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Iron ores matching analysis and optimization for iron-making system by taking energy consumption, CO_2 emission or cost minimization as the objective

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An optimization model for iron-making system covering sinter matching process to blast furnace process is established, in which the energy consumption, CO_2 emission and cost minimizations are taken as optimization objectives. Some key constraints are considered according to practical production experience in the modelling. The combination of linear programming (LP) and nonlinear programming (NLP) methods is applied. The optimal sinter matching scheme under given conditions and the optimization results for different objectives are obtained. Effects of sinter grade and basicity on all the optimal objectives and coke ratio in blast furnace process are analyzed, respectively. The results obtained indicate that compared with the initial values, the energy consumption/CO_2 emission of iron-making system decreases by 2.03% for objectives of energy consumption/CO_2 emission minimizations and 1.89% for the objective of cost minimization, the cost decreases by 17.88% and 18.13%, respectively. All the three criteria decrease with the increasing lump usage, coal powder injection, blast temperature, and decreasing coke ratio for the iron-making system.

iron ore matching, iron-making system, minimum energy consumption, minimum CO_2 emission, minimum cost, performance optimization

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1 Introduction

The iron and steel manufacture is a blooming industry in China in the past decades. It also faces unprecedented challenges: international iron ore price rises because of the shortage of good quality resources with the growing demands, both of the cost and energy consumption of sintering process and iron-making system increase as the great variety of iron ores matched for sintering [1]. Moreover, higher requirements are put forward in the respects of energy conservation, CO_2 emission reduction and cost reduction of iron-making system according to the "green steel industry" concept [2–5]. How to rationally match the various iron ores is key to the sintering process, and has a far-reaching influence on the burden structure and operating strategies in the blast furnace process. The sinter matching scheme has a big influence on the energy consumption, CO_2 emission and cost of the whole iron-making system, as it decides the grade, basicity and chemical composition of finished sinter ore.

On the bases of mechanism and production practice, many researches have tried to study the influence of iron ore matching on the energy consumption, CO_2 emission and

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cost of the sintering process and the whole iron-making system. Kawaguchi et al. [6] applied the synthesis simulation method to the sintering process and got the mass and energy consumption of finished sinter ore. Feng [7] established an expert system of ore matching for sintering with the combination of neural network (NN) and empirical methods, and made a precise forecast of the mass with the corresponding matching scheme. The CVRD firm in Brazil simulated the effect of iron ore microstructure on the finished sinter ore properties with artificial neural network (ANN) method, aiming at the optimal iron ore matching scheme [8]. Li and Kong [9] conducted an optimization and adjustment of the sinter matching scheme and blast furnace charging materials aiming to reduce the unit cost of iron production. The optimal sinter matching scheme, sinter grade and coal ratio in the blast furnace were derived aiming for system cost minimization. Li and Song [10] and Guo [11] combined the calculations of iron ore matching in sintering process and blast furnace iron-making process, and analyzed the influence of the sinter ore properties on the blast furnace burden structure and unit cost of the hot metal. Liu et al. [12] gave an energy value to every material to be matched in the sinter matching process, and applied the linear programming (LP) method to optimize the matching scheme by taking the total energy value of all the matching materials as the optimization objective.

Many researchers have tried to analyze the blast furnace iron-making process and system by using mathematical modelling method and got plenty of meaningful results [13–16]. Based on the material and energy flows relationships, several optimization models have been established with some objectives by using the LP method, aiming to explore effective approaches to achieve the goals of energy conservation, CO_2 emission reduction and cost reduction [17–20]. Larsson et al. [21–24] adopted the mixed integer linear programming (MILP) method to model the iron and steel production system, and conducted integrated optimization analyses of the energy and CO_2 emission with the planned production system schematic outline. The research results provided instructive selections of the operating parameters in each process and the new energy-saving facilities. Ryman et al. [25,26] combined the pinch analysis with MILP method to optimize the energy consumption, CO_2 emission and profits of the whole steel production system. Mohanty et al. [27] applied the ANN to the iron-making process in a rotary kiln, and established the association model for inputs and outputs with plenty of constraints. The genetic algorithm was introduced to carry out a multi-objective optimization of several major operating parameters. The results indicated some possible improvements. Helle et al. [28,29] applied the LP method to model an oxygen enriched blast furnace with top gas recycling, and obtained the optimal production technology parameters by taking CO_2 emission or cost minimization or both as the optimization objectives. Cai et al. [30] introduced the neural network to model the blast furnace iron-making process with considerations of the effects of silicon element content, blast temperature and volume. Based on an in-depth analysis of the energy and resource consumption states for sintering and iron-making processes in Tangshan iron and steel company, Zhou et al. [31] calculated the CO_2 emission due to the carbonaceous energy resources by applying the metallurgical process engineering (MPE) method [32] to the established input-output model. Lu et al. [33] conducted a systematical analysis of the ferrite-flows characters and structures [34] in iron and steel manufacturing process and established an optimization model focusing on the energy intensity in production, and calculated it under five different optimized production schemes. The results showed that increases of lump and scrap usage, and raise of sinter grade played active roles in reducing the energy intensity of whole production system.

Based on the LP theory, Yang et al. [35] established a model for single and multi-objective optimizations in the blast furnace process, in which the coke ratio, hot metal yield and cost were taken as the optimization objectives. Effects of major operating parameters on the optimal performance were analyzed. Taking minimum carbon emission, maximum utilization coefficient and minimum exergy loss of a blast furnace as optimization objectives, Liu et al. [36,37] and Qin et al. [38] established an optimization model with multiple technological constraints based on the material and energy flows. The fuel structure and operating parameters were optimized by using the new sequential quadratic programming (SQP) method proposed by Zhu and Zhang [39]. The effects of blast humility and fuel composition on the results were obtained. Based on refs. [36–38], Zhang et al. [40] established a model consisting of blast blower, hot stove, blast furnace and top pressure recovery turbine unit (TRT), in which the SQP method was adopted to optimize the technology parameters and analyze the effects of blast temperature, coal ratio and oxygen enrichment ratio on the energy consumption and power production in the whole system. Based on the integrated process thought, Zhang et al. [41] established an optimization model focusing on the multi-objectives including energy, CO_2 emission and cost of iron-making process, and obtained the optimal matching scheme and operating parameters by using the MILP method. The practical production datum were introduced to accomplish the calculation and analyze the effects of coal ratio, coke ratio and sinter grade. The results indicated some effective measures to reduce the energy consumption and emission. Liu et al. [42] introduced the constructal theory (CT) [43–48] to a blast furnace, and established an optimization model seeking for the yield maximization. The cost distribution and charging scheme of raw materials were optimized and the effects of some major parameters were analyzed, respectively. Furthermore, considering the widely use of the finite time thermodynamics (FTT)

[49–55] for energy conservation in the iron and steel production process [56–64], Liu et al. [65] combined FTT and CT to establish a new optimization model in blast furnace process. An integrated objective taking both the yield and useful energy into account was optimized, and optimal material cost distribution and major operating parameters were obtained and analyzed. A series of works have established a theoretical frame of generalized thermodynamic optimization for iron and steel production processes [66–68].

What is worthy to be mentioned is that when researchers studied on the sintering matching process, they usually focused on the calculation and prediction of quality, component, productivity and operability based on models established by using the sintering experiments, genetic algorithm or expert system etc. [69]. And when researchers studied on the iron-making process, they usually focused on the coke ratio, energy consumption and yield objectives based on modelling the blast furnace body or process by using empirical simulation, linear programming or input-output methods. What is more, the constraints in the models were usually linearized accordingly and then the linear programming and variables circulation coordination were introduced to solve the relevant problems. It is worth pointing out that this human intervention can be avoided by combining the LP and NLP methods. Thus, based on refs. [10,36–38], an optimization model throughout the system from iron ore matching to hot metal output will be established according to the material and energy balances, chemical reaction mechanism and practical production in this paper. Some constraints are adjusted to be optimal ones and the results will be obtained by combining LP and NLP methods. The minimization of energy consumption, CO_2 emission and cost for unit hot metal production will be taken as objectives. The optimization results under different objectives are compared. The effects of sinter ore grade and basicity on the optimal results will be analyzed, respectively.

2 Optimization model of iron-making system

2.1 Physical model

The physical model of iron-making system is shown in Figure 1, and the main input-output behavior is shown in Figure 2. With the setting grade TFe and basicity *R*, the sinter ore is produced according to optimal matching scheme of iron ores, flux and fuels, which makes the unit energy consumption of finished sinter ore to be $E_{\rm sinter}$, the CO_2 emission $Em_{\rm sinter}$ and the unit cost $c_{\rm sinter}$. Similarly, each process in the iron-making system produces the corresponding product

Figure 1 (Color online) Main material flows in the iron-making system.

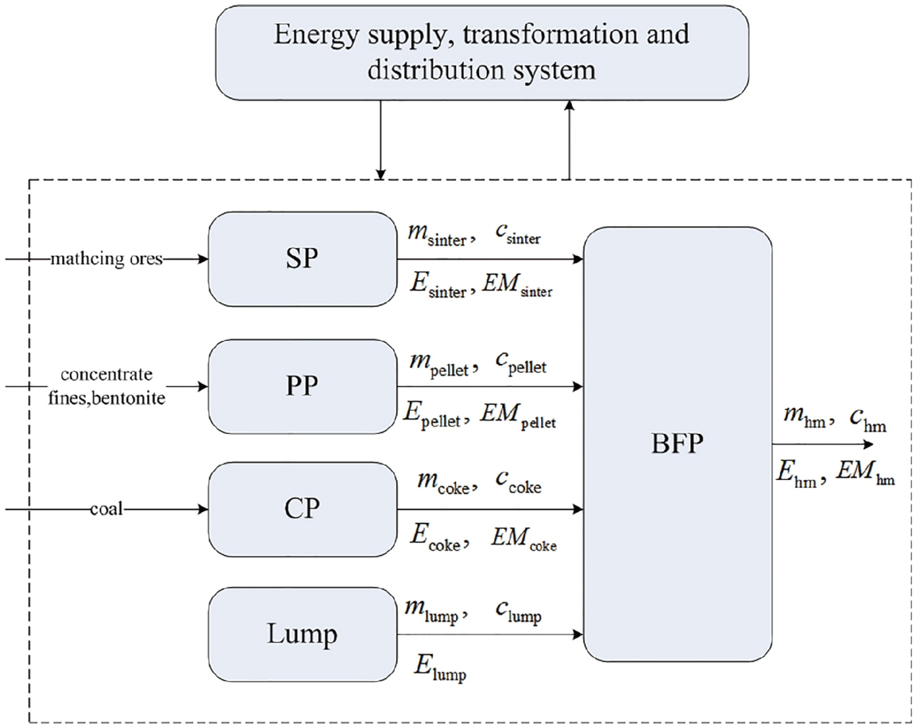

Figure 2 Main inputs and outputs in the iron-making system.

with the unit energy consumption E_k, the CO_2 emission Em_k and the unit cost c_k, where the subscript k represents sinter, pellet, coke and lump, respectively. And then, coke and all the iron ores with their matching mass come to react in the blast furnace to make the hot metal.

The energy supply, transformation and distribution system mainly consists of three parts: 1) external purchase of energy sources such as coal, power, steam, new water and gases; 2) energy transformation, storage and distribution; 3) recovery and utilization of residual heat and energy.

For each process and facility within the iron-making system, there exist complicated material flow and energy flow. Therefore, the material flow and energy flow models for all parts in the system, including the main production processes, the auxiliary system and some key facilities like CDQ, HBS, TRT, etc., are established to make the system model relatively complete. Taking the sintering process as an example, the main input-output behaviors of material flow and energy flow are covered and analyzed, as shown in Figure 3. It is worth noticing that many input and output materials are also energy flows, such as COG, compressed air, coke breeze, anthracite and steam, and some of them come from or go into the energy supply, transformation and distribution system. According to actual production, the recovery and utilization of residual heat is involved in the model to produce steam and electricity. It also indicates that the matching scheme of sintering process has a direct influence on the process and a far-reaching one on the whole iron-making system. With all these material flow and energy flow models, the energy consumption, CO_2 emission and unit cost of each process can be calculated and the linked to the system objectives.

For the instance of many physical and chemical reactions at non-equilibrium state in every process within the iron-making system, some assumptions are necessary to achieve the optimal results when establishing the optimization model: 1) all the physical and chemical processes within the iron-making system are in equilibrium states; 2) all materials involved in the system are ideal mixtures with uniform properties; 3) the temperature of raw materials into the processes before blast furnace, the coke and all the iron ores into the blast furnace are equivalent to that of environment. The environment temperature equals to 298 K, and the other parameters are set according to the actual production in all the processes.

2.2 Optimal design variables

The factors affecting the energy consumption, CO_2 emission and cost of the sintering process and the whole iron-making system are divided into three classes: 1) matching mass of the relevant materials; 2) structural and operating parameters; 3) energy saving facilities. It is worth noticing that the matching scheme of iron ores, flux and fuels in the sintering process directly affects the property and chemical composition of sinter ore, and then has a far-reaching influence on the proportioning and operating parameters of the whole iron-making system. Thus 17 parameters are chosen as the optimal design variables for the system: the matching scheme in the sintering process M ($M = [m_i]$,i=1,2,3…,10), mass ratio of sinter ore m_{sinter}, mass ratio of pellet ore m_{pellet}, mass ratio of lump

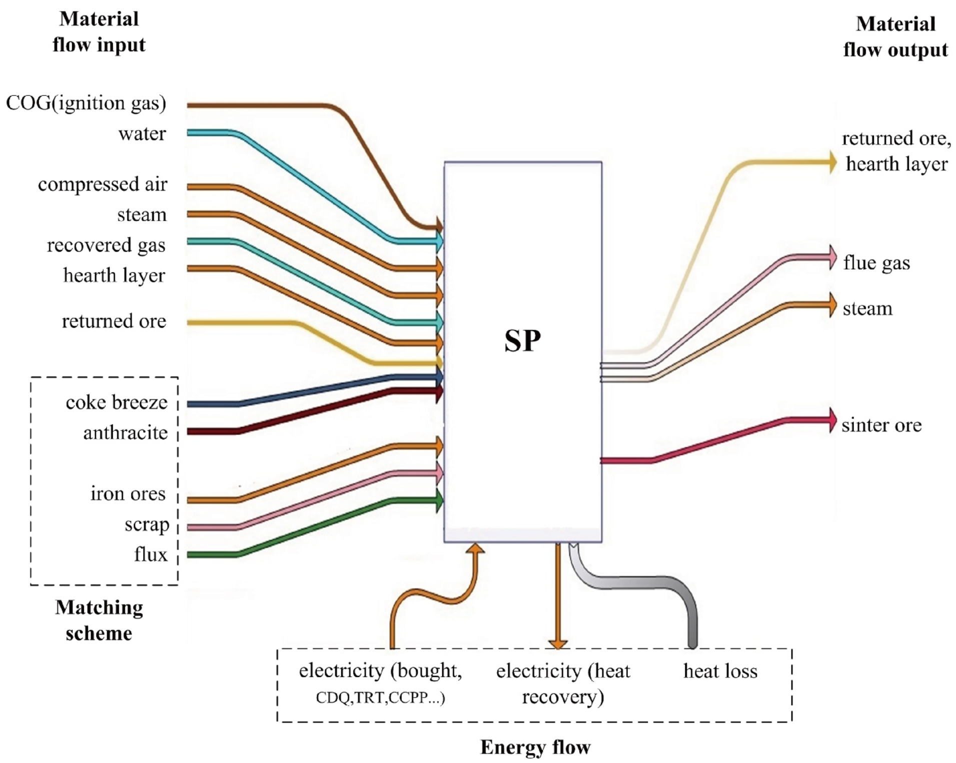

Figure 3 (Color online) Material flow and energy flow in the sintering process.

m_{lump}, coal ratio m_{coal}, coke ratio m_{coke}, blast temperature t_{b} and air volume V_{b}.

2.3 Optimization objectives

Based on the material and energy flows of iron-making system, relevant balance of mass and energy for per process and the whole system can be established. The chemical reaction mechanism, actual production experience, technological constraints and consumption of energy medium are considered. The energy consumption, CO_2 emission and cost of unit product for per process and the iron-making system can be calculated by combining LP and NLP methods.

For each process, the energy consumption or cost of unit production can be expressed as the following equation:

$$E_k = \sum^{s} m_{ik} q_{ik} + \sum^{t} m_{jk} q_{jk} - \sum^{n} m_{lk} q_{lk}, \tag{1}$$

where E_k is the energy consumption or cost of unit production for the k process; m_{ik}, m_{jk} and m_{lk} are the masses of the input, assistant and recycling materials; q_{ik}, q_{jk} and q_{lk} are the unit costs or energy consumptions of the relevant materials, respectively.

For each process, the CO_2 emission of unit production can be expressed as the following equation:

$$Em_k = \alpha E_k, \tag{2}$$

where Em_k is the CO_2 emission for the k process, and α is the coefficient of CO_2 emission to energy consumption (http://wenku.baidu.com/view/e8497b1952d380eb62946d2b.html).

The energy consumption for the whole iron-making system is calculated using the following equation:

$$E = m_{\text{sinter}} E_{\text{sinter}} + m_{\text{pellet}} E_{\text{pellet}} + m_{\text{coke}} E_{\text{coke}} + m_{\text{lump}} E_{\text{lump}} + E_{\text{hm}}. \tag{3}$$

The CO_2 emission for the whole iron-making system is calculated using the following equation:

$$Em = m_{\text{sinter}} (Em)_{\text{sinter}} + m_{\text{pellet}} (Em)_{\text{pellet}} + m_{\text{coke}} (Em)_{\text{coke}} + (Em)_{\text{bf}}. \tag{4}$$

The cost for the whole iron-making system is calculated using the following equation:

$$C = m_{\text{sinter}} c_{\text{sinter}} + m_{\text{pellet}} c_{\text{pellet}} + m_{\text{coke}} c_{\text{coke}} + m_{\text{lump}} c_{\text{lump}} + \sum^{t} m_{\text{bf},j} c_{\text{bf},j}, \tag{5}$$

where $m_{\text{bf},j}$ and $c_{\text{bf},j}$ are the consumption of materials or energy flows, and the relevant costs in the blast furnace process, respectively.

2.4 Constraint conditions

The constraint conditions within the iron-making system can be grouped into four classes: balance constraints, such as material and heat balances, gas balance; process constraints, such as basicity, hot metal composition constraints; operating constraints, such as blast temperature, blast pressure; and range constraints such as iron ore supplies, coal injection rate.

All these constraints mentioned above within this iron-making system optimization model add up to 44 in total.

For the ore matching of sintering process, the matching scheme should meet 18 constraints consisting of mass balance, sinter ore basicity, chemical components, etc., linear and nonlinear ones. In some way, the nonlinear constraints can be changed into linear ones. Thus the LP method works, and the governing equations can be expressed as

$$\begin{cases} l_i \le \sum_j a_j^i m_j \le L_i, \\ p_l \le p \le p_L, \\ \min G(m) = \min(\sum_j b(m_j) g_j(m_j)), \end{cases} \tag{6}$$

where a_j^i is the component or weight coefficient for a certain ore; l_i and L_i are the lower and upper bounds for certain constraints; p is the process constraint and $b(m_j)$ is the weight coefficient for mass function $g_j(m_j)$ and $G(m)$ is the objective function.

For the blast furnace process, the constraints consist of mass and heat balances, slag basicity, chemical components, process parameters, upper and lower bounds, etc., both linear and nonlinear ones. Combination of the LP and NLP methods is applied to solve the optimization problem, the governing equations can be expressed as

$$\begin{cases} p_{ja} \le p_j \le p_{jb}, \\ l_i \le \sum_j w_j^i x_j \le L_i, \\ n_i \le f(w_j^i, x_k, x_j) \le N_i, \\ \min G(x) = \min\left(\sum_j b(x_j) g_j(x_j)\right), \end{cases} \tag{7}$$

where w_j^i is the component or weight coefficient for a certain ore, $b(x_j)$ is the weight coefficient for mass function $g_j(x_j)$, $G(x)$ is the objective function.

2.5 Solution for the optimization model

For the diversified linear and nonlinear constraints of the optimization model, the combination of LP and NLP methods is chosen to solve the problem. The calculation procedure for the material and energy flows in each process is programmed as the basis of the optimization. Moreover, global search method is adopted to generate the start points within the ranges of relevant constraints. Moreover, the “fmincon” optimization function is adopted for its extraordinary talent to solve the multidimensional linear and nonlinear programming problems, so is the sequential quadratic programming algorithm for its good convergence to solve the optimization model with multivariable and multiple constraints. The optimization problem can be solved by the combination of all the methods above.

3 Results and analyses

A practical iron-making system in a steel plant is taken as a case to study. The main parameters of equipment in each process are as following: the height of carbonization chamber is 5.5 m and the effective cooling volume in CDQ is V_{CDQ}=450 m^3; the sintering area is A_{sp}=450 m^2 and the cooling 415 m^2; the size of grate-kiln-cooler system is 4 m×52 m, Φ 4.7×52 m and Φ 4.7×52 m; the production volume of blast furnace is V_{bf}=4350 m^3. The operating parameters are set according to the practical production.

3.1 Optimization results and analyses

Table 1 lists initial iron ore matching scheme and the optimized one in the sintering process with some certain and optimized constraints. It also shows some production requirements and compositional variations for the finished sinter ore after the optimization under the system objectives. Table 2 lists initial fuel and iron ore matching masses and the operating parameters and the optimized ones in the iron-making system. The optimization objectives are compared with those in practical production and there exist several changes after optimization: the lump dosage always increases for its lower unit energy consumption and cost compared with the sinter and pellet, namely increasing the lump dosage into the blast furnace can be an energy-saving and economic way in the iron-making system. The coal ratio reaches its maximum (260 kg/t). The coke ratio significantly decreases by as much as 35.08% from 325.00 kg/t to approximate 211 kg/t. The blasting temperature reaches its maximum (1250°C), and the volume increases somewhat for the changed burden structure and blast humidity. After the optimization, all the system energy consumption, CO_2 emission and cost decrease, respectively: the energy consumption, CO_2 emission decrease by 2.03% and the cost 17.88% when taking the former two as the optimization objectives; the consumption, CO_2 emission decrease by 1.89% and the cost 18.13% when taking the last as the optimization objective. One can see from the results, increasing lump dosage, coal power injection, blasting temperature and decreasing coke ratio are effective approaches to achieve the goals of energy conservation, CO_2 emission reduction and cost reduction.

3.2 Analyses of influence factors

The sinter matching scheme not only affects energy consumption, CO_2 emission and cost of the sintering process, but also has a far-reaching influence on the proportioning and operating parameters of the whole iron-making system. Thus, effects of the grade (TFe) and basicity (R) of sinter ore, which are the leading indicators in the sinter matching scheme process, on the minimum energy consumption, CO_2 emission and cost of whole system and coke ratio in blast furnace process are analyzed, respectively.

Table 1 Changes of chemical components before and after sinter matching optimization in SP

	Before optimization	Range	After optimization
	Matching mass (kg/t)		
m_1	300.10	300.00–1000.00	300.00
m_2	131.24	0.00–1000.00	96.13
m_3	268.66	100.00–1000.00	303.87
m_4	50.00	30.00–50.00	50.00
m_5	78.87	0.00–1000.00	81.78
m_6	50.00	50.00–1000.00	50.00
m_7	20.00	20.00–30.00	20.00
m_8	98.53	60.00–1000.00	94.79
m_9	84.95	10.00–1000.00	85.16
m_{10}	50.00	50.00–70.00	50.00
	Chemical component of sinter ore (%)		
ω_{TFe}	55.68	55–56	56
ω_{FeO}	7	7–8	7
ω_{CaO}	10.19	10–11	10
ω_{MgO}	2	2–2.5	2
$\omega_{Al_2O_3}$	1.70	1.5–3	1.67
ω_{SiO_2}	5.6	≤5.6	5.5
ω_S	0.0184	<0.1	0.0193
R_2	1.8196	1.8–1.82	1.818

Table 2 Variables and results before and after optimizations in the whole system

Variable	Introduction	Symbol	Unit	Actual value	Range	Opt I	Opt II
x_1	Sinter ore ratio	m_{sinter}	kg/t	1036.35	0–1500	1052.9	1068.6
x_2	Pellet ore ratio	m_{pellet}	kg/t	447.79	0–1000	425.3	411.8
x_3	Lump ore ratio	m_{lump}	kg/t	158.52	0–300	164.2	164.5
x_4	Coal ratio	m_{coal}	kg/t	110.00	100–260	260.00	260
x_5	Coke ratio	m_{coke}	kg/t	325.00	180–500	211.1	211.3
x_6	Blast volume	V_b	Nm^3/t	968.7	700–1800	978.3	971.4
x_7	Blast temperature	t_b	°C	1250	1050–1250	1250	1250
–	Energy consumption	E	kgce/t	495.78	–	**485.71**	486.40
–	CO_2 emission	Em	kg/t	1338.61	–	**1311.42**	1313.3
–	Cost	C	yuan/t	2387.9	–	1961.0	**1954.9**

3.2.1 *Taking the energy consumption or CO_2 emission as the optimization objective (Opt I)*

Figures 4–7 show the effects of TFe or R on the minimum energy consumption and CO_2 emission of whole system. One can see from Figures 4 and 6 that with the given R, both the minimum energy consumption and CO_2 emission of iron-making system decrease with the increase of TFe. What is more, the decreasing extent and trend are similar when the TFe increases, namely, the minimum energy consumption of iron-making system decreases by 0.71 kgce/t approximately and the minimum CO_2 emission 1.92 kg/t when the TFe increases by 1%. One can see from Figures 5 and 7 that with the given TFe, both the minimum energy consumption and CO_2 emission of iron-making system decrease with the increase of R. What is more, the decreasing extent and trend are similar when the TFe increases, namely, the minimum energy consumption of iron-making system decreases by 2.36 kgce/t approximately and the minimum CO_2 emission 6.37 kg/t when the R increases by 0.1. The results indicate that increasing the basicity and grade of charging sinter ore are effective ways to

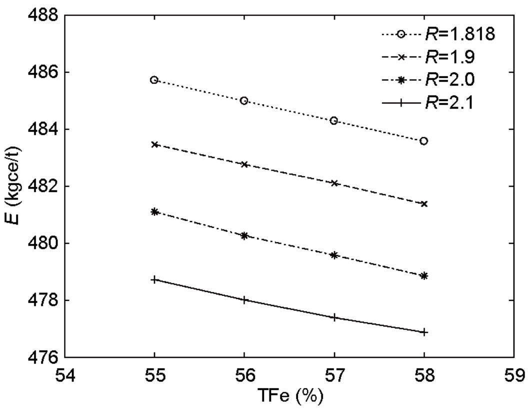

Figure 4 The effect of *R* on *E*-TFe characteristic for Opt I.

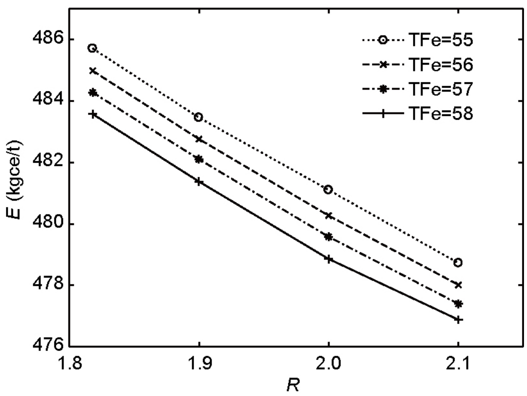

Figure 5 The effect of TFe on *E*-*R* characteristic for Opt I.

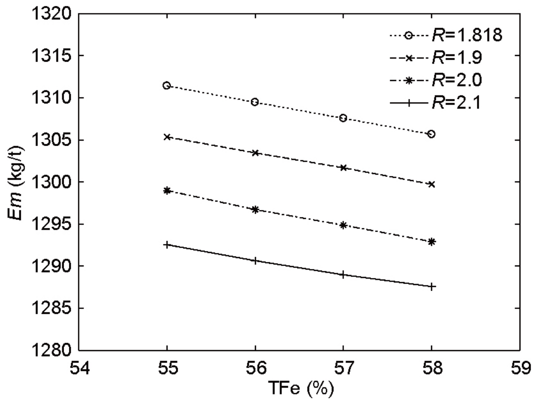

Figure 6 The effect of *R* on *Em*-TFe characteristic for Opt I.

achieve energy conservation and CO_2 emission reduction for the iron-making system.

Figures 8 and 9 show the effects of TFe or *R* on the minimum cost of whole system, respectively. One can see from Figure 8 that with the given *R*, the minimum cost of iron-making system decreases with the increase of TFe. And the higher the *R* is, the larger decrease amount of the minimum cost will be. One can see from Figure 9 that for the given TFe, the minimum cost of iron-making system increases with the increase of *R* within a certain range. And the increasing amplitude of cost increases with the increase in the relevant lower sinter grade (TFe=55%, 56%), and shows an "increase-decrease-increase" trend with the increase in the relevant higher sinter

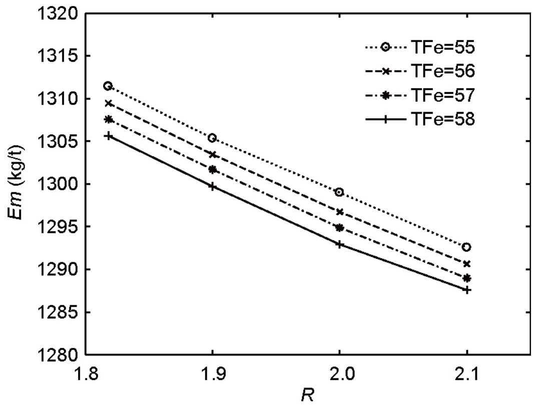

Figure 7 The effect of TFe on *Em*-*R* characteristic for Opt I.

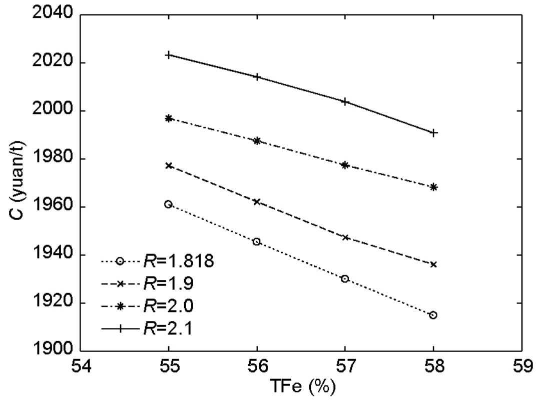

Figure 8 The effect of *R* on *C*-TFe characteristic for Opt I.

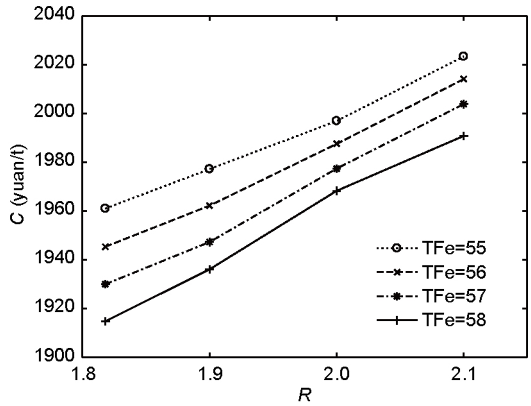

Figure 9 The effect of TFe characteristic on *C*-*R* for Opt I.

grade (TFe=57%, 58%). Namely, the cost of iron-making system is sensitive to the *R* in the range of 1.9 to 2.0, which is more evident in higher TFe.

Figures 10 and 11 show the effects of TFe or *R* on the optimal coke ratio in blast furnace process, respectively. One can see from Figure 10 that for the given *R*, the optimal coke ratio decreases with increase of TFe, and the decreasing amplitude decreases with the increase of *R*. The characteristic is more evident when the *R* is bigger than 1.9, namely, the optimal coke ratio is sensitive to the sinter grade in relevant lower *R*. One can see from Figure 11 that for the given TFe, the optimal coke ratio decreases with the increase of *R* within a certain range. At the same time, the decrease of cost slows down with the increase of *R*. It is worth noticing that when the *R* varies in the range of 1.8–2.1, the cost of iron-making system is sensitive to the TFe varies in the certain range, the optimal coke ratio changes little, namely, given the *R* to be 2.0, the optimal coke ratio is grade-insensitive. The results indicate that increasing the basicity and grade of charging sinter ore are effective ways to reduce the coke ratio in blast furnace, which is in keeping with the goals of energy conservation, CO_2 emission reduction but different from the cost reduction. Moreover, energy conservation and emission reduction has a positive correlation with the coke ratio reduction.

3.2.2 *Taking the cost as the optimization objective (Opt II)*

Figures 12–15 show the effects of TFe or *R* of sinter ore on the minimum energy consumption and CO_2 emission of whole system. One can see from Figures 12 and 14 that with the given *R*, both the minimum energy consumption and CO_2 emission of iron-making system decrease with the increase

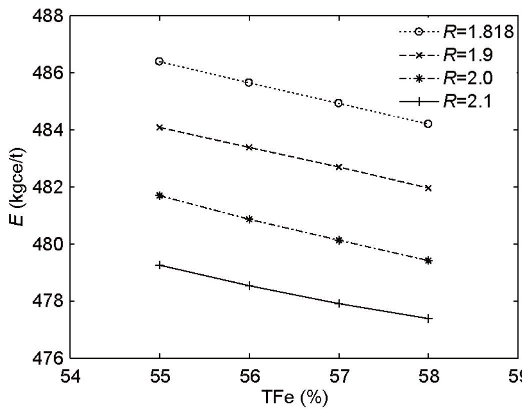

Figure 12 The effect of *R* on *E*-TFe characteristic for Opt II.

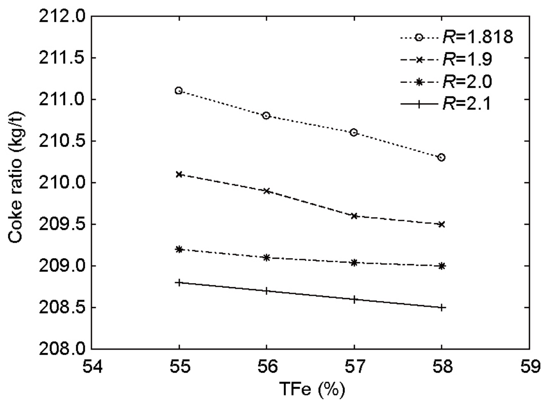

Figure 10 The effect of *R* on TFe versus coke ratio for Opt I.

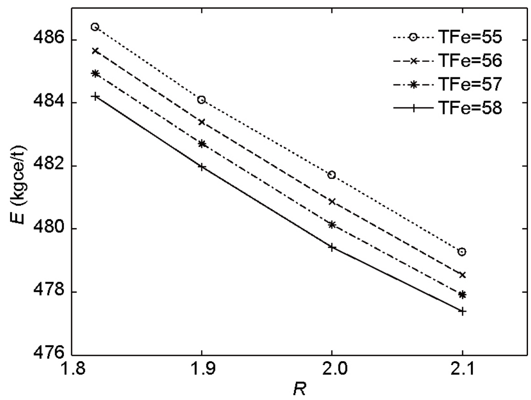

Figure 13 The effect of TFe on *E*-*R* characteristic for Opt II.

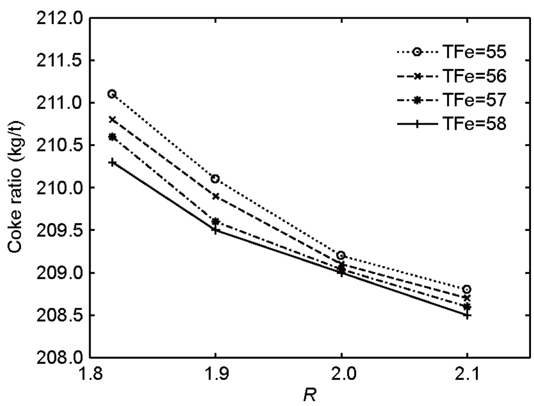

Figure 11 The effect of TFe on *R* versus coke ratio for Opt I.

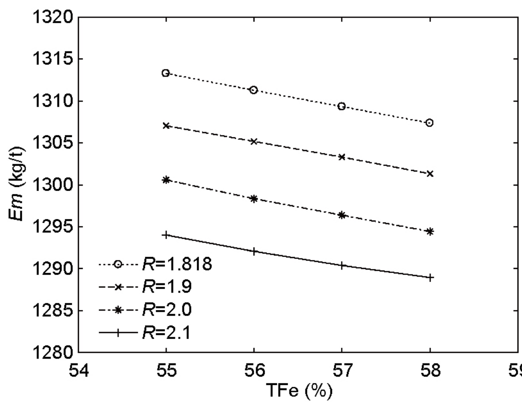

Figure 14 The effect of *R* on *Em*-TFe characteristic for Opt II.

of TFe. What is more, the decreasing extent and trend are similar when the TFe increases, namely, the minimum energy consumption of iron-making system decreases by 0.63–0.76 kgce/t respectively and the minimum CO_2 emission 1.70–2.05 kg/t when the TFe increases by 1%. One can see from Figures 13 and 15 that with the given TFe, both the minimum energy consumption and CO_2 emission of iron-making system decrease with the increase of *R*. What is more, the decreasing extent and trend are similar when *R* increases, namely, the minimum energy consumption of iron-making system decreases by 2.38 kgce/t approximately and the minimum CO_2 emission 6.43 kg/t when *R* increases by 0.1.

Figures 16 and 17 show the effects of TFe or *R* on the minimum cost of whole iron-making system, respectively. One can see from Figure 16 that with the given *R*, the minimum cost of iron-making system decreases with the increase of TFe. And the higher the *R* is, the larger decrease amount of the minimum cost will be. One can see from Figure 17 that for the given TFe, the minimum cost of iron-making system increases with the increase of *R* within a certain range. The increasing amplitude of cost increases with the increase in the relevant lower sinter grade (TFe=55%, 56%), and shows an "increase-decrease-increase" trend with the increase in the relevant higher TFe (TFe=57%, 58%). Namely, the cost of iron-making system is sensitive to the *R* in the range of 1.9 to 2.0, which is more evident in higher TFe. The results indicate that increasing the grade and decreasing the basicity of charging sinter ore are effective ways to reduce cost of iron-making system. That is very different from the results of taking the energy consumption or CO_2 emission as the optimization objective.

Figures 18 and 19 show the effects of TFe or *R* of sinter ore on the optimal coke ratio in blast furnace process, respectively. One can see from Figure 18 that with the given *R*, the optimal coke ratio decreases with increase of TFe, and the decreasing amplitude shows an "increase-decrease-increase" trend. The characteristic is more evident when the *R* is lower than 2.0, namely, the optimal coke ratio is sensitive to the sinter grade in relevant lower *R*. One can see from Figure 19 that for the given TFe, the optimal coke ratio decreases with the increase of *R* in a certain range. At the same time, the decrease of cost slows down with the increase of *R*. Namely, the optimal coke ratio is relevantly insensitive to sinter ore with lower basicity. The results indicate that increasing the basicity and grade of charging sinter ore are effective ways to reduce the coke ratio in blast furnace, which is in keeping with the goals of energy conservation, CO_2 emission

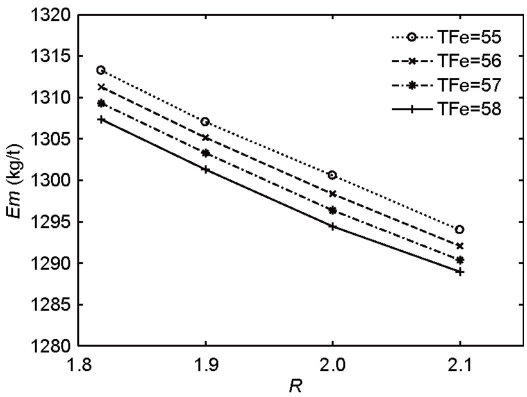

Figure 15 The effect of TFe on *Em*-*R* characteristic for Opt II.

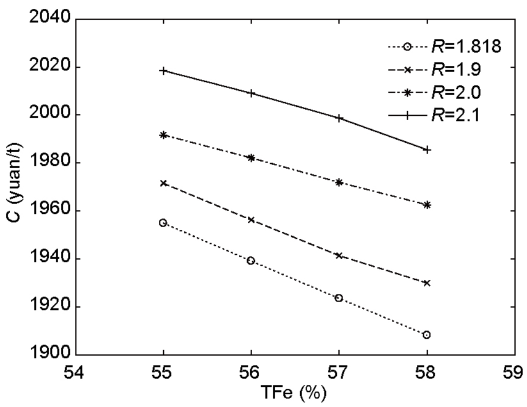

Figure 16 The effect of *R* on *C*-TFe characteristic for Opt II.

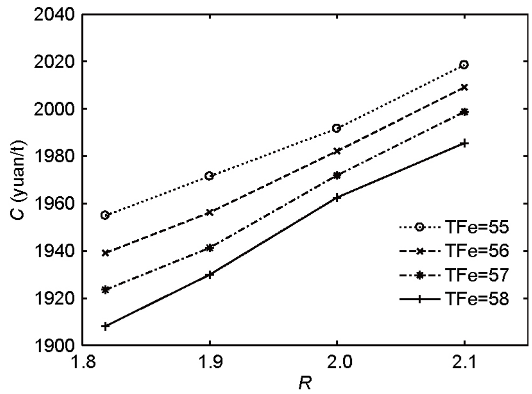

Figure 17 The effect of TFe characteristic on *C*-*R* for Opt II.

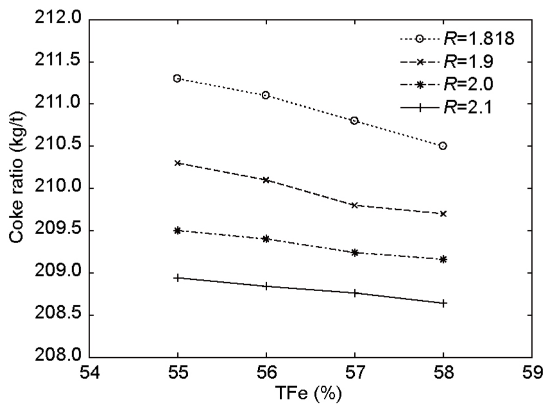

Figure 18 The effect of *R* on TFe versus coke ratio for Opt II.

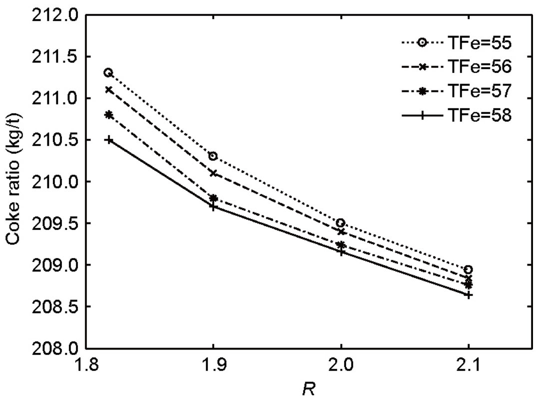

Figure 19 The effect of TFe on *R* versus coke ratio for Opt II.

reduction but different from the cost reduction.

4 Conclusion

Taking minimum energy consumption, CO_2 emission and cost as optimization objectives, an optimization model for iron-making system covering sinter ore matching process to blast furnace is established. 44 constraints, 10 iron ore matching variables and 7 materials and operating variables are included in the model. The combination of linear programming (LP) and nonlinear programming (NLP) methods is applied to solve the problem. The optimal iron ore matching scheme is obtained within the given parameters, and the optimization results of energy consumption, CO_2 emission and cost minimization are obtained. Effects of sinter ore grade and basicity to the three optimization objectives and coke ratio of blast furnace process are analyzed. The major results are listed in the following items:

(1) Compared with the initial values, the energy consumption/CO_2 emission of iron-making system decreases by 2.03% for objectives of energy consumption/CO_2 emission minimizations and 1.89% for the objective of cost minimization, the cost decreases by 17.88% and 18.13%, respectively.

(2) All the three optimal criteria decrease with the increasing lump usage, coal powder injection, blast temperature, and decreasing coke ratio for the iron-making system.

(3) Increasing the basicity and grade of charging sinter ore are effective ways to reduce the energy consumption, CO_2 emission and coke ratio in blast furnace process and the whole iron-making system. Decreasing sinter basicity is positive to reduce the cost of system, what makes an optimal sinter basicity exist to give consideration to all the objectives above.

(4) Taking whichever of minimum energy consumption, CO_2 emission or cost as optimization objective, the cost of iron-making system is always sensitive to the sinter basicity (R) in the range of 1.9 to 2.0 in relevantly high sinter grade, which is more evident in higher sinter grade (TFe).

(5) The optimization model in this paper is more specialized and complete for the iron-making system and the results obtained can provide an guidance to energy conservation, CO_2 emission reduction and cost reduction of iron-making process.

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