RESEARCH ARTICLE OPEN ACCESS

Research on Energy Utilization and Scheme Optimization of a 50MW Combined Cycle Power Plants Unit in an Iron and Steel Plant Based on Exergy Analysis

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ABSTRACT
Combined cycle power plant (CCPP) is widely used in many iron and steel plants to recover the residual energy of gases as a by-product of the steelmaking process. However, in the actual power generation process the unit also experiences a significant energy loss. In this paper, a 50MW combined cycle power plants unit of an iron and steel plant is taken as the research object, and the second law of thermodynamics is used as the basis to establish the thermodynamic model of the unit and conduct an exergy analysis. The results show that the least exergy efficient of the actual operating power plants are the reflux gas section and the Turbine cool air （TCA） section. Its exergy efficiency is 0% and 65.69%. In order to optimize the exergy efficiency of the reflux gas and the TCA. In this paper, the pipeline before the condensate enters the HRSG is modified, and TCA and reflux gas are used to heat the condensate in stages. That is, the recovery of high-temperature air and high-temperature gas exergies, but also to increase the temperature of condensate into the HRSG. This improves the efficiency of the unit. 0.77 GJ/h of exergy recovered from the TCA. Recoverable exergy of the reflux gas is 111.33 GJ/h. After the modification, the exergy efficiency of the TCA was increased to 0.7250. The efficiency of the reflux gas increased to 0.9473. The overall exergy efficiency of the power plant improved from 0.2297 to 0.4132.

Keywords - exergy; efficiency; exergy destruction; TCA; reflux gas; energy saving

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Date of Submission: 18-11-2023 Date of acceptance: 03-12-2023

I. Introduction

Currently, a significant amount of recoverable waste energy remains, stemming from the energy generated during the iron and steel production process Energy loss is the primary cause of inefficiency, limiting the economic development of iron and steel plants[1-3]. Addressing energy loss recovery has become a crucial concern for energy conservation within iron and steel plants[4, 5].

In recent years, the evaluation of production efficiency in iron and steel plants has become a concern for many enterprises[6]. Common approaches to evaluating the thermo-economic performance of generation units can generally be categorized into two groups. One approach involves energy methods based on the first law of thermodynamics, such as the heat balance method and the equivalent enthalpy drop method, which are commonly employed for quantitative analysis. The second category is based on the second law of thermodynamics and encompasses thermoeconomics, among other methods.[7] These approaches are typically utilized for exergy analysis. The methodology of exergy analysis focuses on the irreversibility within the system and its capacity to perform work, better reflecting the actual performance of the unit's components. The exergy loss of each system component can quantify the level of deterioration within the component and reveal its actual thermal efficiency. This information can be invaluable for aiding in the design, analysis, and optimization of a system. M. Ameri [8] et al. conducted an exergy analysis for a 420MW CCPP to find the combustion chamber, which is the component with the highest exergy destruction in the CCPP, and proposed an improvement method to increase the combustion temperature of the combustion chamber, reduce the air leakage from the combustion chamber, and improve the exergy efficiency by making the fuel burn complete. Regulagadda P [9] et al. analyzed the boiler and turbine losses in thermal power plants by using the exergy analysis, and the results showed that: the boiler and the turbine are the parts of the plant where the largest irreversible losses are incurred. Cihan et al.[10] carried out energy and exergy analysis for a combined cycle located in Turkey and suggested modifications to decrease the exergy destruction in CCPPs. Their results showed that combustion chambers, gas turbines and HRSGs are the main sources of irreversibilities, representing over 85% of the overall exergy losses. Hang [11] et al. optimized the combined cycle power plants with the objective of minimum exergy consumption and optimal benefits. Ibrahim T K [12] et al. applied both energy analysis and exergy analysis to the performance analysis of a combustion engine power plant and the results similarly showed that the combustion chamber is the component with the highest losses, with the energy and exergy efficiencies of the whole plant being 34.3% and 32.4%, respectively. To improve the efficiency, additional fuel inlet. Karrabi and Rasoulipour [13] investigated the effect of make-up combustion on a combined cycle unit at different ambient temperatures and load conditions by using the methodology of exergy analysis. The results show that the supplementary combustion increases the total exergy losses and reduces the unit's exergy efficiency. Rosen and Dincer [14] studied industrial process heating with steam through exergy analysis, and concluded that exergy analysis should be used as a central tool in process optimization when large quantities of steam are used in energy centers. Via an exergy analysis of supplementary firing in a heat recovery steam generator in a combined cycle power plant. However, there are still certain limitations in the current research on CCPP. One limitation is that the research focuses on 300MW class or higher-power units, which are actual energy-consuming units in waste heat and energy recovery. However, energy recovery often falls short of meeting the demands of high-power generation[15]. Another limitation is that the exergy loss is only considered for the main components of the CCPP, overlooking additional losses during the unit's actual operation[16]. For instance, losses of high-temperature air and reflux gas in the TCA of the gas turbine component. In this research, a CCPP optimization model is developed, incorporating a heat exchanger to recycle and utilize high-temperature air and high-temperature reflux gas. These are directed to heat up the condensate after the gas compressor, thereby recycling exergy.

II. Research object

2.1. Research object and system parameters

The subject of this paper is an M251S combined cycle power plant located within an iron and steel plant. The thermal system structure of the plant is depicted in Figure 1. It includes a set of Hangzhou Automobile Company's M251S gas turbine (fueled by blast furnace gas), a condensate-supplemented steam turbine, and a double-pressure non-reheat HRSG. The gas turbine, steam turbine, and generator are interconnected by a single shaft. The gas turbine consists of an axial flow compressor with a pressure ratio of 12, a gas compressor with a pressure ratio of 11, and a combustion system consisting of eight low NO_X burners. The high-pressure superheater outlet in the boiler is equipped with a desuperheater to ensure the main steam temperature is not exceeded.

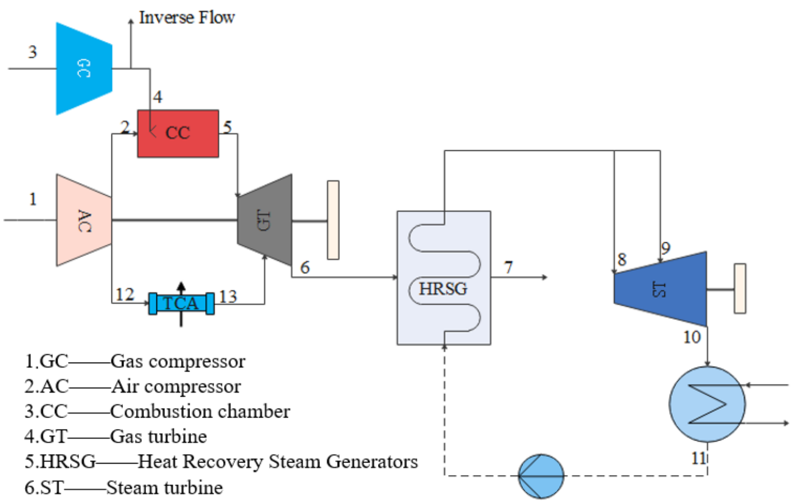

Fig. 1 Thermal system of 50MW CCPP unit before modification

The Table 1 shows the main thermal parameters at each point at full load.

Table 1 The main thermal parameters at each point at full load

Serial number	Name	Temperature /°C	Pressure /MPa	Flow rate /kg·h^{-1}
1	Air compressor inlet air	25	0.1	418500
2	Combustion chamber inlet air	365	1.0	382500
3	Gas compressor inlet gas	25	0.1	197000
4	Combustion chamber inlet gas	365	1.1	179024
5	Combustion chamber outlet flue gas	1104	1.0	560000
6	Gas turbine outlet flue gas	563	0.003	560000
7	Boiler outlet flue gas	110	0.003	560000

8	Steam Turbine Import High Pressure steam	480	5.88	86400
9	Steam turbine make-up steam low pressure steam	203	0.4	11200
10	Steam turbine outlet steam	45.3	0.0082	97600
11	Condenser outlet water	26	0.2	97600
12	TCA Inlet Air	365	1.0	36000
13	TCA outlet air	158	1.0	36000
14	Reflux gas	365	1.1	40000

This iron and steel plant use a double-pressure single-stage inlet boiler. The flue gas is directly discharged from the gas turbine into the HRSG. The flue gas passes through the high-pressure reheater 1, high-pressure superheater 2, high-pressure evaporator, high-pressure economizer, low-pressure superheater, low-pressure evaporator, low-pressure economizer, and feedwater preheater, respectively. The flue gas is then expelled through the stack. In contrast to other CCPP units employing double-pressure parallel distribution, the feedwater in the HRSG passes through the low-pressure pumps and the low-pressure economizer before branching off. A portion of the low-pressure water enters the low-pressure evaporator, while another portion enters the high-pressure drum boiler. From there, it enters the high-pressure economizer via pressure boosting from the high-pressure pumps. The thermal system diagram is depicted in Figure 2.

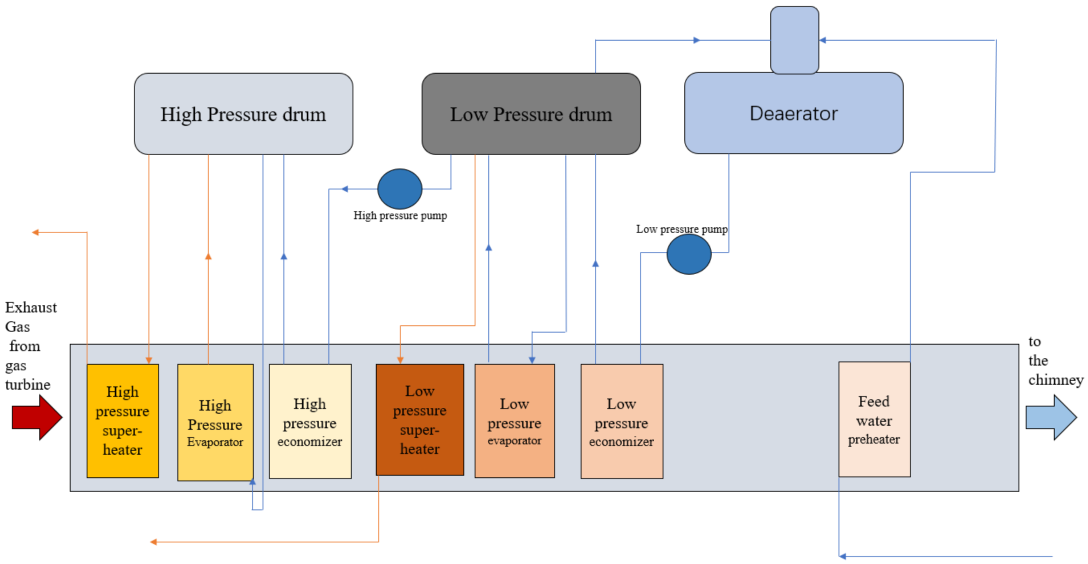

Fig. 2 Thermal system diagram of waste heat boiler

The molar fractions of air, flue gas and BFG are shown in Table 2.

Table 2 Molar fraction of each substance

Materialistic	Air	Flue gas	BFG
N	0.7702	0.7375	0.5382

O	0.2066	0.1072	0.0007
CO	0.00026	0.1400	0.1816
H_2	—	—	0.0268
CO	—	—	0.2482
H_2O	0.01379	0.0086	—
AR	0.0092	0.0067	—

The smaller modules are created by segmenting the portions of the boiler that come into direct contact with the flue gas. The physical parameters of each sub-module under full load conditions are presented in Table 3.

Table 3 Physical parameters of small modules

Serial number	Component	Inlet temperature /℃	Outlet temperature /℃	Inlet pressure /MPa	Outlet pressure /MPa	Flow rate /kg·h-1
1	High pressure superheater 1	381.9	485.3	6.34	6.15	86401
2	High pressure superheater 2	282	392.3	6.51	6.36	86403
3	High Pressure Evaporator	269	282.5	6.53	6.56	86427
4	High pressure economizer	155.3	269	6.69	6.53	86433
5	Low pressure superheater	155.1	209.5	0.41	0.44	11205
6	Low pressure evaporator	143.5	155.7	0.45	0.45	97638
7	Low pressure economizer	105.1	143.5	0.52	0.45	97645
8	Feed water preheater	45.0	105.1	0.13	0.03	97645

2.2. Models and methods of exergy analysis

Based on the second law of thermodynamics, a model for exergy the losses and efficiency of the key equipment of the CCPP can be established as shown in Table 4.[17]

Table 4 Calculation models for exergy destruction and exergy efficiency of CCPP units.[18]

Major equipment	Exergy destruction	Exergy efficiency
Air compressor	$E_{xD\ ,\ AC} = E_{x1} - E_{x2} - E_{x12} + W_{AC}$	$\eta_{ex\ ,\ AC} = \frac{E_{x1} - E_{x2} - E_{x12}}{W_{AC}}$
Gas compressor	$E_{xD\ ,\ GC} = E_{x3} - E_{x4} - E_{x14} + W_{AC}$	$\eta_{ex\ ,\ GC} = \frac{E_{x3} - E_{x4} - E_{x14}}{W_{GC}}$
Combustion chamber	$E_{xD\ ,\ CC} = E_{x2} + E_{x4} - E_{x5}$	$\eta_{ex\ ,\ CC} = \frac{E_{x5}}{E_{x2} + E_{x4}}$
Gas turbine	$E_{xD\ ,\ GT} = E_{x6} - E_{x5} - W_{GT}$	$\eta_{ex\ ,\ GT} = \frac{W_{GT}}{E_{x6} - E_{x5}}$
Heat recovery steam generator	$E_{xD\ ,\ HRST} = \sum_{IN,HRSG} E_x - \sum_{out\ ,\ HRSG} E_x$	$\eta_{ex\ ,\ HRST} = \frac{\sum_{out\ ,\ HRSG} E_x}{\sum_{IN,HRSG} E_x}$
Steam turbine	$E_{xD\ ,\ ST} = E_{x8} + E_{x9} - E_{x10} - W_{ST}$	$\eta_{ex\ ,\ ST} = \frac{W_{ST}}{E_{x8} + E_{x9} - E_{x10}}$
Condenser	$E_{xD\ ,\ Cond} = \sum_{IN,Cond} E_x - \sum_{out\ ,\ Cond} E_x$	$\eta_{ex\ ,\ Cond} = \frac{\sum_{out\ ,\ Cond} E_x}{\sum_{IN,Cond} E_x}$

The above equations were numerically solved and the temperature and enthalpy of each flow of the plant determined. Several simplifying assumptions are made in the analysis, following the approaches of others.

1) All processes are assumed steady-state and steady-flow.

2) Air and combustion products are treated as ideal-gas mixtures.

3) The conditions of the reference environment state are P_0=1.01bar and T_0=298.15K

The calculation formulas for the output work and of the two types of compressors, the gas turbine, and the steam turbine are based on the enthalpy difference of the inlet and outlet working medium[13].

The exergy of the working medium consists of four components: physical exergy, chemical exergy, power exergy, and internal exergy[19]. In actual calculations, power and internal exergy can be ignored, leaving only physical and chemical exergy to be considered. Physical exergy indicates the maximum work potential of the system in its initial state. Exergy is linked to changes in chemical composition at equilibrium. As the CCPP gas turbine cycle involves the combustion of BFG in the combustion chamber, chemical exergy must be taken into account. The exergy of the working medium can be expressed as follows:

$$E_x = E_{x,\ ph} + E_{x,\ ch} \quad (1)$$

Where E_x represents the exergy value of the fluid (kJ/kg), and the subscript ph and ch represent the physical exergy and chemical exergy of the fluid, respectively.

The Combined Cycle Power Plant is a combination of two thermal cycles, involving air, gas, mixed gas, water, water steam, and other working substances. There are significant differences in the thermodynamic properties of all types of working media, so the exergy values need to be calculated separately.

The exergy of water and steam can be expressed as follow：

$$e_{x,\ ph} = (h_x - h_0) - T_0(s_x - s_0) \quad (2)$$

Where $e_{x,ph}$ is the unit exergy value of the fluid (kJ/kg), h_x, h_0, s_x, s_0 are the enthalpy and entropy of the imported and exported industrial masses(kJ/kg), respectively, and T_0 is the reference point temperature（K）

The physical exergy of the ideal flue gas can be expressed as follow：

$$e_x^T = C_p[（T\text{-}T_0）- T_0 ln\frac{T}{T_0}] \quad (3)$$

$$e_x^P = RT_0 ln\frac{P}{P_0} \quad (4)$$

$$e_{x,\ ph} = e_x^T + e_x^P \quad (5)$$

Where R is the flue gas constant (kJ/kg-K); the superscripts T and P refer to the temperature and pressure of the flue gas.

In a combined cycle power plant, the chemical exergy of the flue gas is a key parameter in the calculation of exergy analysis. In the actual calculation process, the exhaust products can be treated as a mixture of ideal flue gas.

The chemical exergy of a chemical mixture can be expressed as follow：

$$e_{x,\ ch,\ mix} = [\sum_{i=1}^{n} x_i e_{x,\ ch,\ i} + RT_0 \sum_{i=1}^{n} x_i ln x_i] \quad (6)$$

Where denotes the molar component of each workpiece of the flue gas mixture. denotes the standard chemical hydrazone of component i.

Exergy efficiency indicates the exergy utilization of a component in the system. Its expression is as follow：

$$\eta_e = \frac{\sum_{i=1}^{n} E_{in,\ i} - \sum_{i=1}^{n} E_{l,\ i}}{\sum_{i=1}^{n} E_{in,\ i}} \quad (7)$$

Where E_M denotes the input value of the thermal system and E_1 denotes the value of the thermal system losses.

When calculating the exergy efficiency of a boiler, the output exergy is divided into several small modules to compute the exergy efficiency of the boiler. The exergy efficiency of the boiler is the increase in exergy value in each small module combined with the ratio of input to the boiler flue gas exergy.

The calculation method is shown as follows：

$$\eta_{HRSG} = \frac{\sum_i E_{X,i}}{E_{x,\ in,\ HRSG} - E_{x,\ out,\ HRSG}} \quad (8)$$

III. Exergy analysis and discussion of former CCPP unit

3.1. Exergy flow analysis of former CCPP unit

Exergy and exergy destruction can be calculated based on the physical parameters of each point and the formula for calculating exergy. The exergy of each component in the cycle is shown in Table 5.

Table 5 Exergy calculation results of each device

Device	Input exergy $/GJ\cdot h^{-1}$	Output exergy $/GJ\cdot h^{-1}$	Exergy destruction $/GJ\cdot h^{-1}$	Exergy efficiency /%
Air compressor	140.00	132.76	7.24	94.82
Gas compressor	750.21	738.02	12.19	98.37
TCA	11.31	7.43	3.88	65.69
Reflux gas	122.05	0.00	122.05	0.00
Combustion chamber	786.14	662.71	123.43	84.29
Gas turbine	662.71	541.62	121.09	81.73
Heat recovery steam generator	148.87	127.17	21.7	85.42
Steam turbine	105.76	72.33	33.43	68.39
Condenser	17.74	14.88	2.01	83.87

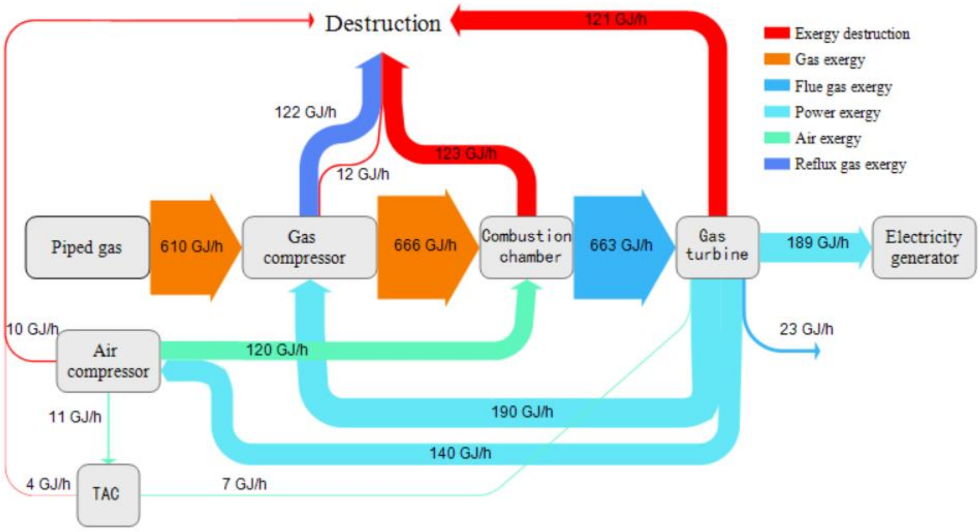

Fig. 3 Exergy flow diagram of gas turbine generation

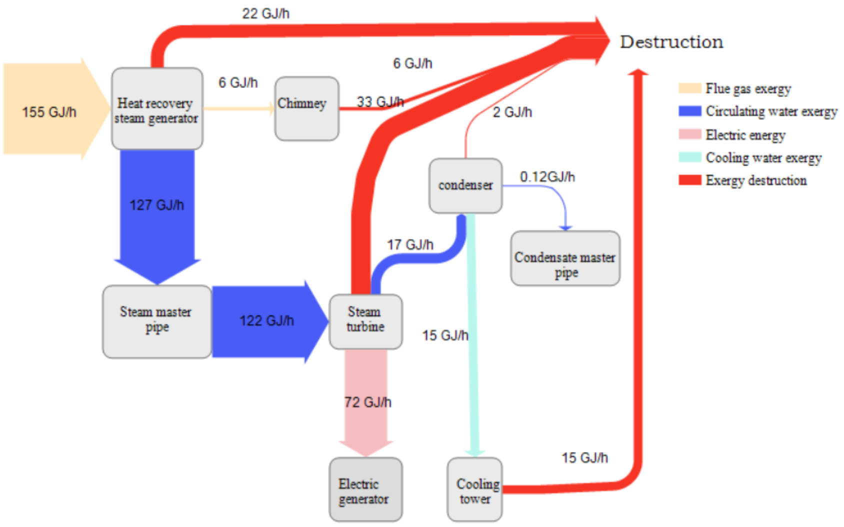

Fig. 4 Exergy flow diagram of recycling generation from Heat recovery steam generator

The entire CCPP unit is treated as a model, and the exergy of the input consists of three parts: namely, the physical exergy and chemical exergy of gas, the exergy of the inlet air of the air compressor, and the exergy of the cooling water of the condenser.

Since air and cooling water enter the system under environmental conditions, their exergy is 0. However, exergy includes the output work of the gas turbine and steam turbine, boiler exhaust, cooling water, and exergy destruction. As boiler exhaust and cooling water are not the primary products of CCPP units, they can be considered as system losses. Therefore, the overall exergy destruction of the system is：

$$\sum_{i=1}^{n} E_{l,\ i}=470.23GJ/h$$

Overall exergy efficiency of the unit is：

$$\eta_{ex,\ CCPP}=0.2297$$

The exergy efficiency of the unit is lower than the thermal efficiency of 0.3062, so the overall efficiency is not high. How to effectively optimize and improve the exergy efficiency of the unit is the key focus of this paper

3.2. Exergy efficiency of key components of former CCPP unit

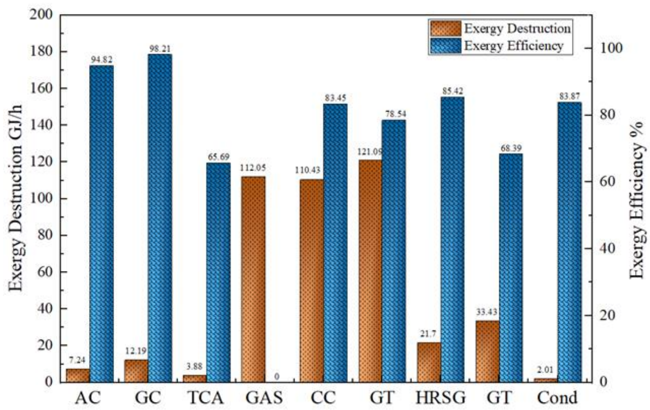

Fig. 5 Exergy destruction and exergy efficiency of CCPP unit components

Analysis of Figure 5 shows that exergy destructions are greatest in the combustor and gas turbine. Most exergy destructions in combustion chambers and gas turbines are internal exergy destruction. The exergy destruction is mainly related to the design and structure of gas turbines, especially the gas turbines. Due to the limitation of materials, gas turbines need to be cooled by low-temperature air in TCA, so considerable exergy destruction will occur during the cooling process. Therefore, if we want to reduce the exergy destruction in combustion chambers and gas turbines, we need to start with design, materials, etc. This increases the cost for units already put into operation. As shown in Figure 5, exergy efficiency is extremely low in two places: reflux gas and TCA air cooler.

Gas is divided at the exit position of the gas compressor, and the amount of gas returned is determined by the load of the unit. About 22% of the total exergy of the gas can be completely wasted, so the exergy destruction rate reaches 100%.

The exergy of TCA involves passing through low-temperature water for heat exchange to lower the temperature of high-temperature and high-pressure air. This air then enters the gas turbine to lower the blade temperature of the gas turbine. However, the heated water did not participate in the cycle; it went directly into the cooling tower to cool down. As a result, the exergy of the high-temperature air was also lost.

Through the above analysis, we can see that the exergy destruction of these two parts has considerable recovery potential. So, the focus of this paper is how to effectively recover the exergy destruction in these two parts.

IV. Energy saving optimization scheme of CCPP unit

4.1. Energy-saving optimization scheme and parameters of CCPP unit

In order to recover the exergy of TCA and the reflux gas, modification of the CCPP unit is necessary. In this paper, the boiler's circulating water system is coupled with the TCA high-temperature air and high-temperature reflux gas pipeline through a heat exchanger. Additionally, the low-temperature condensate is heated up using the method of sectional heating. The system diagram before the modification is depicted in Figure 1, and the system diagram after the modification is presented in Figure 6[20]:

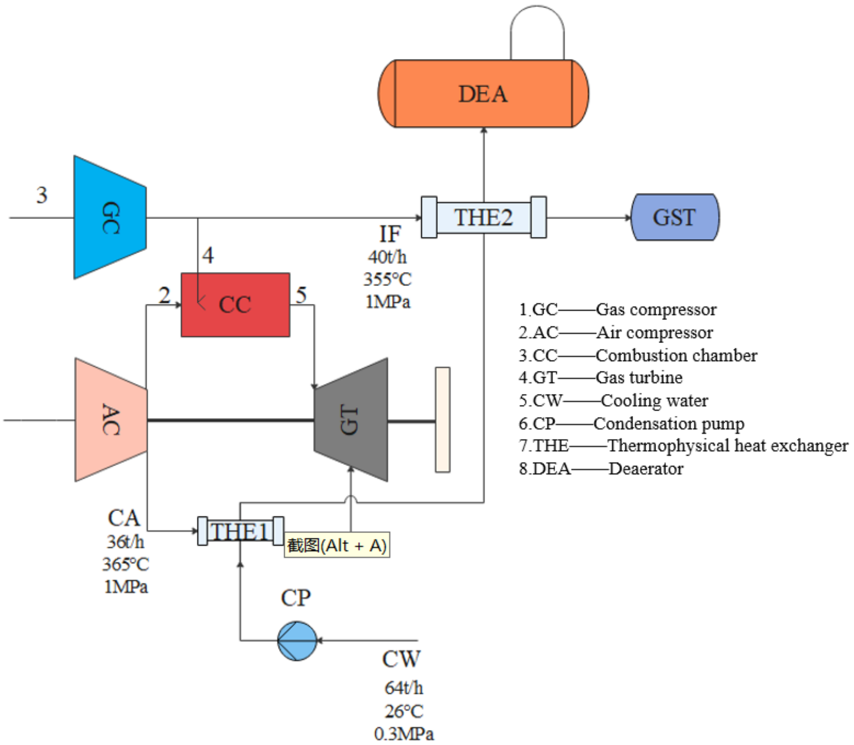

Fig. 6 Schematic diagram of the modified system

The design parameters of the two heat exchangers are shown in Table 6[21]

Table 6 Design parameters of two heat exchangers

Equipment parameters	Air condensate heat exchanger	Gas condensate heat exchanger
Type of heat exchanger	Tube-on-sheet heat exchanger	Tube-on-sheet heat exchanger
Inner diameter of the shell /mm	1000	1110
Tube diameter /mm	Φ25×2.5	Φ25×2.5

Tube length /mm	2000	3000
Tube count	352	764
Heat transfer area /m²	55.26	179.75
Tube side	2	2
Shell side	1	1
Tube pitch /mm	44	44
Tube arrangement	Orthogonal triangle misalignment	Orthogonal triangle misalignment
Amount of baffles	8	8
Baffle spacing /mm	240	360
Connector diameter/mm	100	100

Based on the design parameters of the heat exchanger in Table 6 and the parameters of air and reflux gas at full load, the physical property parameters of the two working substances in the heat exchanger can be calculated, as indicated in Table 7 :

Table 7 Internal physical property parameters of heat exchanger

Physical parameter	Air condensate heat exchanger	Gas condensate heat exchanger
Condensate flow rate /(m/s)	0.46	0.46
Workflow rate /(m/s)	23.26	24.57
Heat transfer coefficient /[W/(m·K)]	296.5	246.17
Condensate inlet temperature /℃	45	72
Condensate outlet temperature /℃	72	110
Air inlet temperature /℃	365	—
Air outlet temperature /℃	158	—
Gas inlet temperature /℃	—	365
Gas outlet temperature /℃	—	90
Air flow rate kg/h	36000	—
Gas flow rate kg/h	—	40000
Condensate flow rate kg/h	68000	68000

4.2. Analysis of optimized CCPP units

Based on the above calculation results, it can be observed that under the full load condition of the unit, the destruction of reflux gas is 122.056 GJ/h, and the exergy of air in the TCA is lost due to cooling, amounting to 3.88 GJ/h. Since the composition of their exergy destruction is different, it is necessary to analyze the composition of their exergy destruction and the percentage of their exergy destruction, as depicted in Figue 7:

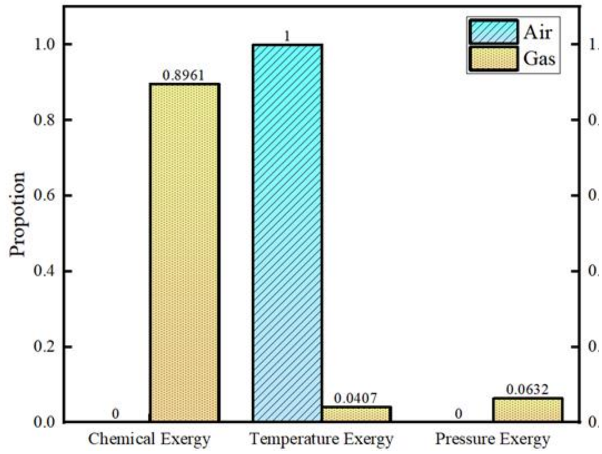

Fig. 7 proportion of exergy destruction between air and gas

Since the composition and pressure of high-temperature air barely change after passing through TCA, the exergy destruction of air in TCA is due to thermal exergy destruction, while that of blast furnace gas is directly lost, resulting in the sum of chemical exergy, pressure exergy, and temperature exergy, with chemical exergy destruction being the largest contributor. The reformed unit introduced in this paper enables the lost gas to be stored after cooling and pressure reduction measures, and finally returned to the gas pipeline for reuse, allowing for the complete recovery of chemical exergy. At full load, an exergy of 109.37 GJ/h can be recovered.

Exergy recovery of pressure in reflux gas. The usual method used in the iron and steel plant is the TRT to recover the residual pressure in gas. Although the pressure of reflux gas meets the standard, the flow rate of reflux gas is not enough. So, if TRT power generation is adopted to recover the pressure exergy of the gas, the exergy of high-temperature and high-pressure gas transfers to the pipe network gas after heat exchange with the circulating condensate water. It then transfers its exergy to the cooler equipped with a depressurization hole plate after cooling and depressurization.

The process of heating water is actually a process of recovering exergy. The temperature of exergy condensate at the inlet and outlet can be seen in Table 7 as 45℃ and 72℃ respectively, and the inlet pressure is 0.3MPa. The pressure loss of water in the air condensate heat exchanger is 1317Pa, but it can be ignored. Similarly, the pressure loss in gas condensate can also be disregarded. Therefore, the recovered exergy after modification can be calculated.[22]

The parameters of each point can be obtained by inquiring the steam enthalpy and entropy table, as shown in Table 8：

Table 8 State parameters of each point

Status point	Temperature /℃	Pressure /MPa	Enthalpy kJ/kg	Entropy kJ/kg·K	Flow rate kg/h
Heat exchanger 1 inlet	45	0.35	188.11	0.6365	68000
Heat exchanger 1 outlet	72	0.35	301.08	0.9774	68000
Heat exchanger 2 inlet	72	0.35	301.08	0.9774	68000
Heat exchanger 2 outlet	110	0.35	460.93	1.4170	68000

The total recovered temperature exergy and the total recovered temperature exergy rate for the variable load case are calculated, as shown in Figure 8：

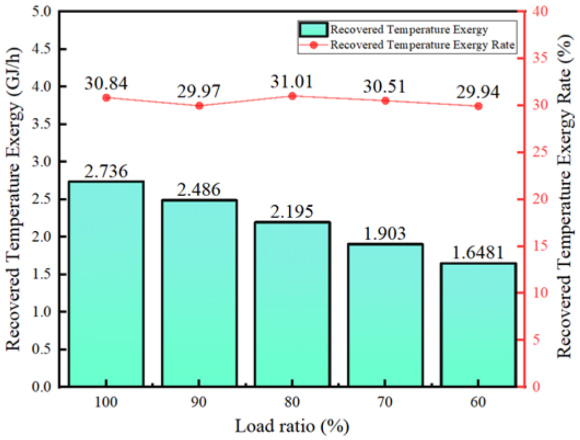

Fig. 8 Exergy recovery amount and recovery rate of recycling devices at different unit load rates

As can be seen from the calculation results, when the load rate went down, the recovered exergy rate of the recovery unit decreased step by step. This decrease in the recovered exergy rate is mainly due to the fact that when the load rate went down, the amount of gas entering the coal press decreased. Additionally, the flow rates of reflux gas, air, and condensate in TCA also decreased, resulting in an overall decrease in the recovered exergy of the system. However, the recovery rate has remained stable at around 30%. The recovery unit has the ability to adapt to different unit loads.

V. Conclusion

The second law of thermodynamics modeling and exergy analysis provided many insightful approaches for analyzing and optimizing the CCPP system in the iron and steel plant. The results of the exergy analysis indicate that the overall exergy efficiency of the iron and steel plant CCPP unit is 0.2297 under full load conditions. The lowest overall exergy efficiency of the unit is associated with the location of the TCA and the coal press outlet reflux gas part, as determined through the analysis. By modifying the unit and coupling it with the boiler circulating water system, along with heat exchange using the circulating water, thermal exergy can be recovered from the total coal gas and air, amounting to 2.736 GJ/h. Furthermore, through the recovery of the reflux gas into the coal pipeline network, the chemical exergy of the gas can be recovered. By recovering and integrating the reflux gas into the gas pipeline network, the total exergy of gas and air can be reclaimed, totaling 109.37 GJ/h, leading to an enhancement in the overall exergy efficiency of the unit.

The recovered exergy rate of the recovery system under different loads is analyzed in this paper. It has been verified that the exergy recovery is relatively stable across different units, with a recovery rate of about 30%. After recovery, exergy destruction of TCA and reflux gas decreased, providing a new idea and optimization direction for optimizing CCPP units.

REFERENCES

[1] WANG K H L. A review of energy use and energy-efficient technologies for the iron and steel industry [J]. Renewable and Sustainable Energy Reviews, 2016, 70.

[2] IBRAHIM T K, MOHAMMED M K, AWAD O I, et al. A comprehensive review on the exergy analysis of combined cycle power plants [J]. Renew Sust Energ Rev, 2018, 90: 835-50.

[3] TRAVERSO A, MASSARDO A F. Thermoeconomic analysis of mixed gas-steam cycles [J]. Applied Thermal Engineering, 2002, 22(1): 1-21.

[4] LIU X J, LIAO S M, RAO Z H, et al. A process-level hierarchical structural decomposition analysis (SDA) of energy consumption in an integrated steel plant [J]. J Cent South Univ, 2017, 24(2): 402-12.

[5] AJBAR A, ALHUMAIZI K, SOLIMAN M A, et al. Model-Based Energy Analysis of an Integrated MIDREX-Based Iron/Steel Plant [J]. Chem Eng Commun, 2014, 201(12): 1686-704.

[6] ROSKILLY R Q W L J Y D W A P. Energy saving technologies and mass-thermal network [J]. Journal of Cleaner Production, 2020, 274(0959-6526).

[7] TIAN Y N, ZHANG T, XIE N N, et al. Conventional and advanced exergy analysis of

large-scale adiabatic compressed air energy storage system [J]. J Energy Storage, 2023, 57: 12.

[8] AMERI M, AHMADI, P.,KHANMOHAMMADI. Exergy analysis of a 420 MW combined cycle power plant [J]. INTERNATIONAL JOURNAL OF ENERGY RESEARCH, 2008, 32(2): 175-83.

[9] REGULAGADDA P D, I.;NATERER, G. F. APPLIED THERMAL ENGINEERING [J]. APPLIED THERMAL ENGINEERING 2010, 30((8-9)): 970-6.

[10] CIHAN A, HACIHAFIZOGLU, O,KAHVECI, K. Energy-exergy analysis and modernization suggestions for a combined-cycle power plant [J]. INTERNATIONAL JOURNAL OF ENERGY RESEARCH, 2006, 30: 115-26.

[11] AL． Z Q W Z Q M J L E. Optimization of energy use with CO 2 emission reducing in an integrated iron and steel plant [J]. Applied Thermal Engineering, 2019, 157.

[12] IBRAHIM T K B, FIRDAUS;AWAD, OMAR I.;ABDULLAH, AHMED N.;NAJAFI, G.;MAMAT, RIZLMAN;HAGOS, F. Y. Thermal performance of gas turbine power plant based on exergy analysis [J]. APPLIED THERMAL ENGINEERING, 2017, 115: 977-85.

[13] KARRABI H, RASOULIPOUR S, ASME. Second law based analysis of Supplementary Firing Effects on the Heat Recovery Steam Generator in a combined cycle power plant; proceedings of the 10th ASME Biennial Conference on Engineering Systems Design and Analysis, Istanbul, TURKEY, F Jul 12-24, 2010 [C]. Amer Soc Mechanical Engineers: NEW YORK, 2010.

[14] ROSEN M A, DINCER I. A study of industrial steam process heating through exergy analysis [J]. International Journal of Energy Research, 2004, 28(10): 917-30.

[15] MANESH M H K, ROSEN M A. Combined Cycle and Steam Gas-Fired Power Plant Analysis through Exergoeconomic and Extended Combined Pinch and Exergy Methods [J]. J Energy Eng-ASCE, 2018, 144(2): 17.

[16] ESPINOSA-CRISTIA J F, FAHAD BREESAM Y, MRABET B M, et al. Exergy and environmental analysis of a novel turbine inlet air cooling technique for power augmentation in a CCPP based on waste energy [J]. Chemosphere, 2023, 338: 139402.

[17] IBRAHIM T K, BASRAWI F, AWAD O I, et al. Thermal performance of gas turbine power plant based on exergy analysis [J]. Applied Thermal Engineering, 2017, 115: 977-85.

[18] COSTA V A F. On the exergy balance equation and the exergy destruction [J]. Energy, 2016, 116: 824-35.

[19] KELLY S, TSATSARONIS G, MOROSUK T. Advanced exergetic analysis: Approaches for splitting the exergy destruction into endogenous and exogenous parts [J]. Energy, 2009, 34(3): 384-91.

[20] ZHANG L, ZHAI H X, HE J Y, et al. Application of Exergy Analysis in Flue Gas Condensation Waste Heat Recovery System Evaluation [J]. Energies, 2022, 15(20): 12.

[21] LIU J Y. Research on structure and application of self-support heat exchanger with pin-finned tubes [J]. 2010.

[22] AZUBUIKE U G, EGBUHUZOR L C, NJOKU H O, et al. Exergy analysis of a steam power plant at full and partial load conditions [J]. Int J Exergy, 2023, 40(2): 182-97.