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Multi-Objective Optimization of Cost Saving and Emission Reduction in Blast Furnace Ironmaking Process

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Abstract: Due to the increasing environmental pressures, one of the most direct and effective way to achieve emission reduction is to reduce the CO_2 emissions of the blast furnace process in the iron and steel industry. Based on the substance conservation and energy conservation of ironmaking process and the engineering method, the carbon loss model was firstly established to calculate the amount of solution loss. Based on this model, the blast furnace emission reduction optimization mathematical model with the cost and CO_2 emissions as objective functions was then established using the multiple-objective optimization method. The optimized results were obtained by using the GRG (Generalized Reduced Gradient) nonlinear solving method. The optimization model was applied to the B# blast furnace of BayiSteel in China. The optimization model was verified by comparing the optimized results with the actual production data. The optimization model was then applied to analyze the effects of coke ratio, coal rate, blast temperature and other factors on the cost, CO_2 emission and solution loss, and some measures to save cost, reduce emissions and reduce solution loss have been proposed.

Keywords: blast furnace; cost; CO_2 emissions; solution loss; multi-objective optimization

1. Introduction

Global anthropogenic CO_2 emissions grew by 1.4% in 2017, reaching a historic high of 32.5 gigatonnes (Gt), a resumption of growth after three years of global emissions remaining flat [1]. And the CO_2 emissions is expected to grow to 37 Gt in 2020 [2]. Since 2012, China has become the world's largest carbon emitter, and its CO_2 emissions accounted for 29% of the world [3]. In 2010, the CO_2 emissions from the iron and steel industry accounted for 15% of China's total CO_2 emissions [4–6]. In China, CO_2 emissions of ironmaking system, including sintering, coking and blast furnace, account for nearly 90% of the iron and steel industry. The CO_2 emissions of blast furnaces process account for more than 70% of ironmaking system [3,4,7–9]. In China, the main CO_2 emission source is blast furnace process that almost entirely uses coke and pulverized coal as fuel [10]. Therefore, the most direct and effective way to achieve emission reduction is to reduce the CO_2 emissions of the blast furnace process in the iron and steel industry.

The CO_2 emissions calculation method of the World Steel Association (WSA) is adopted in this paper. In this method, CO_2 emissions equals the direct emission plus the indirect emission and minus the deductible carbon emission. The direct emission is the CO_2 emissions caused by the consumption of fuels and fluxes in the production process. The indirect emission is the CO_2 emissions emitted by raw materials and energy in their own production processes. The deductible carbon emission is the amount of CO_2 emissions deducted from the sale or reuse of by-products. The emission factors set by the WSA is an international average value, and some emission factors are not applicable to Chinese enterprises. Therefore, the measured emission factors of target blast furnace are used in this model, and the CO_2 emissions of blast furnaces process and the CO_2 emissions of ironmaking system are then calculated respectively. The CO_2 emissions of ironmaking system includes the indirect emission of the upstream processes such as coking and sintering [9,11].

Metallurgical coke is the most important and inevitable raw material in the blast furnace. It is a fuel, a reductant, a carburetant and a permeable medium in the blast furnace. As coke sustains the passages of liquid metal and slag toward the lower part and the high temperature reducing gas toward the upper part, it is regarded as an indispensable material in blast furnace. Besides, coke is the only solid phase in the high temperature zones adjacent to the blast furnace raceways. Therefore, coke quality affects the gas permeability, liquid permeability of the burden and state of hearth [12]. Due to the increase of blast furnace volume, environmental pressures and the increasing scarcity of good quality coking coal, injecting pulverized coal is developed to decrease reliance on coke. With the decrease of coke ratio, the ore to coke ratio increases in the burden, so a lesser amount of coke has to maintain sufficient permeability and performance of blast furnace. The residence time of coke in the blast furnace becomes larger. Coke is deteriorated by the mechanical, thermal and chemical effects when it moves toward lower part of blast furnace. With the prolonging of the residence time of coke, coke suffers more mechanical, thermal and chemical effects than ever before, resulting in increased deterioration of coke. Coke is gasified in the blast furnace shaft by the so-called solution loss reactions with CO_2 and H_2O. Solution loss reaction is the main factor that causes the decrease of coke strength in the blast furnace, except for the inevitable mechanical and thermal effects [13–17]. There are extensive and deep research on the solution loss and deterioration of coke. For example, Wang et al. [16] investigated the effect of solution loss reaction on coke degradation. The results showed that solution loss reactions reduce CSR and degradation coke, and the coke degradation is decreased with increase of ore prereduction rate. Haapakangas et al. [17] studied that the effects of H_2 and H_2O on coke reactivity in a range of temperatures, the effects of H_2 and H_2O on threshold temperature of gasification, and determining activation energies for CO_2 and H_2O. Xing et al. [18] studied the degradation of coke under simulated temperature and gas composition conditions in the blast furnace. Both gasification and annealing decreased the mechanical strength of coke. Compared with annealing at 1673 K, gasification at the same temperature caused larger degradation of all three cokes, and the effect was more significant on the more reactive coke. Fang et al. [19] studied the high temperature compressive strength of coke. It was suggested that the compression strength of coke is in a linear relationship with its carbon loss rate in the scope of real reactions in blast furnace. And the influence of carbon loss rate on the compressive strength is reduced with the increasing temperature. Carbon loss rate is about 30% outside the combustion zone in blast furnace. n experimentally researched the influence of temperature and solution loss reaction to the high temperature compressive strength of coke in laboratory conditions. The results showed that the high temperature compressive strength of coke decreases with the increase of temperature, CO_2 concentration and solution loss reaction extent. Guo et al. [21] researched the solution loss kinetics behavior on coke strength after reaction. The results showed that the temperature of gradient reaction brings the most serious degradation to three cokes are different duo to different reactivity, and the temperature of the high reactive coke is about 1100 °C which is lower than another two cokes. Liu et al. [22] investigated kinetics of coke gasification with CO_2 by non-isothermal thermogravimetry. The results showed that when the gasification temperature is higher than 1200 K, both of the carbon conversion rate and gasification reaction rate increase significantly. When the gasification temperature reaches about 1500 K, the gasification reaction rate attains the maximum. These researches are good for guiding ironmaking process. However, the amount of solution loss in the blast furnace has been seldom reported.

Linear programming, which has been studied early and matured quickly with a well-developed research method, is a basic branch in operations research with a wide range of applications. In linear programming, mathematical model is the most commonly used and effective way to obtain optimal solutions, which means it can make target value achieve maximum or minimum under restrained conditions. When solving the multi-objective optimization issues, the multi-objective programming problem is usually transformed into a single-objective programming problem, so that a solution can be obtained that best meets the requirements. The commonly used methods include a constraint method, a sequential single object method, and an evaluation function method. The method of linear programming can also be used to study the blast furnace process [23,24]. When using the constraint method to complete the objective function, an important index is selected as the objective function, and the remaining indicators are taken as constraints, and the value cannot exceed the one of the single-objective optimizations. When using the sequential single-objective approach, each goal is sorted according to the degree of importance, and then an optimal solution is sought for each goal in a sub-set of the constraint region. When using the evaluation function method, a single-objective evaluation function needed to be constructed according to the actual characteristics of the problem, and then an optimal solution should be found according to the single objective [25].

In order to decrease CO_2 emissions in the iron and steel industry, several technologies have been investigated, such as blast furnace with top-gas recycling (TGR-BF), new smelting reduction process (HIsarna), carbon capture and storage (CCS) [26]. In addition to the technology development endeavors, interest in the utilization of renewable energy sources in ironmaking and steelmaking processes to replace part of the fossil-based reductants and fuels has increased recently. Biocarbon is a promising alternative to fossil-based reductant for reducing greenhouse gas emissions and increasing sustainability of the metallurgical industry. It has been proposed in the scientific literature that biocarbon could replace a small portion of the top-charged coke or all injected reducing agents in the blast furnace (BF) [26,27]. In the next study, we will investigate the impact of biocarbon fuel instead of coke and pulverized coal on the material balance and energy balance in the blast furnace.

In this study, based on the substance conservation and energy conservation of ironmaking process and the engineering method, the carbon loss calculation model is firstly established to calculate the amount of solution loss. And then, based on the carbon loss calculation model, the blast furnace emission reduction optimization mathematical model is established by using the multiple-objective optimization method. And then, this optimization model is used to seek the optimal solution of the model in order to obtain the best burden structure, operation parameters and product quality parameters. Moreover, this optimization model is used to investigate the effects of main operation parameters on the cost, CO_2 emission and carbon loss of B# blast furnace in Bayisteel, which provides a theoretical basis for the stable operation of blast furnace, emission reduction and cost savings.

2. Modeling

2.1. Blast Furnace Carbon Loss Calculation Model

The calculation methods of theoretical coke ratio mainly include combined calculation method, Rist operating line calculation method, regional heat balance calculation method and engineering method. The engineering method is widely used in actual production. The principle of this method is simple, and the calculation is simple. Moreover, this method can accurately reflect the actual situation of energy utilization in the blast furnace by adopting the second whole furnace heat balance, which calculates heat consumption according to the actual oxidation–reduction process in the blast furnace. However, there are some shortcomings in engineering method, such as ignoring the effects of blast humidity and pulverized coal and using the assumed direct reduction degree and unchangeable empirical specific heat capacity. Therefore, the shortcomings of engineering method have been corrected firstly. Besides, carbon loss of direct reduction is calculated by this model based on conservation of carbon. Furthermore, the amount of carbon loss of coupled direct reduction can be calculated by the result of carbon loss of direct reduction. This model assumes the following conditions: all pulverized coal is burned with oxygen; all combustion of carbon and oxygen is incomplete combustion; the distribution ratio of iron to hot metal and slag is 0.999:0.001.

2.1.1. Calculation of Direct Reduction Degree

According to the principles of ironmaking, the formula of direct reduction degree is shown as:

$$r_{\mathrm{d}} = \frac{\omega_{\mathrm{Fe(DR)}}}{\omega_{\mathrm{Fe(HM)}}} \tag{1}$$

where, r_{d} represents the direct reduction degree; $\omega_{\mathrm{Fe(DR)}}$ represents the amount of Fe that is generated by direct reduction, kg/t; $\omega_{\mathrm{Fe(HM)}}$ represents the amount of Fe in hot metal, kg/t.

On the basis of Fe-O-C balance, the amount of Fe element produced by direct reduction could be calculated by the carbon loss of direct reduction. The calculating formula is shown as follows:

$$\omega_{\mathrm{Fe(DR)}} = \frac{56}{12} \times \omega_{\mathrm{C(DR)}} \tag{2}$$

where, $\omega_{\mathrm{C(DR)}}$ is the carbon loss of direct reduction, kg/t.

According to the conservation of carbon, the formula of carbon loss of direct reduction is shown as:

$$\omega_{C(DR)} = \omega_{C(total)} - \omega_{C(Vad)} - \omega_{C([C])} - \omega_{C(XO)} - \omega_{C(H_2O)} - \omega_{C(combustion)} - \omega_{C(dust)} \tag{3}$$

where, $\omega_{C(total)}$ is the total amount of carbon in coke, kg/t; $\omega_{C(Vad)}$ is the amount of carbon in volatiles of coke, kg/t; $\omega_{C([C])}$ is the amount of carbon consumed by hot metal carburization, kg/t; $\omega_{C(XO)}$ is the amount of carbon consumed by non-ferrous oxide direct reduction, kg/t; $\omega_{C(H2O)}$ is the amount of carbon consumed by oxygen of blast moisture, kg/t; $\omega_{C(combustion)}$ is the amount of carbon consumed by combustion of coke in raceway, kg/t; $\omega_{C(dust)}$ is the amount of carbon in dust, kg/t.

2.1.2. Calculation of Carbon Loss

In blast furnace, according to different reaction modes, carbon loss of coke direct reduction reaction can be divided into carbon loss of coupled direct reduction reaction and carbon loss of molten direct reduction reaction. The direct reduction reaction, which is coupled by solution loss reaction and indirect reduction reaction, is regarded as coupled direct reduction reaction. Therefore, the amount of carbon consumed by solution loss reaction is the same as coupled direct reduction reaction. Moreover, molten direct reduction reaction is caused by direct reduction of coke and molten slag.

In this model, the reduction zone of iron oxide in blast furnace is divided into 3 parts as follows:

(1) Indirect reduction zone. In this region, the direct reduction reaction has not occurred. The indirect reduction reaction equations as follows:

$$\mathrm{FeO(s) + CO(g) = Fe(s) + CO_2(g)} \tag{4}$$

$$\mathrm{FeO(s) + H_2(g) = Fe(s) + H_2O(g)} \tag{5}$$

(2) Coupled direct reduction zone. In this region, solution loss reaction and indirect reduction reaction can be coupled into direct reduction reaction. The solution loss reaction equations are shown as:

$$\mathrm{C(s) + CO_2(g) = 2CO(g)} \tag{6}$$

$$\mathrm{C(s) + H_2O(g) = CO(g) + H_2(g)} \tag{7}$$

Equation (4) + Equation (6) and Equation (5) + Equation (7) can obtain direct reduction reaction equation as follows:

$$\mathrm{FeO(s) + C(s) = Fe(s) + CO(g)} \tag{8}$$

(3) Molten direct reduction zone. In this region, the indirect reduction reaction has not occurred. And coke is the only material that remains a solid phase, the direct reduction reaction takes place between coke and molten slag. The molten direct reduction reaction equation is shown as:

$$\mathrm{FeO(l) + C(s) = Fe(l) + CO(g)} \tag{9}$$

The coke consumption in blast furnace is shown in the following ways: combustion in raceway; hot metal carburization; non-ferrous oxide direct reduction; iron oxide direct reduction; volatile matter of coke volatile; coke fines are discharged with gas into dust. The iron oxide direct reduction reaction includes coupled direct reduction reaction and molten direct reduction reaction, and the coke carbon loss of direct reduction includes carbon loss of coupled direct reduction and carbon loss of molten direct reduction.

The following assumptions are made for the calculation of coupled direct reduction carbon loss: the coke carbon loss rate is 30% before coke falling into the raceway [19,28]; before coke falling into raceway, the coke carbon loss is caused by coupled direct reduction, hot metal carburization, coke volatiles and coke fines that is discharged into dust; the carbon loss of molten direct reduction is ignored before coke drops into raceway; the hot metal carburization can be completed 80% before hot metal droplets drop into raceway[29,30].

The formula for carbon loss of coupled direct reduction is as follows:

$$\omega_{C(\mathrm{CDR})} = \phi_{LC} \times \omega_{C(\mathrm{total})} - \omega_{C(\mathrm{Vad})} - \omega_{C(\mathrm{dust})} - \phi_{CC} \times \omega_{C([\mathrm{C}])} \tag{10}$$

where, $\omega_{C(\mathrm{CDR})}$ is the amount of carbon loss of coupled direct reduction, kg/t; ϕ_{LC} is the coke carbon loss rate before coke falling into the raceway, it is 0.3 in assumptions; ϕ_{CC} is the completed ratio of hot metal carburization, it is 0.8 in assumptions.

The formula for carbon loss of molten direct reduction is as follows:

$$\omega_{C(\mathrm{MR})} = \omega_{C(\mathrm{DR})} - \omega_{C(\mathrm{CDR})} \tag{11}$$

where, $\omega_{C(\mathrm{MR})}$ is the amount of carbon loss of molten direct reduction, kg/t.

2.2. Blast Furnace Emission Reduction Optimization Mathematical Model

Based on the carbon loss calculation model, the blast furnace emission reduction optimization mathematical model is established by using the multiple-objective optimization method. And then, this optimization model is used for single-objective and multi-objective optimization of cost and CO_2 emissions.

2.2.1. Optimization Variables

There are many factors that affect the cost and CO_2 emissions of blast furnace process. In order to facilitate calculation and investigate the impact of some variables on the model, the oxygen enrichment rate, blast temperature and blast humidity are fixed values when seeking the optimal solution. The optimization variables of the model are selected based on the raw material structure, fuel structure, operation parameters and product quality parameters of the B# blast furnace in Bayisteel, as shown in Table 1.

Table 1. Optimization variables and optimum solution of single and multiple objective and actual value of blast furnace.

Parameter	Variable	Single Objective Optimization			Multi-Objective Optimization	Actual Value
		Cost	CO_2 Emissions of Blast Furnaces Process	CO_2 Emissions of Ironmaking System		
Sinter consumption (kg/t)	x_1	1518	1005	1005	1337	1309
Pellet 1 consumption (kg/t)	x_2	115	605	605	202	211
Pellet 2 consumption (kg/t)	x_3	0	0	0	0	65
Pellet 3 consumption (kg/t)	x_4	0	0	0	0	50
Ore consumption (kg/t)	x_5	56	0	0	150	28
Flux consumption (kg/t)	x_6	0	0	0	0	4
Coke consumption (kg/t)	x_7	400	410	410	401	425
Pulverized coal consumption (kg/t)	x_8	152	97	97	149	110
Blast volume (m^3/t)	x_9	1394	1268	1268	1390	1371
Oxygen enrichment rate (%)	x_{10}	0	0	0	0	0
Blast humidity (g/m^3)	x_{11}	3	3	3	3	3
Blast temperature (°C)	x_{12}	1112	1112	1112	1112	1112
Gas volume (m^3/t)	x_{13}	1863	1684	1684	1856	1676
Pig iron Fe content (%)	x_{14}	93.871	93.911	93.911	93.871	94.23
Pig iron C content (%)	x_{15}	5.2	5.2	5.2	5.2	4.80
Pig iron Si content (%)	x_{16}	0.4	0.4	0.4	0.4	0.43
Pig iron P content (%)	x_{17}	0.077	0.077	0.077	0.077	0.097
Pig iron Mn content (%)	x_{18}	0.32	0.28	0.28	0.32	0.308
Pig iron S content (%)	x_{19}	0.047	0.047	0.047	0.047	0.02
Pig iron Ti content (%)	x_{20}	0.085	0.085	0.085	0.085	0.12
Theoretical combustion temperature (°C)	—	2073	2141	2141	2077	2133
Cost (RMB/t)	—	1586	1657	1657	1589	1650
CO_2 emissions of blast furnaces process (kg/t)	—	1146	1112	1112	1145	1158
CO_2 emissions of ironmaking system (kg/t)	—	1665	1600	1600	1645	1672
Carbon loss of coupled direct reduction (kg/t)	—	59.00	61.80	61.80	59.37	68.68
Carbon loss of coupled direct reduction as a percentage of total carbon in coke (%)	—	17.13	17.51	17.51	17.17	18.77

2.2.2. Objective Functions

In this model, the cost of blast furnace ironmaking is the net cost of the consumption of raw materials, fuel, air blast, and oxygen enrichment consumed for producing 1 ton of hot metal, after deducting the revenue from the recovery of blast furnace gas. The objective function of cost can be described as follows

$$P = \sum_{i=1}^{n} p_i x_i \tag{12}$$

where, P is the cost of blast furnace ironmaking, and p_i is the unit price of variable x_i.

The calculation of CO_2 emissions in the blast furnace process is based on the conservation of carbon. The carbon emission is that the amount of input carbon minus the amount of deductible carbon emission in the products and by-products. CO_2 emissions of blast furnaces process equals the CO_2 equivalent amount at the input end minus the amount of deductible CO_2 emissions at the output end. The calculation of CO_2 emissions of ironmaking system should add the indirect emission of sinter, pellets, coke, and power medium at the input of blast furnace process emissions. The objective function of CO_2 emission can be written as follows

$$C = Cd + \sum_{i=1}^{n} ci_i x_i = \sum_{i=1}^{n} cd_i x_i + \sum_{i=1}^{n} ci_i x_i \tag{13}$$

where, C is the CO_2 emissions of ironmaking system, Cd is the CO_2 emissions of blast furnace process, cd_i is the direct emission factors of variable x_i and ci_i is the indirect emission factors of variable x_i.

2.2.3. Constraint Conditions

In order to ensure that the operating parameters of the blast furnace are within a reasonable range during the optimization process, the constraint conditions are indispensably established. The constraint conditions can be described as follows

$$Cn_i \leq C_i(x) \leq Cm_i(i = 0, 1, \ldots, m) \tag{14}$$

where, $C_i(x)$ indicates that there are i constraint conditions, Cm_i is the upper limit of the i th constraint condition, and Cn_i is the lower limit of the i th constraint condition.

Constraint conditions include balance constraints, process constraints and specific constraints. Material balance and heat balance are the most basic constraints of the model as the establishment of a model must conform to the conservation of matter and conservation of energy. The process constraints are the constraints on the process parameters, representing the control of the blast furnace ironmaking process. The specific constraints are the constraints on the relationship between the different parameters based on the production statistics.

The balance constraints include material balance, heat balance, element balance, etc. Process constrains include the basicity constraint of slag, product parameter constraints, etc. Specific constraints include theoretical combustion temperature constraint, bosh gas volume constraint, etc.

3. Results and Discussions

3.1. Different Objective Optimization Results

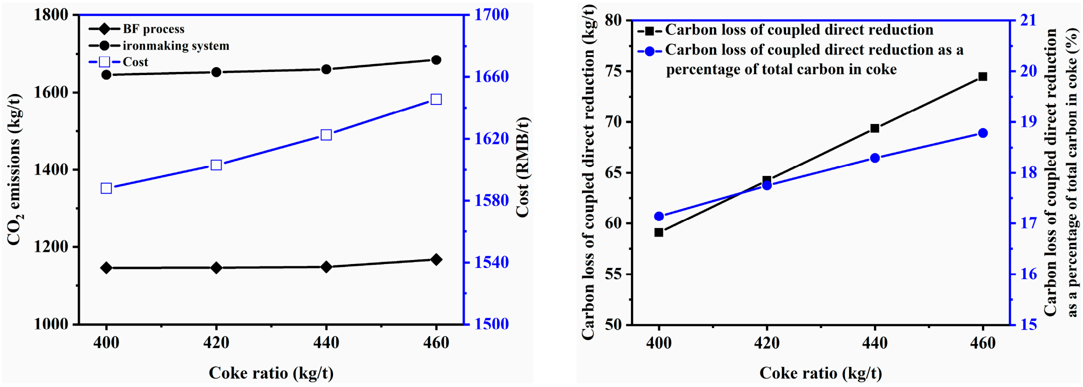
In the optimization model, the Generalized Reduced Gradient solving method is used in the single objective optimization, and the evaluation function method is used in the multi-objective optimization. Firstly, the single-objective optimization of cost, CO_2 emissions of blast furnaces process, and CO_2 emissions of ironmaking system are performed respectively. And then, multi-objective optimization is solved by the evaluation function method. Finally, the optimization results are compared with the actual production data to verify the reliability of multi-objective optimization. After multi-objective optimization of cost and CO_2 emissions, the results show that the cost is decreased by 60.94 RMB/t (RMB is the currency of China), the CO_2 emissions of blast furnaces process is reduced by 12.80 kg/t, the CO_2 emissions of ironmaking system is reduced by 27.16 kg/t and the carbon loss of coupled direct reduction is reduced by 9.31 kg/t, as shown in Table 1.

3.2. Analysis of Main Influence Factors

In order to investigate the influence of main factors such as coke ratio, coal rate, blast temperature, blast humidity, oxygen enrichment rate and burden metallization ratio on the cost, carbon loss and CO_2 emissions in the blast furnace production process, the control variables method is used for major factors respectively based on the blast furnace optimization model under the same conditions of other constraints, and multi-objective optimization is conducted to obtain the impact of major factors on costs, carbon loss of coupled direct reduction, CO_2 emissions of blast furnace process, and CO_2 emissions of ironmaking system.

3.2.1. Coke Ratio and Coal Rate

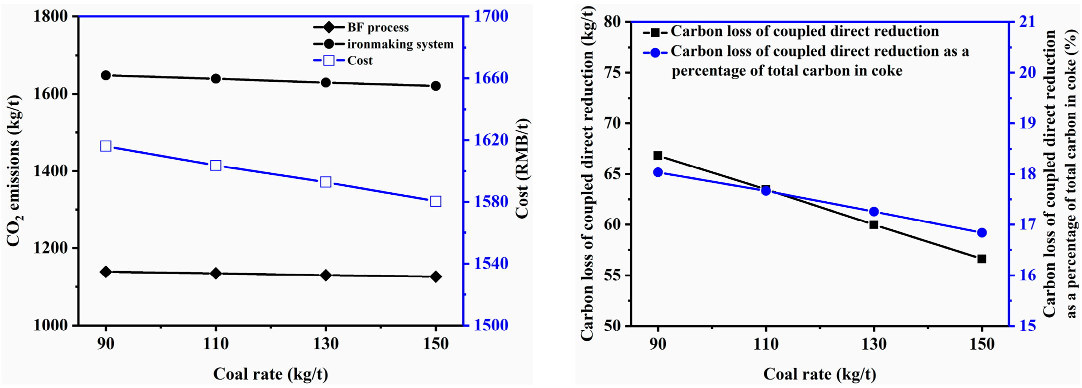
Figure 1a shows the relationship between the coke ratio and the cost and CO_2 emissions. It can be seen that with the increase of coke ratio, there is an increase of cost, and both CO_2 emissions slightly increase. Figure 1b shows the relationship between the coke ratio and carbon loss of coupled direct reduction and its percentage of total carbon in coke. This figure shows that as coke ratio increases, the carbon loss of coupled direct reduction and its percentage of total carbon in coke increase.



(**a**) (**b**)

Figure 1. (**a**) Effect of coke ratio on cost and CO_2 emissions; (**b**) Effect of coke ratio on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

Figure 2a shows the relationship between the coal rate and the cost and CO_2 emissions. It can be seen from the figure that as coke ratio increases, the cost and CO_2 emissions decrease, and both the decrement of CO_2 emissions are small. Figure 2b shows the effect of coal rate on carbon loss of coupled direct reduction and its percentage of total carbon in coke. This figure shows that with increase of coal rate, the carbon loss of coupled direct reduction and its percentage of total carbon in coke decrease.



(**a**) (**b**)

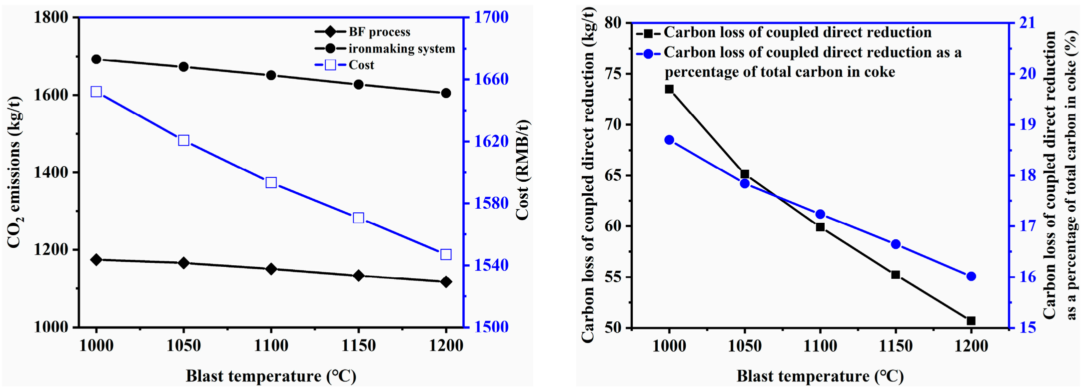
Figure 2. (**a**) Effect of coal rate on cost and CO_2 emissions; (**b**) Effect of coal rate on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

Since coke can be partly replaced by injection of pulverized coal, and the price of coke is much higher than that of pulverized coal, so the increase of coal rate can reduce the cost. With the decrease of coke ratio and the increase of coal rate, the volume of bosh gas increases, and the proportion of reducing components in the bosh gas increases, resulting in deterioration of the kinetic conditions of the solution loss reaction. Hence, with the decrease of coke ratio and the increase of coal rate, the carbon loss of coupled direct reduction decreases. However, coke is indispensable material in the blast furnace, as it sustains the passages of liquid metal and slag toward the lower part and of high temperature reducing gas toward the upper part. Hence, coke ratio cannot be too small. If coke ratio is too small, the smooth operation of blast furnace may not be ensured. Besides, in order to maintain the theoretical combustion temperature within a reasonable range, the coal rate cannot be increased without limit. Although the coke ratio and coal rate have little effect on CO_2 emissions, reducing coke ratio and increasing coal rate can also slightly reduce CO_2 emissions. Therefore, it is necessary to reduce coke ratio and increase coal rate as much as possible within a reasonable range. According to actual production statistical data of B# blast furnace in Bayisteel, the reasonable range of the coke ratio is about 370–500 kg/t, and the reasonable range of coal rate is about 20–170 kg/t.

3.2.2. Blast Temperature

Figure 3a shows the effect of blast temperature on the cost and CO_2 emissions. As can be seen from the figure, with the increase of blast temperature, the cost and CO_2 emissions reduce. Figure 3b shows the relationship between the blast temperature and carbon loss of coupled direct reduction and its percentage of total carbon in coke. It can be seen from the figure that with the increase of blast temperature, the carbon loss of coupled direct reduction and its percentage of total carbon in coke reduce.

As the blast temperature increases, the physical heat brought by the blast increases, so the chemical heat emitted by carbon combustion decreases accordingly, and the carbon emission also decreases. In addition, increasing the blast temperature also provides conditions for increasing the amount of pulverized coal. And injection of pulverized coal can replace part of coke. As the blast temperature increases, the amount of carbon loss of coupled direct reduction decreases. With the increase of blast temperature, the coke ratio decreases, and the proportion of reducing components in the bosh gas increases, resulting in deterioration of the kinetic conditions of the solution loss reaction. Therefore, increasing the blast temperature can reduce the cost, CO_2 emissions and carbon loss of coupled direct reduction.



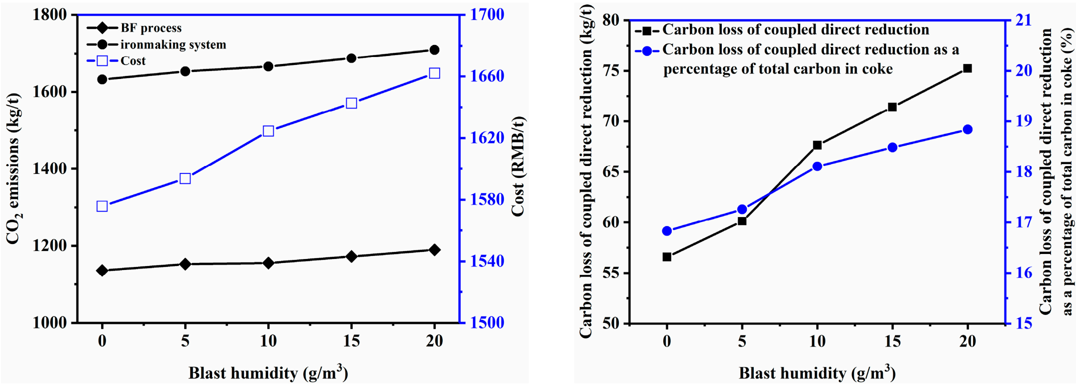
(**a**) (**b**)

Figure 3. (**a**) Effect of blast temperature on cost and CO_2 emissions; (**b**) Effect of blast temperature on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

3.2.3. Blast Humidity

Figure 4a shows the effect of blast humidity on the cost and CO_2 emissions. The figure shows that as the blast humidity increases, the cost and CO_2 emissions increase. Figure 4b shows the relationship between the blast humidity and carbon loss of coupled direct reduction and its percentage of total carbon in coke. It can be seen from the figure that with the increase of blast humidity, the carbon loss of coupled direct reduction and its percentage of total carbon in coke increase.

With the increase of blast humidity, the heat consumption in raceway increases, so carbon consumption increases accordingly, and the carbon emission also increases. Moreover, as the blast humidity increases, the theoretical combustion temperature decreases. In order to maintain the theoretical combustion temperature within a reasonable range, it is necessary to reduce the amount of pulverized coal and increase the amount of coke. As the coke ratio is increased, the specific surface area of coke is increased, resulting in an increase in carbon loss of coupled direct reduction. Accordingly, decreasing the blast humidity can reduce the cost, CO_2 emissions and carbon loss of coupled direct reduction.



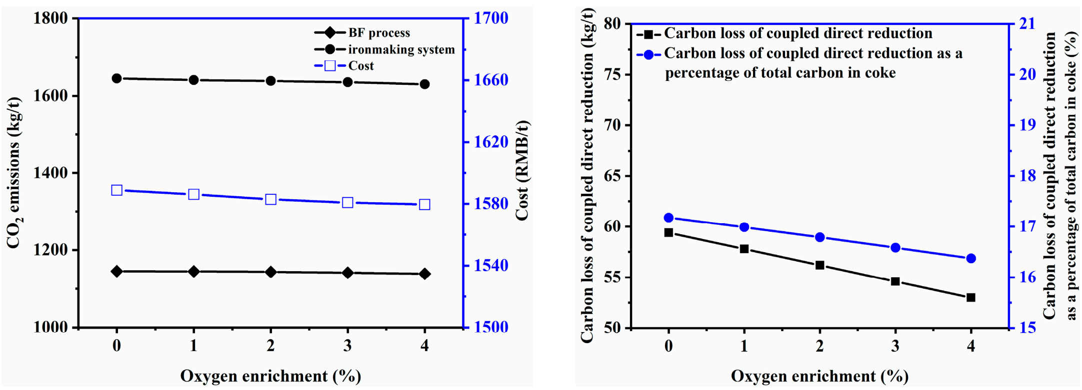
(**a**) (**b**)

Figure 4. (**a**) Effect of blast humidity on cost and CO_2 emissions; (**b**) Effect of blast humidity on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

3.2.4. Oxygen Enrichment Rate

Figure 5a shows the effect of oxygen enrichment rate on the cost and CO_2 emissions. The figure shows that as the oxygen enrichment rate increases, the cost decreases and CO_2 emissions decreases slightly. Figure 5b shows the relationship between the oxygen enrichment rate and carbon loss of coupled direct reduction and its percentage of total carbon in coke. It can be seen from the figure that with the increase of oxygen enrichment rate, the carbon loss of coupled direct reduction and its percentage of total carbon in coke decrease.

As the oxygen enrichment rate increases, the theoretical combustion temperature increases. In order to maintain the theoretical combustion temperature within a reasonable range, it is necessary to increase the amount of pulverized coal, leading to decrease the amount of coke, thereby reducing the cost. As the coke ratio is decreased, the specific surface area of coke is decreased, resulting in a decrease in carbon loss of coupled direct reduction. Therefore, increasing the oxygen enrichment rate can reduce the cost, CO_2 emissions and carbon loss of coupled direct reduction.



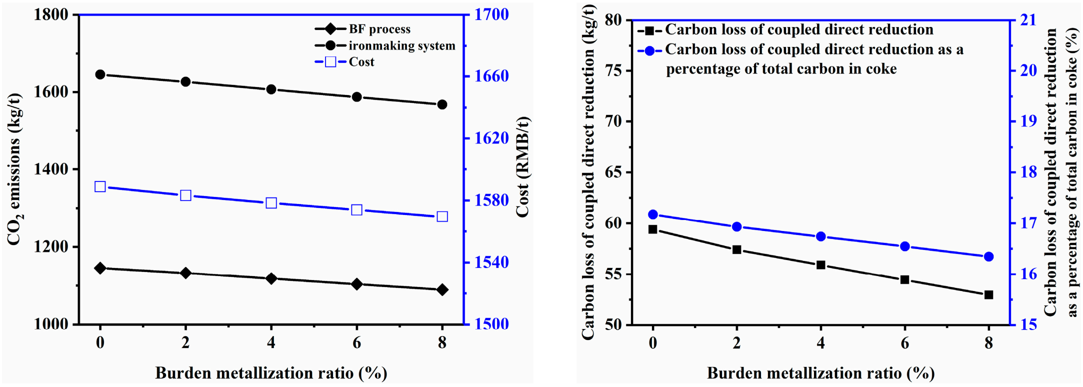
(**a**) (**b**)

Figure 5. (**a**) Effect of oxygen enrichment rate on cost and CO_2 emissions; (**b**) Effect of oxygen enrichment rate on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

3.2.5. Burden Metallization Ratio

Figure 6a shows the effect of burden metallization ratio on the cost and CO_2 emissions. The figure shows that as the burden metallization ratio increases, the cost and CO_2 emissions decreases gradually. Figure 6b shows the relationship between the burden metallization ratio and carbon loss of coupled direct reduction and its percentage of total carbon in coke. It can be seen from the figure that with the increase of burden metallization ratio, the carbon loss of coupled direct reduction and its percentage of total carbon in coke decrease.

The method of increasing the burden metallization rate is to add scrap iron to blast furnace. As the burden metallization rate increases, the amount of scrap iron that does not undergo the oxidation–reduction reaction in the blast furnace increases, resulting in the decrease in cost, CO_2 emissions and carbon loss of coupled direct reduction. In addition, the melting of scrap iron will absorb a large amount of heat, so the burden metallization rate should not be too large.



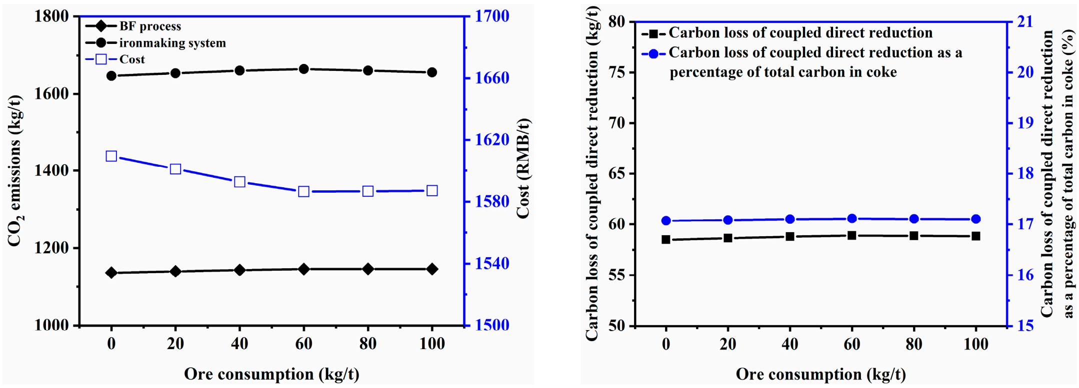
(**a**) (**b**)

Figure 6. (**a**) Effect of burden metallization ratio on cost and CO_2 emissions; (**b**) Effect of burden metallization ratio on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

3.2.6. Ore Consumption

Figure 7a shows the effect of ore consumption on the cost and CO_2 emissions. The figure shows that as the ore consumption increases, the cost significantly reduces first, and then the cost slightly increases. When the ore consumption is 60 kg/t, the cost is the lowest. It can be seen that with the increase of ore consumption, CO_2 emissions of blast furnaces process increases firstly, and the increment of CO_2 emissions becomes smaller after the amount of ore exceeds 60 kg/t. And, it can be seen that with the increase of ore consumption, the CO_2 emissions of ironmaking system increases first and then decreases, the CO_2 emissions of ironmaking system is the maximum when the ore consumption reaches 60 kg/t. Figure 7b shows the relationship between the ore consumption and carbon loss of coupled direct reduction and its percentage of total carbon in coke. It can be seen from the figure that with the increase of ore consumption, the carbon loss of coupled direct reduction and its percentage of total carbon in coke remains basically unchanged.

Because the ore is cheaper than other iron-bearing raw materials, the use of ore can significantly reduce costs. However, the use of ore with a relatively low iron grade will result in an increase in the slag ratio. When the ore consumption reaches 60 kg/t, the slag ratio reaches the upper limit of the relative constraint condition. As the ore consumption is further increased, in order to make the slag ratio meet the constraint conditions, it is necessary to reduce the consumption of sinter and increase the consumption of pellet, resulting in a slight increase in cost and a decrease in the CO_2 emissions of ironmaking system. In addition, the use of large amounts of ore can cause a decrease in slag basicity, which may affect the performance of blast furnace, so the ore consumption should not be too large.



(**a**) (**b**)

Figure 7. (**a**) Effect of ore consumption on cost and CO_2 emissions; (**b**) Effect of ore consumption on carbon loss of coupled direct reduction and its percentage of total carbon in coke.

4. Conclusions

Based on the conservation of material and energy of ironmaking process and the engineering method, the blast furnace carbon loss calculation model is firstly established. A multi-objective optimization mathematical model is then established with cost and CO_2 emissions as objective functions based on the carbon loss calculation model. The optimal solutions of blast furnace burden structure and operating parameters for single object and multiple objects are solved respectively. After the multi-objective optimization, the optimal solution shows that the cost is reduced by 60.94 RMB/t, the CO_2 emissions of blast furnaces process is reduced by 12.80 kg/t, and the CO_2 emissions of ironmaking system is reduced by 27.16 kg/t. Based on the optimization model, the influence of main factors such as coke ratio, coal rate, blast temperature, blast humidity, oxygen enrichment rate and burden metallization ratio on the cost, CO_2 emissions and carbon loss are analyzed. The measures to reduce cost, reduce emissions and reduce carbon loss in blast furnace production are as follows: reduce the coke ratio and increase the coal rate within a suitable range; increase the blast temperature; minimize the blast humidity; appropriately increase the oxygen enrichment rate and burden metallization rate.

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Nomenclature

r_d	direct reduction degree
$\omega_{Fe(DR)}$	the amount of Fe that is generated by direct reduction, kg/t
$\omega_{Fe(HM)}$	the amount of Fe in hot metal, kg/t
$\omega_{C(DR)}$	the carbon loss of direct reduction, kg/t
$\omega_{C(total)}$	the total amount of carbon in coke, kg/t
$\omega_{C(Vad)}$	the amount of carbon in volatiles of coke, kg/t
$\omega_{C([C])}$	the amount of carbon consumed by hot metal carburization, kg/t
$\omega_{C(XO)}$	the amount of carbon consumed by non-ferrous oxide direct reduction, kg/t
$\omega_{C(H2O)}$	the amount of carbon consumed by oxygen of blast moisture, kg/t
$\omega_{C(combustion)}$	the amount of carbon consumed by combustion of coke in raceway, kg/t
$\omega_{C(dust)}$	the amount of carbon in dust, kg/t
$\omega_{C(CDR)}$	the amount of carbon loss of coupled direct reduction, kg/t
ϕ_{LC}	the coke carbon loss rate before coke falling into the raceway
ϕ_{CC}	the completed ratio of hot metal carburization
$\omega_{C(MR)}$	the amount of carbon loss of molten direct reduction, kg/t

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