4580   | 0.1928   |
| DEA   | 0.92      | 0.1967   | 0.2205   | 0.0171       | 0.1210   | 0.1928   |
| FWP   | 0.2778    | 0.2436   | 0.3228   | 0.0649       | 0.3235   | 0.2363   |
| HPH3  | 0.14      | 0.1967   | 0.2377   | 0.0032       | 0.2085   | 0.1928   |
| HPH2  | 0.14      | 0.1967   | 0.2410   | 0.0016       | 0.2246   | 0.1928   |
| HPH1  | 0.14      | 0.1967   | 0.2548   | 0.0013       | 0.2961   | 0.1928   |
| User  | 0         | 0.1967   | 0.1967   | 0            | 0.1928   | 0.1928   |
| AHP   | 0.6090    | -        | -        | 0            | 0.2403   | 0.3486   |
| SWHE  | 0         | 0.1967   | 0.4106   | 0            | 1.0871   | 0.3235   |
| RAC   | 1.35      | -        | -        | -            | 0.1809   | 0.8992   |
| GEN   | 36.99     | 0.2311   | 0.2337   | 0.0666       | 0.0108   | 0.2311   |
| CON   | 16.07     | 0.1961   | 0.4549   | 0.0200       | 1.3164   | 0.1921   |
| Stack1| 0         | 0.1862   | 0.1862   | -            | 0.1802   | 0.1802   |
| Stack2| 0         | -        | -        | -            | 0.8992   | 0.8992   |

The comparison of exergy efficiency and unit exergoeconomic cost is shown in Figure 4. The heat output of the CHP plant includes process steam and hot water. The steam turbine extraction is directly supplied to the process user. The hot water is heated by the steam extracted from the steam turbine. In addition, in the waste heat recovery case, the absorption heat pump also provides a part of the heating load, so the average cost of the hot water is calculated by the exergy value, as shown in equation (12).

$$c_{hw}^* = (c_{p,AHP}^* \cdot E_{AHP} + c_{p,SWHE}^* \cdot E_{SWHE})/(E_{AHP} + E_{SWHE})$$

After the application of waste heat recovery, the overall exergy efficiency of the system increased from 32.94% to 34.14%. The process steam cost decreased slightly from 0.20 RMB/kWh fell to 0.19 RMB/kWh, and the cost of hot water decreased greatly, from 0.41 RMB/kWh to 0.34 RMB/kWh. The economic model includes fuel cost, waste cost, flue gas treatment cost, and operation cost including waste heat recovery equipment. Therefore, the economic benefits of waste heat recovery can be indicated by the unit exergoeconomic cost comparison.
6. Conclusion

In this paper, models of waste heat recovery based on rolling-cylinder ash cooler and absorption heat pump are established, and the economic benefits of waste heat recovery are studied through exergoeconomic analysis. Among them, the rolling-cylinder ash cooler is used to recover the waste heat of the bottom ash. The absorption heat pump is driven by the steam turbine extraction steam to recover the waste heat of the circulating cooling water and preheat the return water. The analyzing result of the base case (no waste heat recovery) and the waste heat recovery case (applying the rolling-cylinder ash cooler and the absorption heat pump) shows that the system exergy efficiency is increased from 32.94% to 34.14%, and the performance of the heat network heat exchanger has been significantly improved. The unit cost of hot water has dropped from 0.41 RMB/kWh to 0.34 RMB/kWh, of which a decrease of 17.1%. As indicated by the analysis result, further optimization of heat integration is the improvement direction of the CHP system.

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