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Exergy Analysis of a Coke Dry Quenching System

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Coke Dry Quenching (CDQ) process has been successfully applied in the No.3 coke oven plant of China Steel Corporation for the purposes of energy saving as well as sustainable CO_2 reduction. To get more insight into the energy utilization efficiency of the CDQ system, the exergy analysis methodology based on the first and second laws of thermodynamics was proposed in this study, and the exergy balance analysis for the CDQ system was conducted under the normal operating conditions. The results indicated that the exergy efficiency of the CDQ system was 65.6%, whereas its energy efficiency was 85.2%. The gap between energy and exergy efficiencies of 19.6% implied that the process internal losses and the interaction between the CDQ system and the environment played an important role in usable energy transformation process. With the combined operation of the CDQ system and the cogeneration plant, an annual energy saving of 8.8 million US dollars and a CO_2 reduction of 144,415 ton/year have been achieved.

1. INTRODUCTION

Energy utilization efficiency is an important topic that has been received great attention in various industrial enterprises. From the viewpoint of energy management, the application of thermodynamics analysis on a system offers an efficient way to trace the process effectiveness. The methods performed to evaluate the process effectiveness include the energy and exergy balance analyses.(1,2,3) Basically, the energy balance analysis is based on the first law of thermodynamics, in which all forms of energy are treated as the same grade without consideration of the process internal losses and the interaction with the environment. In contrast, the exergy balance analysis is based on the combination of the first and second laws of thermodynamics, in which, the maximum work can be obtained from a given form of energy by using the environmental parameters as the reference state. In other words, the exergy analysis of a system can overcome the limitations of the energy balance analysis to calculate the irreversibility and evaluate the maximum available work for a system.

The Coke Dry Quenching (CDQ) process has been extensively applied in modern coke oven plants[4] for the purposes of energy saving as well as coke quality improvement. To demonstrate the superiority of the CDQ process over the traditional Coke Wet Quenching (CWQ) process[5] in the issue of energy saving, G. Bisio and G. Rubatto performed a thermodynamic analysis over the above-mentioned two processes. The results showed that the exergy destroyed by the CDQ process is approximately half that of the exergy destroyed by the CWQ process. In the CDQ process, the incandescent coke is cooled down by means of an inert gas to suppress its gasification and subsequent combustion behavior. For the commercial design of a large scale CDQ system, the coke is generally quenched from around 1,000℃ to below 200℃, whereas the cooling gas is heated up from 130℃ to around 1,000℃. To enhance the energy utilization efficiency, the CDQ system is usually integrated with a power generation or cogeneration system to recover and convert the cooling gas heat into usable energy forms such as electricity and steam for process heating and room heating.(4)

Energy saving and sustainable CO_2 reduction have become one of the key issues in the iron-making industry. To meet the increasing demand for improving the process energy efficiency, a CDQ system, in which the process waste heat was designed to be recovered by a co-generation plant, has been installed in the No.3 coke oven plant of China Steel Corporation to replace the conventional wet quenching process. Figure 1 illustrats the process flow diagram of the installed CDQ system.

As described above, the coke dry quenching process involves sophisticated heat, mass transfer and combustion phenomena. For the purposes of process control and of getting more insight into the CDQ system, the exergy analysis methodology of the CDQ system was proposed in this study and the analysis result was compared with that of the energy balance in the CDQ system. Moreover,

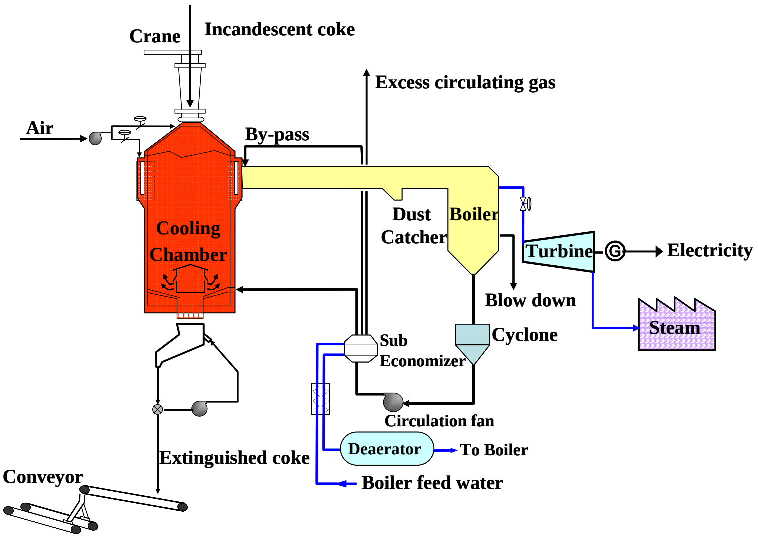

Fig. 1. Process flow diagram of CDQ system.

the benefits of energy saving and CO_2 reduction achieved by the operation of the CDQ system were also explored.

2. MATHEMATICAL MODEL

The CDQ system installed in China Steel Corporation was principally composed of a cooling chamber, waste heat boiler, steam turbine-generator set, air supply system and balance of plant system. In such a process, the heat transfer phenomena between coke, cooling gas, energy transfer devices and the environment were involved. In addition, the combustion reaction of the coke volatile matter and the circulating gas also needed to be considered. Therefore, three types of exergy flow, comprising the work transfer, the heat transfer and the energy transfer associated with mass transfer, had to be considered in analyzing this system.

For exergy analysis, the work of a given form of energy is equivalent to exergy.(2) The exergy of a heat transfer at the control surface is determined from the maximum work that could be obtained from it using the environment as a reservoir of zero-grade thermal energy. For the energy transfer associated with mass transfer, three categories of the materials can be found in this system, they are: (1) the stream of coke; (2) the streams of various gases including the air stream, volatile matter stream and the circulating gas stream; and (3) the water and steam streams of the waste heat boiler. Furthermore, the total exergy of the above-mentioned streams can be separated into physical exergy and chemical exergy. Physical exergy represents the maximum work obtainable when the substance under consideration is brought from its initial state to the environmental state, which involves only thermal interaction with the environment. Chemical exergy represents the maximum work obtainable when the substance under consideration is brought from the environmental state to the dead state by processes involving heat transfer and the exchange of substances with the environment. Table 1 summarizes the characteristics of the exergy flows for the CDQ system.

Table 1 Exergy flows of the CDQ system

Item	Description	Category
1	Incandescent coke	Physical exergy
2	Solution loss & combustion	Chemical + Physical exergy
3	V.M. combustion	Chemical + Physical exergy
4	Boiler feed water	Physical exergy
5	Auxiliary power	Physical exergy
6	Air	Physical exergy
7	Steam	Physical exergy
8	Electricity	Work
9	Extinguished coke	Physical exergy
10	Circulating gas bleeding	Physical exergy
11	Boiler blow down	Physical exergy
12	Heat loss to the ambient	Heat

The reference environmental conditions specified herein for temperature and pressure are 298.15 K and 1.01325 bar, respectively. The detailed mathematical model for exergy calculation was described as follows.

2.1 Exergy of the Gas Streams

The gas streams of the CDQ system include the air, the circulating gas and the volatile matter (V.M.) of the coke. The thermodynamic behavior of the gases follows the ideal gas model. For the air stream, since it entered the CDQ system at the ambient condition, the exergy contribution to the CDQ system was zero. The main components of the circulating gas were CO_2, CO, H_2, O_2 and N_2, whereas the volatile matter was composed of CO and H_2. The physical and chemical exergy flux of both streams can be calculated by Eq. (1) and Eq. (2), respectively.

$$e^{ph}_{mix} = \left(T - T_0\right)\cdot\sum_{i=1}^{n} x_i C^{eph}_{p,i} + R\cdot T_0\cdot\ln\left(\frac{P}{P_0}\right) \text{ .... (1)}$$

$$e^{ch}_{mix} = \sum_{i=1}^{n} x_i \cdot e_{0,i} + R\cdot T_0\cdot\sum_{i=1}^{n} x_i\cdot\ln x_i \text{ .... (2)}$$

The isobaric heat capacity($C^{eph}_{p,i}$) and the standard chemical exergy(e^0) of the gas at the reference environmental state (T_0:298.15 K, P_0: 1.01325 bar) are presented in Table 2.

2.2 Exergy of the Coke

The chemical exergy of the ash in the coke can be considered to be zero$^{(2)}$, therefore, the chemical exergy of the coke can be expressed as Eq. (3).

$$e^{ch}_{co} = x_c \cdot e_{0,c} \text{ .... (3)}$$

For the physical exergy of coke, the specific heat of the coke can be expressed as Eq. (4).

$$C_P = -2.289\times10^{-13}\,T^4 + 1.008\times10^{-9}\,T^3 - 1.716\times10^{-6}\,T^2 + 1.440\times10^{-3}\,T - 1.765\times10^{-1} \text{ .... (4)}$$

The R^2 coefficient of determination is equal to 0.99. In accordance with the relation of the specific heat with temperature, the physical exergy can be determined by Eq. (5) to Eq. (7).

$$h = \int C_p(T)\ dT \text{ .... (5)}$$

$$s = s_0 + \int \frac{C_p}{T} dT \text{ .... (6)}$$

$$e^{ph} = \left(h - h_0\right) - T_0\left(s - s_0\right) \text{ .... (7)}$$

2.3 Exergy of Steam and Feedwater of the Waste Boiler System

The physical exergy of the steam and feedwater can be obtained by Eq. (7), in which, the enthalpy and the entropy values can be obtained from the thermodynamics table.$^{(1)}$

3. EXERGY ANALYSIS OF THE CDQ SYSTEM

Figure 2 presents the schematic diagram of the control volume for the CDQ system. In accordance with the design specification, the capacity of the system was 160 t/h. For incandescent coke at a temperature of around 1,050°C, the dry quenched coke outlet temperature was below 200°C. In addition, by adding air to the circulating gas stream in the gas duct, the combustible components in the circulating gas (CO and H_2) were partly burnt, and the circulating gas temperature was raised to around 980°C before entering the waste boiler. With the heat recovery by a cogeneration plant, the electrical power generation rate was designed to be 7,500 kW, and the steam generation rate was 85 t/h at the temperature and pressure conditions of 285°C and 21 kg/cm^2, respectively. The exergy analysis conducted in this work was based on the actual operation conditions. All the measurements were determined by an arithmetic average of the instrument readings measured in site on an hourly basis.

The coke considered in this study was composed of 87% carbon, 12.5% ash and 0.5% of volatile matter. The chemical composition of the circulating gas is shown in Table 3.

For the steady-state, steady-flow process (SSSF process), the exergy balance for a control volume can be formulated as Eq.(8).

$$\sum \dot{m}_{in}\cdot e_{in} - \sum \dot{m}_{out}\cdot e_{out} + \sum \dot{Q}_{CV} - \sum \dot{W}_{CV} - I = 0$$

....(8)

In accordance with the mathematical model described in the previous paragraph, the exergy fluxes entering and leaving the control volume are presented as Table 4 and Table 5, respectively. Meanwhile, the energy fluxes of the CDQ system based upon the first law of thermodynamics is also shown in Table 4 and Table 5. The results indicated that the irreversibility for the CDQ system was 66,056 MJ/h, indicating 414.14 MJ of the exergy was destroyed for each ton of coke extinguished. Furthermore, the energy balance

Table 2 Exergy flow of the CDQ system

Component	CO_2	CO	H_2	O_2	H_2O	N_2
$C^{eph}_{p,i}$ (kJ/kmol-K)	5.96	4.30	4.22	4.25	4.85	4.30
e^0 (kJ/kmol)	20,140	275,430	23,8490	3,970	11,710	720

Table 3 Chemical composition of the circulating gas

Component	CO_2	CO	H_2	O_2	N_2	Total
Content(%)	18.19	0.07	0.02	0.02	81.70	100

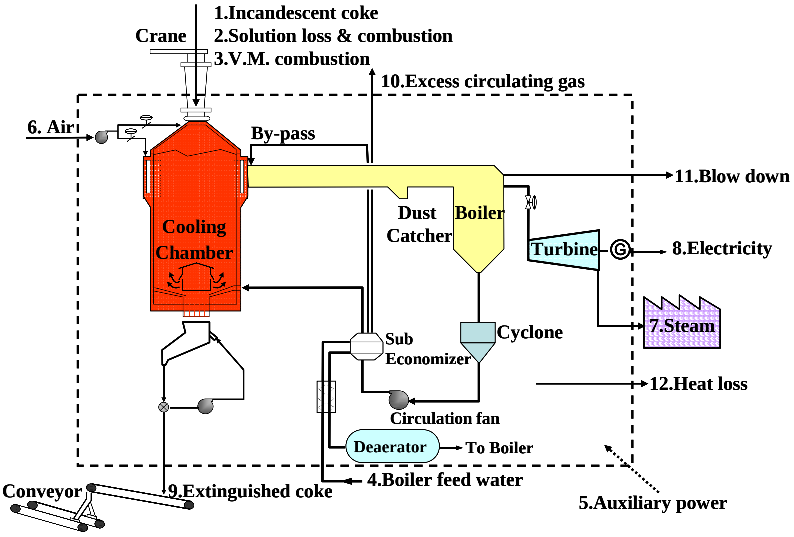

Fig. 2. Schematic diagram of the control volume for CDQ system.

Table 4 Energy and exergy fluxes inward control volume

Item		Energy		Exergy	
		Energy flux (MJ/h)	Percentage (%)	Exergy flux (MJ/h)	Percentage (%)
1	Coke	245,040	69.69	113,814	56.24
2	S.L. chemical reaction	55,778	15.87	49,211	24.32
3	V.M. chemical reaction	30,774	8.76	30,145	14.90
4	Boiler feedwater	10,265	2.91	85	0.05
5	Electricity consumption	9,083	2.58	9,083	4.49
6	Air	655	0.19	0	0.00
	Total	351,595	100.00	202,338	100.00

Table 5 Energy and exergy fluxes outward control volume

Item		Energy		Exergy	
		Energy flux (MJ/h)	Percentage (%)	Exergy flux (MJ/h)	Percentage (%)
7	Steam	272,365	77.48	105,672	52.22
8	Electricity generation	27,157	7.72	27,157	13.42
9	Coke	21,304	6.06	2,811	1.39
10	Circulating gas bleeding	3,353	0.95	456	0.23
11	Boiler blow down	538	0.15	185	0.09
12	Heat loss/Irreversibility	26,879	7.64	66,056	32.65
	Total	351,595	100.00	202,338	100.00

analysis depicted that 85.2% of the process energy was transformed into usable energy forms (steam and electricity). Although the energy efficiency reached 85.2%, the exergy analysis result indicated that the exergy efficiency of the CDQ system was only 65.6%. The gap between energy and exergy efficiencies was therefore found to be 19.6%, suggesting that the process internal losses and the environmenal conditions played an important role in the usable energy transformation process.

4. ENERGY SAVING AND CO_2 REDUCTION

The analysis of the annual energy saving and CO_2 emission reduction is presented in this section. In accordance with the operation records, the actual elec-

Table 6 Annual energy saving and CO_2 reduction analyses

Items	Operation conditions	Benefits	
		Savings (US$ /year)	CO_2 reduction (ton/year)
Steam production(t/h)	91	6,833,406	121,165
Power generation (kW)	7,543	2,993,133	34,935
Additional power consumption (kW)	2,523	- 1,001,139	- 11,685
Total		8,825,400	144,415

trical power generation rate was 7,543 kW. Moreover, 91 t/h of the steam was produced and supplied to the Kaohsiung Coastal Industrial Park for the purpose of process heating. Table 6 summarizes the breakdown of energy savings and CO_2 reduction per year. The economic evaluations were converted to US dollars ($). These calculations were performed based on the following assumptions:

(1) Natural gas heating value: 39,629 kJ/Nm^3
(2) Cost of steam: 10.3 US$/t
(3) Cost of electricity: 0.055 US$/kWh
(4) CO_2 emission conversion factor of electricity: 0.637 kg/kWh
(5) Operation hours: 7,271 h/year

As shown in Table 6, the total economic benefits for energy saving exceeded 8.8 million US dollars per year. In addition, the CO_2 emission reduction was 144,415 ton/year.

5. CONCLUSION

An exergy analysis methodology based on the first and second laws of thermodynamics for the CDQ system was proposed in this study. In accordance with the design of the CDQ system, three types of exergy flows, comprising the work transfer, the heat transfer and the energy transfer associated with mass transfer, needed to be considered to analyze exergy balance of the CDQ system. The analysis results indicated that the irreversibility for the CDQ system was 66,056 MJ/h under the normal operating conditions, implying that 414 MJ of exergy was destroyed for each ton of coke extinguished. Furthermore, the exergy analysis result depicted that the exergy efficiency of the CDQ system was 65.6%, whereas the energy efficiency of the CDQ system was 85.2%. The gap between energy and exergy efficiencies of 19.6% implied that the process internal losses and the interaction between the CDQ system and the environment played an important role in usable energy transformation process.

The Coke Dry Quenching (CDQ) process has been successfully applied in the No.3 coke oven plant of China Steel Corporation. With the combined operation of the CDQ system and the cogeneration plant, the total economic benefits for energy saving has exceeded 8.8 million US dollars per year. In addition, the CO_2 emissions showed a reduction of 144,415 ton/year.

6. NOMENCLATURE

$C_{p,i}^{eph}$ ： Specific heat (kJ/kmol-K)
C_p ： Specific heat (kJ/kg-K)
e^{ph} ： Physical exergy (kJ/kg)
e_{co}^{ch} ： Chemical exergy of the coke (kJ/kmol)
e_{mix}^{ph} ： Physical exergy of the gas (kJ/kmol)
e_{mix}^{ch} ： Chemical exergy of the gas (kJ/kmol)
$e_{0,c}$ ： Standard chemical exergy of the carbon (410,820 kJ/kmol)
$e_{0,i}$ ： Chemical exergy of the ith species (kJ/kmol)
e_{in} ： exergy entering the control volume (kJ/kg)
e_{out} ： exergy entering the control volume (kJ/kg)
h ： Enthalpy (kJ/kg)
h_0 ： Enthalpy at the environmental state (kJ/kg)
$\dot{m}_{in}$ ： Mass flow rate (input)
$\dot{m}_{out}$ ： Mass flow rate (output)
P ： Pressure (bar)
P_0 ： Pressure at the environmental state (1.01325 bar)
R ： Gas constant (8.3144 kJ/kmol-K)
s ： Entropy (kJ/kg-K)
s_0 ： Entropy at the environmental state (kJ/kg-K)
T ： Temperature (K)
T_0 ： Temperature at the environmental state (298.15 K)
x_i ： Molar fraction of the ith species
x_c ： Molar fraction of the carbon

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