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ANALYSIS OF POWER GENERATION PROCESS EXERGY EFFICIENCY OF LARGE CDQ WASTE HEAT BOILER UNDER THE BACKGROUND OF DOUBLE CARBON

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ABSTRACT

This paper analyzes the power generation technology of coke dry quenching (CDQ) waste heat boiler, and compares the exergy efficiency of medium temperature medium pressure boiler and high temperature high pressure boiler. The scheme of high temperature ultrahigh pressure primary intermediate reheat boiler to further improve the power generation efficiency of CDQ waste heat is put forward, and the exergy efficiency is analyzed. The bottleneck problem of further improving power generation efficiency by CDQ waste heat power generation and the exergy efficiency limit under the current process conditions are obtained.

Keywords: *CDQ; waste heat power generation; exergy efficiency*.

1. INTRODUCTION

Coke dry quenching (CDQ) is one of the key technologies for the green development of the iron and steel industry. Its advantages in quality improvement, energy saving and environmental protection have been widely recognized in the industry (Wang et al., 2019; Gilyazetdinov et al., 2019). With the development and progress of CDQ technology, the processing capacity of CDQ has reached 260 t/h, and the matched boiler turbine generator unit has also developed from medium temperature and medium pressure unit to high temperature and high pressure unit. The power generation per ton of coke has increased from 113 kWh/t to 145 kWh/t.

With the promotion of the national "double carbon" (carbon emission peak, carbon neutrality) policy, the industrial technological progress and the increase of industrial competition pressure, it is urgent to further explore the improvement of power generation efficiency of CDQ. Many researchers (Danilin, 2018; Rubekina et al., 2018; Jaafari et al., 2021; Wang et al., 2019) conducted a comprehensive analysis on the steam turbine system of the CDQ boiler, which reflected the unique advantages of the exergy analysis, and also pointed out that the process with the greatest loss was the waste heat boiler. The ability of mutual transformation among various forms of energy is not the same. If this conversion ability is taken as the evaluation standard, the "quality" of various forms of energy can be evaluated (Gangadharan et al., 2022; Sun et al., 2015). The energy analysis theory based on the first law and the second law of thermodynamics is undoubtedly superior to any other energy analysis method in terms of its scientific nature and its guiding role in practice (Danilin et al., 2014; Taketomi et al., 2004).

When the system reversibly changes from an arbitrary state to a state in equilibrium with a given environment, theoretically, the part of energy that can be infinitely converted into any other energy form is called Exergy. Correspondingly, all energy that cannot be converted into energy is called Anergy. Any energy (E) is composed of two parts: Exergy (E_x) and Anergy (A_n),

$$E = E_{\mathrm{x}} + A_{\mathrm{n}} \tag{1}$$

Based on the exergy balance and the calculation of exergy efficiency, this paper analyzes the exergy balance and exergy efficiency of medium temperature and medium pressure units and high temperature and high pressure units in the CDQ waste heat power generation industry. Based on the above process, the feasibility of high temperature and ultrahigh pressure primary intermediate reheat unit in CDQ waste heat power generation industry is calculated.

2. CALCULATION OF THERMAL EFFICIENCY OF WASTE HEAT BOILER OF CDQ UNIT

2.1 Mathematical model of electromagnetic field

A 260t/h CDQ unit developed by a company is used to compare the thermal efficiency of matching medium temperature and medium pressure boiler and steam turbine generator set with that of matching high temperature and high pressure boiler and steam turbine generator set. See Table 1 for calculation of steam production and thermal efficiency of waste heat boiler from the perspective of steam production and thermal efficiency of boiler.

From the perspective of boiler steam production, the steam production of the medium temperature and medium pressure unit is relatively large, and the demand for power generation in the plant area is small. The users with large steam demand are more suitable. From the perspective of boiler thermal efficiency, the thermal efficiency of medium temperature and medium pressure boiler is also slightly higher. From the above calculation, it can be seen that the thermal efficiency analysis has no advantages in the scheme planning. Therefore, the exergy analysis method is introduced and the exergy efficiency of large CDQ waste heat boiler power generation process is calculated in this paper.

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Table 1 Calculation of steam production and thermal efficiency of waste heat boiler

Sensible heat parameters of red coke	
CDQ output /(t/h)	260
Red coke temperature (average) /°C	1 050
Coke discharge temperature(average) /°C	200
Red coke sensible heat /(kJ/h)	389 304 500
Medium temperature and medium pressure boiler parameters	
Steam pressure /MPa	3.43
Steam temperature /°C	435
Steam enthalpy /(kJ/kg)	3 301.49
Feed water pressure /MPa	4.2
Feed water temperature /°C	104
Feed water enthalpy /(kJ/kg)	439.07
Steam production /(t/h)	136.0
Boiler efficiency /%	81.23
High temperature and high pressure boiler parameters	
Steam pressure /MPa	8.83
Steam temperature /°C	535
Steam enthalpy /(kJ/kg)	3 472.79
Feed water pressure /MPa	9.8
Feed water temperature /°C	104
Feedwater enthalpy /(kJ/kg)	443.17
Steam production /(t/h)	128.5
Boiler efficiency /%	80.45

3. EXERGY ANALYSIS OF WASTE HEAT BOILER OF CDQ UNIT

From the perspective of thermal efficiency calculation, the advantages of high parameter units can not be found, so the method of exergy analysis is introduced.

3.1 Calculation basis of exergy efficiency of waste heat boiler of CDQ unit

The flue gas conditions and compositions at the inlet of the two waste heat boilers are consistent. The chemical imbalance and combustion characteristics are not considered, and only the exergy efficiency boiler is calculated. The total amount of circulating gas is 3.7×10^4 m³/h.

1) Description of environmental benchmarks

The ambient reference state temperature is adopted, but the ambient physical reference state temperature T_0 is set as 293.15 K (20 °C) according to the local conditions. Therefore, when the air enters the boiler, the value of exergy should be taken as zero.

2) Description of calculation basis

Physical property data used except those given in known conditions ,the properties of steam are selected from "Steam Tables in Sl-Unit".

3.2 Exergy balance and Exergy efficiency of medium temperature and pressure steam boiler

The exergy efficiency calculation is performed for the boiler parameters provided in Table 1. The evaporation capacity of medium temperature and medium pressure waste heat steam boiler is 136.0 t/h, and the steam parameters are: pressure is 3.43 MPa, temperature is 708.15 K (435 °C); The feed water temperature is 377.15 K (104 °C). The maximum temperature of flue gas in the furnace is 1163.15 K (890 °C); The exhaust gas temperature is 398.15 K (125 °C); Constant pressure heat capacity of exhaust gas, taken as a constant, with a value of 1.3713 kJ/m³•K. The system adopted is the outer side of the boiler wall, including the flue gas duct to the inlet of the circulating fan (as shown in Fig. 1).

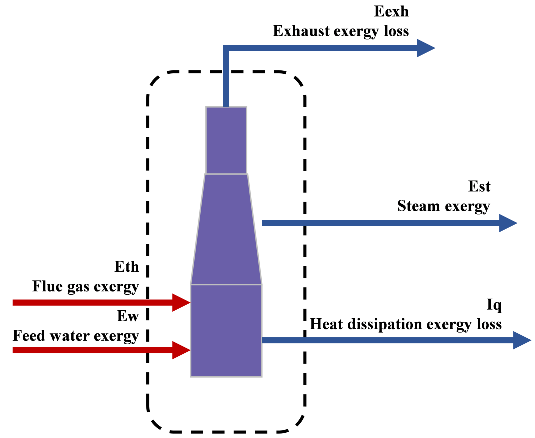

Fig. 1 Calculation range of Exergy efficiency of CDQ waste heat boiler

(1) Calculation of exergy of various media

The total heat entering the boiler is the heat carried by the circulating gas, which is calculated according to Equation (2):

$$\begin{aligned}E_{\mathrm{Th}} &= V_{\mathrm{T}}\int_{T_0}^{T_{\mathrm{h}}} C_p\left(1-\frac{T_0}{T}\right)dT \\ &= V_{\mathrm{T}}C_p\left[\left(T_{\mathrm{h}}-T_0\right)-T_0\ln\left(\frac{T_{\mathrm{h}}}{T_0}\right)\right] \\ &= 236.429\ \mathrm{GJ/h}\end{aligned} \tag{2}$$

Where: E_{Th} is exergy of flue gas t, GJ/h; V_{T} is volume flow of flue gas, Nm³/h; C_p is specific heat capacity of flue gas at constant pressure, taking the fixed value of 1.3713, kJ/m³·K; T_{h} is flue gas temperature at the boiler inlet, K; T_0 is ambient temperature, K.

The chemical composition imbalance between the exhaust gas and the environment is not considered, only the thermal imbalance is considered and the exhaust gas is considered as pure substance. $P=P_0$, $e^{0}=0$, so the exergy loss of exhaust gas is calculated according to Equation (3):

$$\begin{aligned}I_{\mathrm{exh}} &= E_{\mathrm{exh}} \\ &= V_{\mathrm{T}}\int_{T_0}^{T_{\mathrm{g}}} C_p\left(1-\frac{T_0}{T}\right)dT \\ &= V_{\mathrm{T}}C_p\left[\left(T_g-T_0\right)-T_0\ln\left(\frac{T_g}{T_0}\right)\right] \\ &= 7.739\ \mathrm{GJ/h}\end{aligned} \tag{3}$$

Where: I_{exh} is exergy loss of exhaust gas of boiler, GJ/h; E_{exh} is exhaust gas exergy of boiler, GJ/h; T_{g} is exhaust gas temperature of boiler, K.

Based on the accuracy required by the engineering analysis, the physical exergy of the fly ash entering the boiler and the physical exergy of the dust removal cannot be considered.

The enthalpy and entropy of feed water are obtained from the steam table, and are calculated according to Equation (4):

$$H_{\mathrm{w}} = M_{\mathrm{w}}\left(h_{\mathrm{w}}-h_0\right) = 48.315\ \mathrm{GJ/h} \tag{4}$$

Where: H_{w} is Total feed water enthalpy of boiler per unit time, GJ/h; M_{w} is feed water flow of boiler, kg/h; h_{w} is feed water enthalpy of boiler, kJ/kg; h_0 is enthalpy of ambient water, kJ/kg.

The feed water exergy is calculated according to Equation (5):

$$E_{\mathrm{w}} = M_{\mathrm{w}}\left[\left(h_{\mathrm{w}}-h_0\right)-T_0\left(S_{\mathrm{w}}-S_0\right)\right] = 6.375\ \mathrm{GJ/h} \tag{5}$$

Where: E_{w} is feed water exergy of boiler per unit time, GJ/h; S_{w} is boiler feed water entropy, kJ/kg·K; S_0 is environmental water entropy, kJ/kg·K.

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According to the above steps, the enthalpy of steam at the boiler outlet is calculated according to Equation (6):

$$H_{st} = M_{st}\left(h - h_0\right) = 437.619 \text{ GJ/h} \tag{6}$$

Where: H_{st} is total enthalpy of main steam per unit time, GJ/h; M_{st} is main steam flow, kg/h; h is enthalpy of main steam, kJ/kg.

The exergy of the steam at the boiler outlet is calculated according to Equation (7):

$$E_{st} = M_{st}\left[\left(h - h_0\right) - T_0\left(S - S_0\right)\right] = 172.101 \text{ GJ/h} \tag{7}$$

Where: E_{st} is total steam exergy at the boiler outlet per unit time, GJ/h; S is entropy value of main steam at boiler outlet, kJ/kg·K.

The exergy loss I_q caused by the heat dissipation of the boiler to the environment is a part of the external exergy loss, which can be obtained from the corresponding steam output loss and calculated according to Equation (8):

$$I_q = Q_f = 11.679 \text{ GJ/h} \tag{8}$$

Where: I_q is loss of heat dissipation exergy of boiler per unit time, GJ/h; Q_f is heat dissipation exergy of boiler, GJ/h.

(2) Input and output exergy balance

The internal exergy loss I_{int} can be obtained from the equilibrium relationship listed by subtracting the total exergy of the entry points from the total exergy of the exit points. The internal exergy loss is intangible and often difficult to detect. In many thermal equipment, the internal exergy loss often constitutes the main part of exergy loss. Therefore, this form of exergy equilibrium is very important. According to the above calculation results, the input and output exergy balance table of medium temperature and medium pressure boiler in Table 2 can be obtained:

Table 2 Exergy balance of medium temperature and medium pressure boiler

	Input exergy		*Output exergy*			*Internal loss exergy*
Unit	E_{Th}	E_w	E_{st}	I_{exh}	I_q	I_{hex}
GJ/h	236.429	6.375	172.101	7.082	11.679	51.942

The internal exergy loss in table (2) is composed of two items. One is the exergy loss (I_{hex}) of heat transfer from the flue gas to the working medium, which is equal to the difference between the exergy provided by the flue gas and the exergy received by the water medium, and then minus the exergy loss I_q caused by the heat dissipation to the environment. It is calculated according to Equation (9):

$$I_{hex} = \left(E_{Th} - E_{exh}\right) - \left(E_{st} - E_w\right) - I_q = 51.942 \text{ GJ/h} \tag{9}$$

Where: I_{hex} is heat transfer exergy loss of flue gas to working medium per unit time, GJ/h.

(3) Exergy balance between payment and income

The exergy efficiency and local exergy loss rate can be obtained by the equilibrium equation of payment and income. In the medium temperature and medium pressure boiler of this scheme, the payment exergy shall be calculated according to Equation (10):

$$E_p = E_{Th} = 236.429 \text{ GJ/h} \tag{10}$$

Where: E_p is payment exergy per unit time, GJ/h.

The income exergy is calculated according to Equation (11):

$$E_g = E_{st} - E_w = 165.726 \text{ GJ/h} \tag{11}$$

Where: E_g is income exergy per unit time, GJ/h.

Exergy loss is calculated according to Equation (12):

$$I = E_{Th} - \left(E_{st} - E_w\right) = 70.703 \text{ GJ/h} \tag{12}$$

Where: I is exergy loss per unit time, GJ/h.

According to the above calculation, the second law η_e (exergy efficiency) of medium temperature and medium pressure boiler is obtained as follows according to Equation (13):

$$\eta_e = \frac{E_g}{E_p} = 70.10\ \% \tag{13}$$

Where: η_e is exergy efficiency.

3.3 Exergy balance and exergy efficiency of high temperature and high pressure steam boiler

The evaporation capacity of the high temperature and high pressure steam boiler is 128.5 t/h, and the steam parameters are: pressure is 8.83 MPa, temperature is 808.15 K (535 °C); The feed water temperature is 377.15 K (104 °C). The maximum temperature of flue gas in the furnace is 1163.15 K (890 °C); The exhaust gas temperature is 398.15 K (125 °C); Constant pressure heat capacity of exhaust gas, taken as a constant, with a value of 1.3713 kJ/m³•K. The system adopted is the outer side of the boiler wall, including the flue gas and air duct (as shown in Fig. 1).

The values of various media are calculated according to Equation (2) - (9), and the results are shown in Table 3.

Table3 Exergy balance of high temperature and high pressure boiler

	Input exergy		*Output exergy*			*Internal loss exergy*
Unit	E_{Th}	E_w	E_{st}	I_{exh}	I_q	I_{hex}
GJ/h	236.429	6.712	191.595	7.739	11.679	32.128

The calculation method of payment exergy, income exergy and loss of exergy high temperature and high pressure boiler is same as medium temperature and medium pressure steam boiler. According to the above calculation, the exergy efficiency of the high temperature and high pressure steam boiler is obtained according to Equation (13): η_e=78.20 %.

3.4 Comparison of two types of CDQ waste heat boilers

From the above analysis, it can be seen that although the thermal efficiency of the two boilers is very high, the thermal efficiency of the two boilers is more than 70%. In particular, the thermal efficiency of medium temperature and medium pressure boiler is higher, but its exergy efficiency is not high. Moreover, there is a strong contrast with the numerical value of thermal efficiency, and the exergy efficiency of medium temperature and medium pressure boilers with high thermal efficiency is very low. This data truly reflects the effective energy utilization rate of the boiler. Because the thermal efficiency does not reflect the influence caused by the large internal exergy loss.

This analysis mainly focuses on the internal exergy loss rate and heat dissipation exergy loss of the boiler, while other exergy losses, such as heat exchange exergy loss of red coke and circulating gas, emission loss of circulating gas and incomplete combustion of circulating gas, are not considered.

At the same time, the proportion of other exergy losses is relatively small. Therefore, in order to greatly improve the exergy efficiency of the boiler, it is necessary to reduce the internal exergy loss caused by heat transfer in the boiler, which requires the boiler to be combined with power production as a link of energy utilization, and the use of high temperature and high-pressure boilers has obvious advantages.

3.5 Exergy analysis of high temperature and ultrahigh pressure primary intermediate reheat boiler

In order to further improve the exergy efficiency of the circulation system, this paper proposes a scheme of high temperature and ultrahigh pressure CDQ waste heat boiler with one intermediate reheat[12, 13]. The reheater exists in the high temperature and ultrahigh pressure primary intermediate reheat boiler, which further improves the exergy efficiency of the system. It is slightly different from the calculation range of the first two boilers (see Fig. 2).

The evaporation M_w of high temperature and high pressure waste heat steam boiler is 117.1 t/h, steam parameters are: the pressure P is 17.5 MPa, temperature T is 808.15 K (535 °C); The reheating steam inlet pressure P is 3.55 MPa, the temperature T is 627.15 K (354 °C),the reheating steam outlet pressure P is 3.40 MPa, the temperature T is 808.15 K (525 °C); The feed water temperature T_w is 377.15 K (104 °C). The highest temperature of the flue gas in the furnace (T_h) is 1 163.15 K

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(890 °C). The exhaust temperature T_g was 398.15 K (125 °C). The volume constant pressure heat capacity (C_p) of exhaust gas is taken as a constant, and its value is 1.3713 kJ/m³·K. The system taken is the outside of the boiler furnace wall, including the smoke duct, etc. (as shown in Fig. 2)

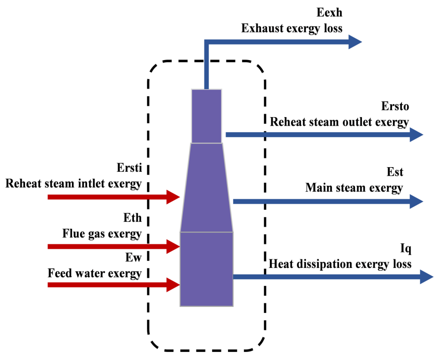

Fig. 2 Calculation exergy efficiency range of primary intermediate reheat boiler

According to the above parameters, the input and output exergy balance table of medium temperature and medium pressure boiler in Table 4 can be obtained:

Table 4 Exergy Balance of Intermediate primary reheat boiler

	Input exergy			*Internal loss exergy*
Unit	E_{Th}	E_{resti}	E_w	I_{hex}
GJ/h	236.429	145.939	7.236	1.603
	Output exergy			
Unit	E_{st}	E_{resto}	I_{exh}	I_q
GJ/h	176.205	192.378	7.739	11.679

According to the above calculation, the exergy efficiency of the high temperature and ultrahigh pressure primary intermediate reheat boiler is obtained according to Equation (13): η_e=91.11 %.

According to the smoke loss and heat loss are basically comparable to the existing boiler, the above calculation is carried out. It can be seen from table 4 that the internal exergy loss has been reduced to 1.603 GJ/h. Considering the current technical conditions are difficult to realize, it can be concluded that the technology of CDQ waste heat boiler is limited by the flue gas temperature at the boiler inlet (890 °C), and the intermediate reheat steam parameters cannot be improved more. The limiting value of the exergy efficiency will not exceed 91.11 %.

4. CONCLUSIONS

This paper analyzes the exergy efficiency of medium temperature and medium pressure boiler, high temperature and high pressure boiler and high temperature and ultrahigh pressure primary reheat boiler. The comparison of the analysis results is shown in Table 5. The specific conclusions are as follows:

(1) The exergy efficiency of CDQ waste heat boiler with high temperature and ultrahigh pressure primary intermediate reheat boiler proposed in this paper, which increased by 28.54% compared with a medium temperature and medium pressure steam boiler and 16.51% compared with a high temperature and high pressure steam boiler.

(2) Limited by the flue gas temperature at the boiler inlet, it is difficult to break through the main steam temperature of 535 °C and reheat steam temperature of 525 °C of the primary intermediate reheat boiler unit, and there is still a gap compared with the current mature power generation boiler unit;

(3) The feasibility of increasing the flue gas temperature at the inlet of CDQ boiler should be further explored in the future.

Table 5 Comparison of Exergy efficiency of three boilers

Project	*Medium temperature and medium pressure boiler*	*High temperature and high pressure boiler*	*High temperature and ultrahigh pressure primary intermediate reheat boiler*
Exergy efficiency	70.10 %	78.20 %	91.11 %
Main parameters	Steam pressure: 3.45 MPa Steam temperature: 435 °C	Steam pressure: 8.83 MPa Steam temperature: 535 °C	Main steam pressure: 17.50 MPa Steam temperature: 535 °C Reheat steam pressure: 3.40 MPa Reheat steam temperature: 525 °C

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