EVALUATION AND ANALYSIS OF EXERGOECONOMIC PERFORMANCE FOR THE CALCINATION PROCESS OF GREEN PETROLEUM COKE IN VERTICAL SHAFT KILN

by

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The main objective of this paper is to establish a mathematical framework to analyze the complex thermal economic performance of the calcination process. To find the factors affecting exergy efficiency loss, different exergy destruction is investigated in detail. Furthermore, the exergy flow cost model for exergy cost saving has also been developed. The results show that the vertical shaft furnace is a self-sufficiency equipment without additional fuel required, but the overall exergy destruction accounts for 54.11% of the total exergy input. In addition, the energy efficiency of the waste heat recovery boiler and thermal deaerator are 83.52% and 96.40%, whereas the exergy efficiency of the two equipment are 65.98% and 94.27%. Furthermore, the import exergy flow cost of vertical shaft furnace, waste heat recovery boiler and thermal deaerator are 366.5197 RMB per MJ, 0.1426 RMB per MJ, and 0.0020 RMB per MJ, respectively. Based on the result, several suggestions were proposed to improve the exergoeconomic performance. Assessing the performance of suggested improvements, the total exergy destruction of vertical shaft furnace is reduced to 134.34 GJ per hours and the exergy efficiency of waste heat recovery boiler is raised up to 66.02%. Moreover, the import exergy flow cost of the three different equipment is reduced to 0.0329 RMB per MJ, 0.1304 RMB per MJ, and 0.0002 RMB per MJ, respectively.

Key words: *calcinations process, vertical shaft furnace, exergy analysis, exergy flow cost, exergoeconomic analysis*

Introduction

Green petroleum coke (GPC), as the by-product of petroleum refineries [1, 2], could be used as the unique material to manufacture calcined petroleum coke (CPC) through calcination process, which is one of the main raw materials used for anode in the aluminum electrolytic industry [3]. Although the traditional rotary kilns are still commonly employed in China [4, 5], the vertical shaft furnace (VSF) has become widely adopted for the calcination process, due to its higher level of product quality, less carbon burning loss and lower process energy consumption. Nevertheless, with the ever rising energy cost, large-scale materials and energy consumption have hindered the development of the calcination industry

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[6-8]. In order to improve the efficiency and rationality of energy utilization, it is crucial to evaluate and optimize the energy consumption of the calcination process coupling with the economic concepts.

Recently, several researches have been carried out on studying the calcination process. Firstly, Xiao *et al.* [9] established a two-fluid mathematical model to simulate the heterogeneous reacting flow of petroleum coke calcination in the shaft. Moreover, Elkanzi [10] adopted a numerical model, *i.e.* HYSYS, to simulate the petroleum coke calcination based on industrial data, and found the relationship between the real density of CPC and the calcination temperature. Morever, based on the First law of thermodynamics, Filkoski *et al.* [11] were devoted to the research of flue gas waste heat recovery from shaft kiln. As the condition of flue gas is similarly with that from VSF, the five different options of waste heat utilization could give great reference significance for calcination process in order to improve the overall energy efficiency. In addition, Dolianitis *et al.* [12] developed a 3-D computational model to study the energy efficiency of glass furnace, which is proven to be an excellent work in energy analysis area. Furthermore, many studies on material and energy flow model have been proposed in the past, but mainly on the metallurgical process [13, 14], construction industry [15] and cement industry [16]. However, limited exergy and exergoeconomic studies have been directed towards the calcination process, compared with the prosperity and development in other fields [17-19]. Lazzaretto *et al.* [20] applied the specific exergy costing, *i.e.* SPECO, approach to the calculation of exergy efficiency and the auxiliary costing equations for the thermal system. Gaggioliet *et al.* [21] proposed cost allocation equations for cogeneration system, based on the extraction method and equivalent method. In their research, the exergy cost of products should take various operational conditions into consideration. Furthermore, Regulagadda *et al.* [22] made a thermodynamic analysis of a subcritical boiler with turbine generator and discovered that boiler and turbine contributing to the highest exergy losses within the system. Therefore, there is a knowledge gap to evaluate the thermal and economic performance of calcination process.

Calcination *via* VSF is a complex energy used and high energy consumption process, therefore it needs to have a thermal evaluation. In addition, the exergy flow way is an advanced method and seldom applied in the calcinations process, so this work has great necessity and scientific value. Furthermore, based on the coupling exergy and economic principles, we can see whether the high quality energy is used in the high cost place. The main objective of this research is to find a suitable mathematical framework to analyze the complex thermal-economic performance of the calcination process. Then, the exergy efficiency and exergy flow cost must be calculated. At last, some improvements that aim at raising up the exergy efficiency and reducing the exergy flow cost should be recommended. Since the calculation process using VSF has been widely applied in China, a lot of calcination plants have adopted the method described in the paper

Although the material and energy analysis has been widely applied in the calcination process, the exergy evaluation on this area, especially towards VSF is still not adopted. Therefore, based on the coupling exergy and economic principles and firstly introduced it into calcination process, this work has great necessity and scientific value. This paper presents a comprehensive methodology to analyze the exergy and exergoeconomic in the calcination process based on our previous research works [23, 24]. The subject matter of the present work has a distinct feature of process flow with unique physical reaction and chemical reaction, new methods of exergy and exergoeconomic evaluation, multiple perspective analysis of exergy destruction and ways on exergy flow cost saving, *etc.* As for the complex calcination process, an advanced mathematical model for the mass, energy and exergy flow has been developed. Meanwhile, model of exergy destruction on combustion, heat transfer and dissipate heat was considered. Moreover, the new exergoeconomic model was set up to calculate the exergy flow cost of the calcination process and the exergy flow cost allocation equations based on the definition of exergy quality coefficient were firstly proposed and applied. Furthermore, improvements on rationality of energy utilized and possibly exergy cost saving of the calcination process were also discussed.

Methodology

As the traditional energy analysis methods based on the First thermodynamic law only reveal the conservation of energy quantity, but ignore the difference of energy availability due to the irreversibility occurred during the heat transfer process. The exergy model based on the Second thermodynamic law has been established in this article, and also defined exergy destruction to quantify the irreversible losses in the calcination process. Furthermore, considering the unequal cost of exergy and exergy destruction for each equipment, exergoeconomic analysis combining exergy and economic means was firstly introduced consequently.

Briefly description of the calcination process

The calcination process of GPC in the VSF has been studied in the past years. A schematic of the process is shown in fig. 1. The process consists of three major equipment, including the VSF, the waste heat recovery boiler (WHRB) and the thermal deaerator (TD). After crushed to the specified size and blended according to the blending ratio, GPC is then calcined *via* VSF with the complex chemical reactions happened inside as shown in tab. 1. Afterwards, CPC is cooled to a temperature below 80 °C by the cooling water jacket installed under the VSF and then delivered to the user. Meanwhile, the flue gas from VSF with high heat content is recovered in WHRB by exchanging heat with boiler feeding water to generate steam for energy saving and then sent to the flue gas treatment system. Furthermore, as the important equipment in the process, TD is used to remove the oxygen out of the demineralized water to reduce the corrosion on the interface of the equipment.

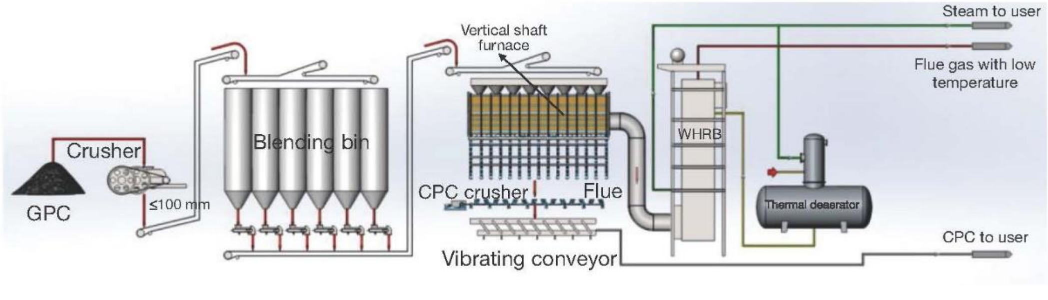

Figure 1. A schematic of the calcination process

Mathematical model of exergy flow

To analyze the exergy flow of the calcination process, the formulation of the exergy flow balance is introduced and expressed in eq. (1). The input exergy flow of the control unit must be identical to the exergy flow output together with the exergy destruction generated within the control unit:

$$\sum_{\mathrm{i}} Ex_{i,\mathrm{IN}} = \sum_{\mathrm{i}} (Ex_{i,\mathrm{OUT}} + ED_i) \tag{1}$$

where $Ex_{\mathrm{i,IN}}$, $Ex_{\mathrm{i,OUT}}$, and ED_{i} denote the total exergy input, output, and destruction within the control unit, respectively.

Table 1. Reactions occurred in VSF

Reaction	Equation	Number of reaction equation
Carbon combustion reaction	$C + O_2 = CO_2$	Reaction 1
Sulfur combustion reaction	$S + O_2 = SO_2$	Reaction 2
Volatile matter combustion reaction	$2H_2 + O_2 = 2H_2O$	Reaction 3
	$CH_4 + 2O_2 = CO_2 + 2\ H_2O$	Reaction 4
	$2C_2H_6 + 7O_2 = 4CO_2 + 6\ H_2O$	Reaction 5

The exergy of a flow consists of physical exergy and chemical exergy as expressed in eq. (2). The physical exergy is generated due to the imbalance by the difference temperature and pressure from the environment. While, the chemical exergy is produced by the imbalance of the chemical composition towards the standard reference material:

$$Ex_k = Ex_{k,\mathrm{PE}} + Ex_{k,\mathrm{CE}} \tag{2}$$

where $Ex_{k,\mathrm{PE}}$ and $Ex_{k,\mathrm{CE}}$ denote the physical exergy and chemical exergy of the exergy flow, respectively. Meanwhile, based on the exergy generation principle [25], the physical exergy is closely related with the enthalpy and entropy change, which expressed:

$$Ex_{k,\mathrm{PE}} = (H - H_0) - T_0(s - s_0) \tag{3}$$

$$H - H_0 = mC_P(T - T_0) \tag{4}$$

$$Ex_{k,\mathrm{PE}} = mC_P(T - T_0) - m\left[C_P \ln\left(\frac{T}{T_0}\right) - \mathrm{R}\ln\left(\frac{P}{P_0}\right)\right] \tag{5}$$

where H, s, P, and R denote the enthalpy, entropy, pressure, and gas constant, respectively.

The chemical exergy of element and ideal gas mixtures is calculated based on the standard chemical exergy, *i.e.* tab. 2, and expressed in eq. (6) [26].

Table 2. Standard chemical exergy

Element	Standard chemical exergy e_n^θ [kJmol^{-1}]	Ideal gas	Standard chemical exergy e_n^θ [kJN^{-1}m^{-3}]
S	602.79	CH_4	35665
C	410.53	C_2H_4	58814
		CO	11470
		H_2	10380

$$Ex_{k,\mathrm{CE}} = \sum_{n=1}^{N} x_n e_n^\theta + \mathrm{R}'T_0\sum_{n=1}^{N} x_n \ln x_n \tag{6}$$

where x_n and R' denote the gas, *i.e.* n, volume content and gas constant, *i.e.* 0.371 kJ/m^{3}K.

Based on the Second law of thermodynamics, entropy can be created but cannot be destroyed. Therefore, the exergy destruction is defined, which is the counterpart of the increase of entropy principle, and is expressed:

$$ED_i = T_0 s_{\text{gen}} \tag{7}$$

where s_{gen} is the entropy generation in the process.

Combustion exergy destruction, *i.e.* Ex_{CED}, is produced due to the irreversibility of the combustion reaction, which generates irreversible work. On the conditions of no preheated fuel or combustion, combustion exergy destruction is expressed:

$$Ex_{\text{CED}} = T_0 \Delta s + Q_{\text{L}} \frac{T_0}{T_{\text{ad}} - T_0} \ln \frac{T_{\text{ad}}}{T_0} \tag{8}$$

Exergoeconomic model of the process

Although the mathematical model of exergy flow could analyze the quantity and quality of the energy, the unequal cost caused by the irreversibility loss of the process is insoluble. Thus, the exergoeconomic theory is applied to analyze the calcination process for calculating the exergy flow cost based on the energy quality difference.

According to the cost balance equation in the field of economics, the exergy flow cost equation for one unit is:

$$\sum (c_{\text{IN},k} Ex_{\text{IN},k}) + c_{\text{NE}} = \sum (c_{\text{OUT},j} Ex_{\text{OUT},j}) \tag{9}$$

where $c_{\text{IN},k}$, $Ex_{\text{IN,k}}$, c_{NE}, $c_{\text{OUT,j}}$, and $Ex_{\text{OUT},j}$ denote the unit exergy inlet flow cost, exergy flow inlet, non-energy cost, unit exergy outlet flow cost, exergy flow outlet of the unit, respectively.

Meanwhile, non-energy cost is simplified to comprise the equipment cost, *i.e.* c_{EQ}, and resource cost, *i.e.* c_{R}. Furthermore, c_{EQ} is prorated:

$$c_{\text{EQ}} = \frac{CRF \lambda Z}{3600N} \tag{10}$$

where CRF, λ, Z, and N denote equipment cost recover factor, equipment maintenance factor, equipment cost, and annual operation hours of equipment, respectively.

In addition, CRF is defined:

$$CRF = \frac{\omega(1+\omega)^Y}{(1+\omega)^Y - 1} \tag{11}$$

where ω and Y denote equipment discount rate and equipment running time, respectively.

However, when the number of exergy flow, *i.e.* m, is more than the number of exergy flow cost equation, *i.e.* i, it is obliged to establish exergy flow cost allocation equation to seal off the whole cost calculation equations, so as to calculate the exergy flow cost of the system. It should be noted that the number of exergy flow cost allocation equation is $m - i$. In addition, due to the fact that different quality of exergy flow should have different exergy flow cost, the exergy quality coefficient, *i.e.* $\theta_{x,y}$, is firstly defined to reflect the difference on quality between the two exergy flows and support the establishment of exergy flow cost allocation equation, which is expressed:

$$\theta_{x,y} = \frac{\dfrac{Ex_x}{m_x}}{\dfrac{Ex_y}{m_y}} \tag{12}$$

where Ex_x, m_x, Ex_y, and m_y denote the exergy flow and mass flow of medium x and y, respectively.

Consequently, the exergy flow cost allocation equation is follow:

$$c_x \theta_{x,y} = c_y \tag{13}$$

where c_x and c_y denote the exergy flow cost of medium x and y, respectively.

Results

In the present study, evaluations are performed based on the operational data and boundary conditions obtained from on-site industrial measurements and the corresponding control parameters. Other information is specified based on the average values commonly adopted during practical productions. The ambient temperature and environment pressure remain constant during the process, which is taken as 298.15 K and 1 atm, respectively. Some technological parameters used in the present study are summarized in tab. 3.

Table 3. Technological parameters related to the operational condition of the calcination process

Parameter	Value	Unit	Instrument
CPC production capacity per hour	34.56	[th^{-1}]	Weigh feeder
Specification of GPC			
Moisture	8	[wt.%]	Muffle furnace
Volatile matter	11	[wt.%]	Muffle furnace
Ash content	0.3	[wt.%]	Muffle furnace
Sulfur content	3	[wt.%]	Muffle furnace
Fixed carbon content	88.7	[wt.%]	Calculation
Composition of volatile matter			
H_2	37.33	[vol%]	Gas composition analyzer
CH_4	28.00	[vol%]	Gas composition analyzer
C_2H_4	34.67	[vol%]	Gas composition analyzer
Vertical shaft furnace			
Shaft number per VSF	72	Shaft/Num.	
Actual furnace number	4	Num.	
Temperature of GPC	25	[°C]	Infrared thermometer
Temperature of CPC	80	[°C]	Infrared thermometer
Temperature of flue gas outlet	925	[°C]	Temperature sensor

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Table 3. Continuation

Temperature of circulating cooling water inlet	25	[°C]	Thermometer
Temperature of circulating cooling water outlet	33	[°C]	Thermometer
Combustion rate of volatile matter in VSF	96	[wt.%]	Standard data
Combustion rate of sulfur in VSF	17	[wt.%]	Standard data
Carbon loss in VSF	2.5	[wt.%]	Standard data
Evaporation rate of moisture in VSF	100	[wt.%]	Standard data
Waste heat recovery boiler			
Temperature of outlet steam	450	[°C]	Temperature sensor
Pressure of outlet steam	3.82	[MPa]	Differential pressure transmitter
Temperature of WHRB feeding water	105	[°C]	Temperature sensor
Temperature of flue gas out of WHRB	190	[°C]	Temperature sensor
Discharge rate of WHRB	5	[wt.%]	Standard data
Air leakage coefficient of flue before WHRB	20	[vol%]	Standard data
Air leakage coefficient of WHRB	2	[vol%]	Standard data
Thermal deaerator			
Temperature of inlet steam	104	[°C]	Temperature sensor
Pressure of inlet steam	0.025	[MPa]	Differential pressure transmitter
Temperature of desalted water inlet	25	[°C]	Thermometer
Coefficient of steam loss in TD	2	[wt.%]	Standard data

It should be noted that the air leakage coefficient of flue before WHRB is calculated by the O_2 content and flow volume of the flue gas out of VSF and into WHRB. Similarly, the air leakage coefficient of WHRB is calculated by the O_2 content and flow volume of the flue gas into WHRB and out of WHRB. Usually these two parameters are standard and stable if the negative pressure is unchanged.

Exergy flow analysis of the calcination process

The results of exergy balance calculation of VSF, WHRB and TD are summarized in tab. 4.

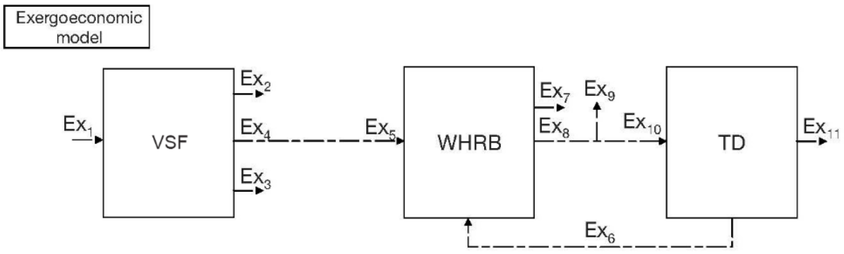

Figure 2. The schematic of the exergoeconomic model

Table 4. Exergy flow balance of VSF, WHRB, and TD

Exergy flow balance of VSF				Exergy flow balance of WHRB			
$Ex_{\mathrm{VSF,IN}}$ [GJh^{-1}]		$Ex_{\mathrm{VSF,OUT}}$ [GJh^{-1}]		$Ex_{\mathrm{WHRB,IN}}$ [GJh^{-1}]		$Ex_{\mathrm{WHRB,OUT}}$ [GJh^{-1}]	
$Ex_{\mathrm{VSF,GPC}}$	0.00	$Ex_{\mathrm{VSF,FG}}$	96.66	$Ex_{\mathrm{WHRB,FG}}$	84.26	$Ex_{\mathrm{WHRB,ST}}$	55.59
$Ex_{\mathrm{VSF,CA}}$	0.00	$Ex_{\mathrm{VSF,CPC}}$	0.13	$Ex_{\mathrm{WHRB,LA}}$	0.00	$Ex_{\mathrm{WHRB,FG}}$	7.53
$Ex_{\mathrm{VSF,VMCE}}$	233.35	$Ex_{\mathrm{VSF,MEE}}$	1.57	$Ex_{\mathrm{WHRB,BFW}}$	1.79	$Ex_{\mathrm{WHRB,WW}}$	0.00
$Ex_{\mathrm{VSF,SCE}}$	3.83	$Ex_{\mathrm{VSF,CCWO}}$	$1.44\cdot10^{-4}$			$Ex_{\mathrm{WHRB,DHED}}$	4.22
$Ex_{\mathrm{VSF,CCE}}$	29.22	$Ex_{\mathrm{VSF,CCWHE}}$	23.85			$Ex_{\mathrm{WHRB,HTED}}$	17.66
$Ex_{\mathrm{VSF,CCWI}}$	0.00	$Ex_{\mathrm{VSF,DHED}}$	14.66			$Ex_{\mathrm{WHRB,EED}}$	1.05
		$Ex_{\mathrm{VSF,CED}}$	114.41	Total	86.05	Total	86.05
		$Ex_{\mathrm{VSF,HTED}}$	11.23	Exergy flow balance of TD			
		$Ex_{\mathrm{VSF,EED}}$	3.88	$Ex_{\mathrm{TD,IN}}$ [GJh^{-1}]		$Ex_{\mathrm{TD,OUT}}$ [GJh^{-1}]	
				$Ex_{\mathrm{TD,ST}}$	1.90	$Ex_{\mathrm{WHRB,BFW}}$	1.79
				$Ex_{\mathrm{TD,DW}}$	0.00	$Ex_{\mathrm{TD,LS}}$	0.04
						$Ex_{\mathrm{TD,DHED}}$	0.06
						$Ex_{\mathrm{TD,EED}}$	0.01
Total	266.40	Total	266.40	Total	1.90	Total	1.90

Table 5. Technological parameters related to the calculation of exergy flow cost

Parameter	Value	Unit
Equipment cost recover factor, λ	1.05	
Annual operation hours, N	8322	hours
Equipment discount	0.05	
Equipment running time	25	years
Replenishment rate of circulating cooling water	3	wt.%
Resource cost		
GPC	2000	RMB per tone
CPC	2600	RMB per tone
Demineralized water	2	RMB per tone
Water	1.3	RMB per tone
Equipment cost		
VSF	13000000	RMB per numero
WHRB	8000000	RMB per numero
TD	2000000	RMB per numero

NOTE: The currency ratio of US dollar against RMB is 1 USD = 6.461 RMB when calculated.

Exergoeconomic model evaluation of the calcination process

By integrating the exergy flow in the calcination process, the schematic of the exergoeconomic model is shown in fig. 2, where Ex_1 to Ex_{11} denote the exergy flow of volatile matter, circulating cooling water exergy flow, CPC, flue gas from VSF, flue gas to WHRB, boiler feeding water, flue gas out off WHRB, steam from WHRB, residual steam, steam to TD and loss steam of TD, respectively. In addition, the parameters related to the calculations of exergy flow cost are summarized in tab. 5.

Based on the calculation structure of mentioned exergy flow cost equations, the results of the exergy flow cost are shown in tab. 6.

Table 6. The calculated exergy flow cost of calcination process

Exergy flow cost	Parameter	Value	Unit
c_1	Exergy flow cost of volatile matter in GPC	0.0329	RMB per MJ
c_2	Exergy flow cost of circulating cooling water	366.4868	RMB per MJ
c_3	Exergy flow cost of CPC	712.8328	RMB per MJ
c_4	Exergy flow cost of flue gas from VSF	0.0619	RMB per MJ
c_5	Exergy flow cost of flue gas to WHRB	0.0855	RMB per MJ
c_6	Exergy flow cost of boiler feeding water	0.0571	RMB per MJ
c_7	Exergy flow cost of flue gas out off WHRB	0.9764	RMB per MJ
c_8	Exergy flow cost of steam from WHRB	0.0005	RMB per MJ
c_9	Exergy flow cost of residual steam	0.0005	RMB per MJ
c_{10}	Exergy flow cost of steam to TD	0.0020	RMB per MJ
c_{11}	Exergy flow cost of loss steam of TD	0.0020	RMB per MJ

Discussion

Evaluation and analysis of exergy flow

According to the calculated results of the exergy flow balance towards the calcination process in tab. 3, the major exergy destruction is the combustion exergy destruction, *i.e.* $Ex_{\mathrm{VSF,CED}}$, in VSF, which is caused by the volatile matter combustion during the calcination. The total exergy destruction of VSF is 54.11%, which accounts for more than 50% of the total exergy output. Furthermore, the heat transfer exergy destruction of WHRB, $Ex_{\mathrm{WHRB,HTED}}$, is the second largest exergy destruction, which depends on the temperature difference between flue gas and steam. As for the TD, the exergy destruction is very low, because it is a system with only one exergy flow input and multi exergy flow output. Moreover, the energy efficiency of the WHRB and TD are 83.52% and 96.40%, whereas the exergy efficiency of the two equipment are 65.98% and 94.27%.

Evaluation and analysis of economic performance

The import exergy flow cost of the three different equipment is calculated according to tab. 6, and the equipment with the biggest import exergy flow cost is VSF, *i.e.* 366.5197 RMB per MJ. In addition, the import exergy flow cost of WHRB and TD are

0.1426 RMB per MJ and 0.0020 RMB per MJ, respectively. Therefore, the energy consumption of the calcination process is accordance with the principle that high quality goods should be with high price in economics. However, the exergy flow cost of the flue gas from VSF is 0.0629 RMB per MJ, which is increased to 0.0855 RMB per MJ when it flows into WHRB. Hence, it is necessary to save this part of cost increasing, which is caused by the decrease of energy quality. Similarly, the exergy flow cost of steam coming from WHRB (*i.e.* 0.0005 RMB per MJ) is much lower than that into TD. Subsequently, due to the low energy quality, the exergy flow cost of circulating cooling water is high, *i.e.* 366.4868 RMB per MJ.

Possible improvements

In order to improve the thermal and economic performance of the calcination process, several suggestions are proposed in the present study. Firstly, due to the high temperature difference between the flue gas from the outlet of VSF, *i.e.* 925 °C, and inlet of WHRB, *i.e.* 757 °C, this is a great potentiality for energy and exergy saving, as well as exergy flow cost reduction. Thus, it should enhance the insulation performance of flue duct between VSF and WHRB to reduce temperature drop of the flue gas. On the other hand, the sealing of flue duct gate on the outlet of VSF and inlet of WHRB should be optimized which could reduce the air leakage coefficient of flue duct before WHRB from 20% to 10% and raise the flue gas temperature of the boiler inlet from 757 °C to 838 °C.

Secondly, the cooling method of CPC by adopting circulating cooling water with cooling water jacket has been successfully applied in many anode plants in China, however, some problems have also been exposed, including low heat transfer efficiency, high net water consumption and fouling rate on the inner surface of the cooling water jacket. Therefore, it is suggested to make use of the vaporization cooling method instead of the traditional cooling way. As a result, the high heat contained in the CPC is fully recycled, which is converted in the form of steam to be utilized by TD. Meanwhile, it can cancel the transportation path of the steam from WHRB to TD, which could avoid the high quality steam used in the low functional operation place, *i.e.* TD, with the temperature and pressure reduction.

Thirdly, the internal structure of VSF could be optimized by adding the preheating channel of combustion air, which could not only raise the temperature of flue gas on the outlet of VSF to 950 °C, but also reduce the combustion exergy destruction in VSF.

Based on the discussion, considering all improvement measures are implemented, as depicted in figs. 3-5, the mass, energy and exergy balance are then re-calculated. Thereby, the total exergy destruction of VSF is reduced to 134.34 GJ per hours and the exergy efficiency of WHRB is raised up to 66.02%. In addition, the resultant exergy flow cost has also been undated, as shown in tab. 7. Obviously, the import exergy flow cost of the three different equipment are reduced to 0.0329 RMB per MJ, 0.1304 RMB per MJ and 0.0002 RMB per MJ, respectively. Moreover, the exergy flow cost of the flue gas into WHRB is optimized to 0.0758 RMB/MJ, which reduce the exergy flow cost of waste heat recovery system.

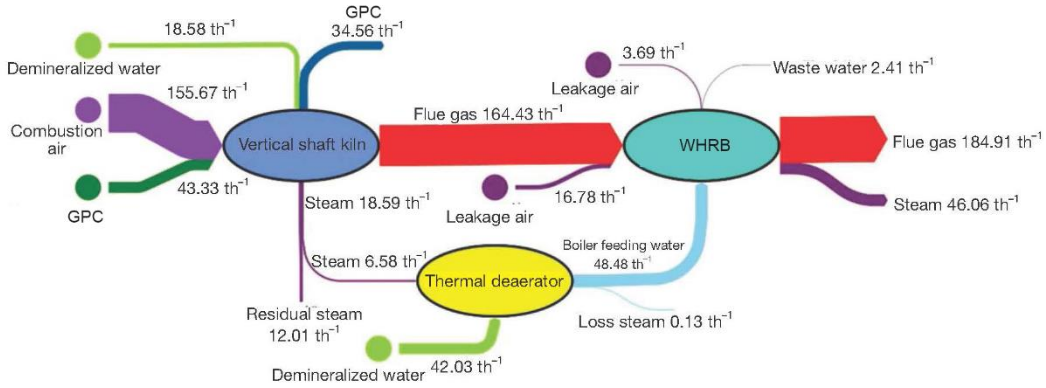

Figure 3. Sankey diagram of the material flow with the suggested improvements

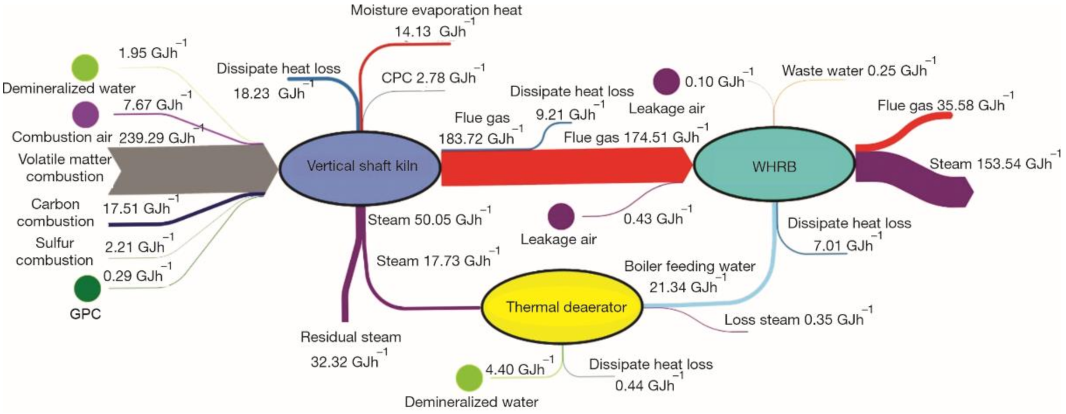

Figure 4. Sankey diagram of the energy flow with the suggested improvements

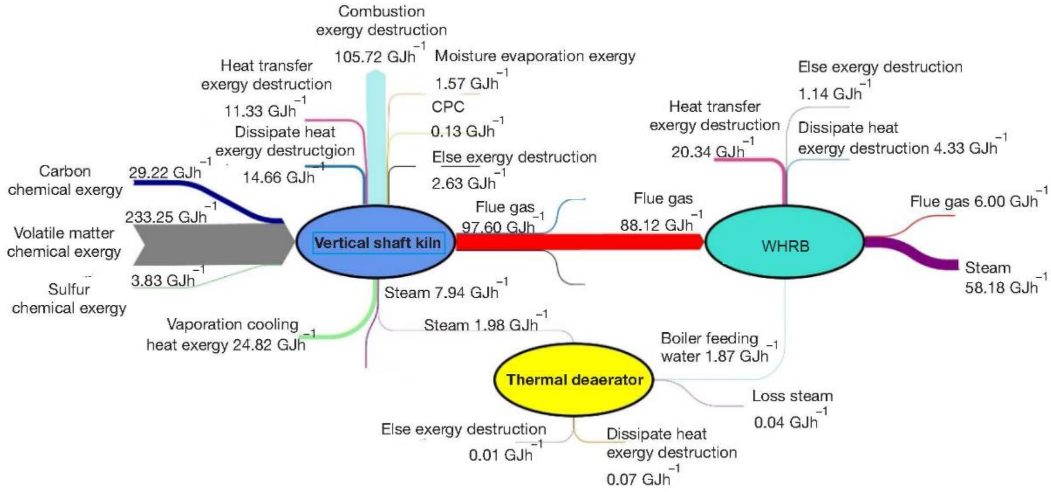

Figure 5. Sankey diagram of the exergy flow with the suggested improvements

Table 7. The calculated exergy flow cost of calcination process with suggested improvements

Exergy flow cost	Parameter	Value	Unit
c_1	Exergy flow cost of volatile matter in GPC	0.0329	RMB per MJ
c_2	Exergy flow cost of steam from VSF	0.002	RMB per MJ
c_3	Exergy flow cost of CPC	712.8328	RMB per MJ
c_4	Exergy flow cost of flue gas from VSF	0.0621	RMB per MJ
c_5	Exergy flow cost of flue gas to WHRB	0.0758	RMB per MJ
c_6	Exergy flow cost of boiler feeding water	0.0547	RMB per MJ
c_7	Exergy flow cost of flue gas out off WHRB	1.1350	RMB per MJ
c_8	Exergy flow cost of steam from WHRB	0.0006	RMB per MJ
c_9	Exergy flow cost of residual steam	0.0002	RMB per MJ
c_{10}	Exergy flow cost of steam to TD	0.0002	RMB per MJ
c_{11}	Exergy flow cost of loss steam of TD	0.0002	RMB per MJ

Conclusions

- The present paper provides a comprehensive analysis of the calcination process using a thermal model based on the First and Second thermodynamic law in conjunction with the exergoeconomic theory. All three major equipment involved in the process are discussed in detail, including the VSF, WHRB boiler and TD.
- For the thermal analysis, the VSF is a self-sufficiency equipment without additional fuel required, but the overall exergy destruction accounts for 54.11% of the total exergy input. In addition, the energy efficiency of the WHRB and TD are 83.52% and 96.40%, whereas the exergy efficiency of the two equipment are 65.98% and 94.27%.
- In order to evaluate the cost of the system, the exergy flow cost mathematical model is established based on the exergoeconomic theory. The import exergy flow cost of VSF, WHRB, and TD are 366.5197 RMB per MJ, 0.1426 RMB per MJ, and 0.0020 RMB per MJ, respectively.
- Several possible improvements are proposed to improve the calcination process on rational energy utilization and exergy cost saving. Flue duct between VSF and WHRB are recommended to enhance insulation performance. Moreover, it is proposed to adopt the vaporization cooling method instead of the traditional cooling way on the cooling water jacket. Furthermore, the internal structure and control mode of the VSF is recommended to optimize. With the suggested improvements, the total exergy destruction of VSF is reduced to 134.34 GJ per hours and the exergy efficiency of WHRB is raised up to 66.02%. Moreover, the import exergy flow cost of the three different equipment are reduced to 0.0329 RMB per MJ, 0.1304 RMB per MJ, and 0.0002 RMB per MJ, respectively.
- Based on our previous work, the present study has extended the model considerations and forwarded the formulations combining the exergy and economic principle. The exergy and exergoeconomic analysis also obtain new findings and conclusions on the calcination process. With the advanced mathematical model and considerations of exergoeconomic, it provides new sights and a more rational energy-using and comprehensive cost-saving

route for other researchers. In addition, the results come from several CPC plants which have been rectified for 2-3 years and operated smoothly now.

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Nomenclature

c	– exergy flow cost
C_P	– specific heat, [kJkg^{-1}K^{-1}]
CCWI	– circulating cooling water inlet
CCWO	– circulating cooling water outlet
CRF	– cost recover factor
e_n^θ	– standard chemical exergy, [kJmol^{-1}]
ED	– exergy destruction, [GJh^{-1}]
Ex	– exergy flow, [GJh^{-1}]
H	– enthalpy
P	– pressure
Q	– quantity of heat
R	– gas constant, [Jmol^{-1}K^{-1}]
R′	– gas constant, [kJm^{-3}K^{-1}]
s	– entropy
T	– temperature, [K]
x	– gas volume content
Y	– equipment running time

Greek symbols

ω	– equipment discount rate
θ	– exergy quality coefficient

Subscripts

CCE	– carbon combustion exergy
CPC	– calcined petroleum coke
CCWHE	– heat exergy of circulating cooling water
CE	– chemical exergy
CED	– chemical exergy destruction
DHED	– dissipate heat exergy destruction
EED	– else exergy destruction
EQ	– equipment
FG	– flow gas
HTED	– heat transfer exergy destruction
G/gen	– generated
GPC	– green petroleum coke
IN	– input
L	– low
LA	– leakage air
LS	– loss steam
MEE	– moisture evaporation exergy
NE	– non-energy
OUT	– output
PE	– physical exergy
ST	– steam
SCE	– sulfur combustion exergy
VM	– volatile matter
VMCE	– volatile matter combustion exergy
WW	– waste water
WHRB	– waste heat recovery boiler

Acronyms

BFW	– boiler feeding water
CA	– combustion air
HYSYS	– name of a process simulation software
TD	– thermal deaerator
VSF	– vertical shaft furnace

References

[1] Bamas, R., Presence and Control of Polycyclic Aromatic Hydrocarbons in Petroleum Coke Drying and Calcination Plants, *Fuel Processing Technology*, *60* (1999), 2, pp. 111-118

[2] Zhan, X., *et al*., Catalytic Effect of Black Liquor on the Gasification Reactivity of Petroleum Coke, *Applied Energy*, *87* (2010), 5, pp. 1710-1715

[3] Azari, K., *et al*., Mixing Variables for Prebaked Anodes Used in Aluminum Production, *Powder Technology*, *235* (2013), Feb., pp. 341-348

[4] Martins, M. A., *et al*., Modeling and Simulation of Petroleum Coke Calcination in Rotary Kilns, *Fuel*, *80* (2001), 11, pp. 1611-1622

[5] Bui, R. T., *et al*., Model-Based Optimization of the Operation of the Coke Calcining Kiln, *Carbon*, *31* (1993), 7, pp. 1139-1147

[6] Yue, Q., *et al*., Resources Saving and Emissions Reduction of the Aluminum Industry in China, *Resources, Conservation and Recycling*, *104* (2015), Nov., pp. 68-75

[7] Xiao, J., *et al*., A Real-Time Mathematical Model for the Two-Dimensional Temperature Field of Petroleum Coke Calcination in Vertical Shaft Calciner, *Jom*, *68* (2016), 8, pp. 2149-2159

[8] Shan, Y., *et al*., Rapid Growth of Petroleum Coke Consumption and its Related Emissions in China, *Applied Energy*, *226* (2018), Sept., pp. 494-502

[9] Xiao, J. *et al*., Modeling and Simulation of Petroleum Coke Calcination in Pot Calciner Using Two-Fluid Model, *Jom*, *68* (2015), 2, pp. 643-655

[10] Elkanzi, E. M., Simulation of the Coke Calcining Processes in Rotary Kilns, *Chemical Product and Process Modeling*, *2* (2007), 3, pp. 1-14

[11] Filkoski, R., *et al*., Energy Optimisation of Vertical Shaft Kiln Operation in the Process of Dolomite Calcination, *Thermal Science*, *22* (2018), 5, pp. 2123-2135

[12] Dolianitis, I. *et al*., Waste Heat Recovery at the Glass Industry with the Intervention of Batch and Cullet Preheating, *Thermal Science*, *20* (2016), 4, pp. 1245-1258

[13] Wei, Y. M., *et al*., An Empirical Analysis of Energy Efficiency in China‘s Iron and Steel Sector, *Energy*, *32* (2007), 12, pp. 2262-2270

[14] Guo, Z. C., Fu, Z. X., Current Situation of Energy Consumption and Measures Taken for Energy Saving in the Iron and Steel Industry in China, *Energy*, *35* (2010), 11, pp. 4356-4360

[15] Rodriguez, M. T. T., *et al*., Combining LCT Tools for the Optimization of an Industrial Process: Material and Energy Flow Analysis and Best Available Techniques, *Journal of Hazardous Materials*, *192* (2011), 3, pp. 1705-1719

[16] Stefanovic, G., *et al*., CO_2 Reduction Options in Cement Industry: The Novi Popovac Case, *Thermal Science*, *14* (2010), 3, pp. 671-679

[17] Bejan, A., Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, *International Journal of Heat & Fluid Flow*, *10* (1988), 1, pp. 87-88

[18] Camdali, U., *et al*., Second Law Analysis of Thermodynamics in the Electric Arc Furnace at a Steel Producing Company, *Energy Conversion and Management*, *44* (2003), 6, pp. 961-973

[19] Dominguez, A., *et al*., Exergy Accounting Applied to Metallurgical Systems: The case of Nickel Processing, *Energy*, *62* (2013), Dec., pp. 37-45

[20] Lazzaretto, A., Tsatsaronis, G., SPECO: A Systematic and General Methodology for Calculating Efficiencies and Costs in Thermal Systems, *Energy*, *31* (2006), 8-9, pp. 1257-1289

[21] Gaggioli, R. A., Wepfer, W. J., Exergy Economics: I. Cost Accounting Applications, *Energy*, *5* (1980), 8-9, pp. 823-837

[22] Regulagadda P., *et al*., Exergy Analysis of a Thermal Power Plant with Measured Boiler and Turbine Losses, *Applied Thermal Engineering*, *30* (2010), 8-9, pp. 970-976

[23] Rong, W., *et al*., Exergy Assessment of a Rotary Kiln-electric Furnace Smelting of Ferronickel Alloy, *Energy*, *138* (2017), Nov., pp. 942-953

[24] Rong, W., *et al*., Energy and Exergy Analysis of an Annular Shaft Kiln with Opposite Burners, *Applied Thermal Engineering*, *119* (2017), June, pp. 629-638

[25] Michaelis, P., *et al*., Exergy Analysis of the Life Cycle of Steel, *Energy*, *23* (1998), 3, pp, 213-220

[26] Morris, D. R., Szargut, J., Standard Chemical Exergy of Some Elements and Compounds on the Planet Earth, *Energy*, *11* (1986), 8, pp. 733-755

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