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Research Article

Optimization of the Parameters Affecting the Metallization Degree of Sponge Iron in a Midrex Plant Using Central Composite Design

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ABSTRACT

This research used response surface methodology with a central composite design to optimize the metallization degree of the Midrex-type Gohar plant of Golgohar Iron and Steel Development Company, Sirjan City. For this purpose, the effect of furnace bed temperature, bustle gas temperature, process gas CO_2, reformed gas CO_2, and process gas flow/ton was investigated on the metallization degree of the sponge iron. The statistical analysis showed that the furnace bed temperature is the most effective parameter for the quality of the sponge iron in Midrex, and the most significant interaction was observed between the furnace bed temperature and the reformed gas CO_2. The coefficient of determination and the standard error for the model were obtained at 0.9901 and less than 5%, respectively, which indicates the model was optimal. According to the optimization results, the best metallization degree of 93 was obtained in the furnace bed temperature of 727 °C, process gas CO_2 of 17.29%, bustle gas temperature of 859.55 °C, reformed gas CO_2 of 2.98%, and process gas flow/ton of 1146 Nm^3/ton.

1. Introduction

Currently, steel is produced by two main methods: 1. Preparation of molten iron in blast furnaces and then steel production in converter furnaces, and 2. Direct reduction of iron pellets and sponge iron production followed by steel production in electric arc furnaces. In countries with rich natural gas resources, direct reduction methods are widely used due to the environmental pollution and expensive processes of blast furnaces [1, 2]. Direct reduction is when the iron oxide (pellet or iron ore) is converted into sponge iron using a reduction agent. The iron produced in the direct reduction method contains a high percentage of iron and small amounts of impurities (silica, alumina, etc.), which is suitable for use in electric arc furnaces [3, 4].

Direct reduction methods are divided into different types based on the ore, furnace, and reductant agent type, as shown in Table 1.

In countries with rich natural gas resources, gas-based methods are highly developed. One common gas-based direct reduction method is the Midrex process, which includes three main parts: furnace, reformer, and heat recovery unit. In this method, the reduction gas produced from the reforming of natural gas in the reformer (including CO and H_2) moves against the direction of iron oxide flow, which causes the iron oxide to be reduced [5-7]. In

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direct reduction methods, the metallization degree (MD) of sponge iron is defined as follows (8):

$$MD = \frac{metallic\ iron\ in\ sponge\ iron}{total\ iron\ in\ sponge\ iron} \times 100 \qquad \text{Eq.(1)}$$

In Midrex plants, the MD of sponge iron affected several parameters such as the furnace bed temperature, bustle gas temperature, process gas CO_2, reformed gas CO_2, and process gas flow/ton [9, 10].

The response surface methodology is a collection of mathematical and statistical techniques whose purpose is to analyze, by an empirical model, problems as the one posed. This process was used to optimize processes where the desired response is affected by several variables. For example, if in a chemical process, increasing the reaction efficiency by changing the effective parameters is considered, the observed response (Y) as a function of different process variables (X_1, X_2, ... X_k) will be as follows:

$$Y = f(X_1, X_2, \dots, X_k) + \varepsilon \qquad \text{Eq.(2)}$$

where ε is a variable not calculated in the f function and is a statistical error [11, 12]. Many studies have been conducted to optimize and model the Midrex process regarding product quality and minimize energy consumption and carbon dioxide emissions, all summarized in Table 2. In this research, the effect of furnace bed temperature, bustle gas temperature, process gas CO_2, reformed gas CO_2 and process gas flow/ton was investigated on the metallization degree of sponge iron in Golgohar iron and steel development company (Gohar plant) using Design Expert 7 software and the process mentioned above parameters were optimized to improve the metallization degree of the produced sponge iron.

Table1. Different direct reduction methods [4].

Process	Type of ore use	Type of reductant	Type of reactor
Midrex	Pellet/Lump	Gaseous	Shaft
HYL	Pellet/Lump	Gaseous	Shaft, Fluid Bed
SL/RN, ACCAR, Davy DRC	Pellet/Lump	Coal	Kiln
Fastmet, Inmetco	Fines	Coal	Heart
Circofer, Finex	Fines	Coal	Fluid Bed
Circored, Finmet, Iron Carbide	Fines	Gaseous	Fluid Bed

Table 2. Literature review for optimization and modeling the Midrex process.

Optimization Type	Subject Studied	Result	References
Simulation studies with Computational Fluid Dynamics (CFD)	The effect of dual gas injection system on the distribution of process variables and energy consumption	By using the double gas system, the degree of regeneration is improved, and energy consumption is reduced	[13]

Thermodynamic studies with FactSage software	A thermodynamic model was presented for the effect of process parameters on the metallization degree and carbon content of the product.	The model used is very practical for real conditions and has good predictions.	[14]
Simulation studies with Feed Forward Neural network (FNN)	Different furnace zones, including reduction, transition, and cooling, were modeled using FNN data.	The results were in good agreement with the real conditions of the Midrex plant.	[15]
Thermodynamic studies with the Kalina cycle	Waste heat recovery from MIDREX plants was investigated from energy and exergy viewpoints.	The result shows that more than 2 MW of electricity is extractable via the Kalina cycle with a mixture of ammonia and water.	[16]
Distinct element method simulations (DEM)	The reduction zone of the furnace was modeled by applying mass and energy balance for the solid and gas phases.	The results were in good agreement with the real conditions of the Midrex plant.	[17]
Mathematical models	In this research, steelmaking using direct reduction was studied in terms of the amount of CO_2 emission and the costs of raw materials.	The results showed that steelmaking with the Midrex shaft furnace ironmaking stage is very beneficial.	[18]

Mathematical models	In this research, steelmaking using direct reduction was studied in terms of metallization degree, the operating costs of the DRI and the EAF as well as the total operating cost of the plant	The results showed that steelmaking with the Midrex shaft furnace ironmaking stage is very beneficial.	[19]
Mathematical models	The mass and energy balance of the reformer and furnace and their relationship were modeled, and the effects of crucial input parameters on the product's metallization degree and carbon content were studied.	The results showed that product quality is greatly affected by process parameters.	[20]
Multiscale Process Modeling by Aspen Plus software	Furnace, reformer, recuperators, and scrubbers were modeled to reduce the carbon dioxide in the process.	The results were in good agreement with the real conditions of the Midrex plant.	[21]
Thermodynamic studies with FactSage software	A thermochemical model for estimation of emissions and energy requirement of a MIDREX plant up to crude steel production.	The NG-MIDREX-EAF has the potential to reduce emissions at identical net energy consumption.	[22]
Response Surface Methodology (RSM) with Design Expert software	The effect of process parameters was investigated on the metallization degree of the sponge iron.	The statistical analysis showed that the furnace bed temperature is the most influential parameter on the quality of the sponge iron in Midrex.	Current Study

2. Research Methodology

2.1. Determination of effective process parameters

This research monitored the effective process parameters of iron reduction at the Gohar plant (located at Golgohar Iron and Steel Development Company, Sirjan City) for one month. This study was performed on the condition that the input iron pellet charge to the furnace was the same (iron pellet charge composition: 60% of Golgohar iron pellets and 40% of Goharzamin iron pellets). The change interval of the most important reduction process parameters affecting the metallization degree of the sponge iron was determined, which is given in Table 3.

2.2. Experiment design and data analysis

To experiment design, the response surface methodology by the central composite design of response surface methodology to achieve a desirable model consisting of 43 trials plus 10-center points, using the statistical Design Expert software was used. The model used in this design is usually the quadratic model, whose relationship is defined as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \qquad \text{Eq.(3)}$$

where the predicted response (y) depends on the constant coefficient (β_0), linear effects (β_1, β_2, β_3), interactions (β_{12}, β_{13}, β_{23}), and square coefficients (β_{11}, β_{22}, β_{23}) [11, 23]. The Design Expert 7 software was used to design and analyze the data. The corresponding results of the experiment design (metallization degree) are shown in Table 4. It should be noted that the measured values in the tables are average numbers and close to those obtained from thermometers and analyzers in the Midrex process.

3. Results and discussion

3.1. Choosing the appropriate fitted model

The quadratic model was the model that was fitted after the analysis and showed the best results. As shown in Table 5, the model is completely significant because the values of P and F for the model were less than 0.0001 and 154.81, respectively. On the other hand, all selected variables are also significant. The lack of fit of the model is also acceptable (P=0.4509).

In addition, the data in Table 6 shows that the model has a determination coefficient (R^2) close to 1 (0.9901), which means that the model is a good fit for the data. The values of the adjusted and predicted determination coefficients are 0.9837 and 0.9664, respectively, which is an acceptable level for the model. Also, the adequate precision representing the signal-to-noise ratio is higher than 4, which is 65.111 for the presented model [24, 25]. In addition, the variation coefficient and standard deviation are small, which confirms the presented model.

Based on the results obtained from the software, the quadratic model presented to predict the metallization degree is in the form of Eq.(4):

$$MD = 91.24 + 0.39A + 0.097B + 0.066C - 0.33D + 0.14E + 0.041AB + 0.036AC - 0.10AD + 0.059AE - 0.035BC - 0.059BD + 0.036BE - 0.006875CD + 0.075CE - 0.082DE + 0.12A^2 - 0.030B^2 + 0.091C^2 + 0.12D^2 - 0.10E^2 \qquad \text{Eq.(4)}$$

Table 3. Effective parameters and their corresponding levels.

Selected variables	Unit	Level	
		+1	-1
Furnace bed temperature	℃	727	630
Bustle gas temperature	℃	860	849
Process gas CO_2	%	17.33	16.11
Reformed gas CO_2	%	3.69	2.98
Process gas flow/ton	Nm^3/ton	1146	1084

Table 4. Answers related to the experiments presented in the central composite design.

Test number	Furnace bed temperature	Bustle gas temperature	Process gas CO_2	Reformed gas CO_2	Process gas flow/ton	Metallization degree
1	678.50	854.50	16.70	3.34	1115	91.6
2	630	849	17.30	3.69	1084	91.5
3	630	849	17.30	2.98	1084	91.78
4	678.50	854.50	16.70	3.34	1115	91.6
5	630	849	16.11	3.69	1084	91.45
6	630	860	17.30	3.69	1084	91.30
7	630	860	16.11	3.69	1146	91.55
8	727	849	16.11	2.98	1084	92.42
9	727	860	17.30	2.98	1146	93.50
10	678.50	854.50	16.70	3.34	1115	91.65
11	630	849	16.11	2.98	1084	91.56
12	678.50	854.50	16.70	3.34	1115	91.53
13	630	849	17.30	2.98	1146	92.15
14	630	860	16.11	2.98	1084	91.56
15	630	860	17.30	2.98	1084	91.76
16	727	860	16.11	3.69	1084	91.80
17	727	849	17.30	2.98	1146	93.30
18	727	860	16.11	3.69	1146	92.30
19	678.50	854.50	16.70	3.34	1115	91.66
20	630	860	17.30	3.69	1146	91.45
21	630	849	16.11	3.69	1146	91.25
22	630	860	16.11	2.98	1146	92
23	678.50	854.50	16.70	3.34	1115	91.55
24	727	860	17.30	3.69	1084	91.85
25	630	849	16.11	2.98	1146	91.80
26	630	860	16.11	3.69	1084	91.45
27	727	860	16.11	2.98	1084	92.50
28	630	860	17.30	2.98	1146	92.26
29	630	849	17.30	3.69	1146	91.40
30	727	849	17.30	3.69	1084	92
31	727	849	16.11	3.69	1084	91.80
32	727	849	16.11	2.98	1146	92.65
33	727	860	17.30	2.98	1084	92.76
34	727	860	16.11	2.98	1146	93.10
35	727	849	16.11	3.69	1146	91.76
36	727	860	17.30	3.69	1146	92.46
37	727	849	17.30	3.69	1146	92.10
38	678.50	854.50	16.70	3.34	1115	91.65
39	727	849	17.30	2.98	1084	92.66
40	678.50	854.50	16.70	3.34	1115	91.67
41	678.50	854.50	16.70	3.34	1041.27	91.20
42	678.50	854.50	16.70	3.34	1115	90.78
43	678.50	841.42	16.70	3.34	1115	91.2
44	793.85	854.50	16.70	3.34	1115	92.40
45	678.50	854.50	15.29	3.34	1115	90.50
46	678.50	854.50	16.70	4.18	1115	90.76
47	563.15	854.50	16.70	3.34	1115	90.69
48	678.50	854.50	16.70	3.34	1188.73	91.70
49	678.50	854.50	16.70	3.34	1115	90.88
50	678.50	854.50	16.70	2.49	1115	92.35
51	678.50	854.50	18.12	3.34	1115	90.88
52	678.50	867.58	16.70	3.34	1115	91.55
53	678.50	854.50	16.70	3.34	1115	91

Table 5. The results of variance analysis related to the quadratic model.

Source	Sum of Squares	Freedom Degrees	Mean Squares	F Value	P Value
Model	16.33	20	0.82	154.81	<0.0001 (Significant)
Furnace bed temperature (A)	6.52	1	6.52	1236.42	<0.0001
Process gas CO_2 (B)	0.40	1	0.40	76.62	<0.0001
bustle gas temperature (C)	0.19	1	0.19	3561	<0.0001
reformed gas CO_2 (D)	4.60	1	4.60	872.88	<0.0001
Process gas flow/ton (E)	0.85	1	0.85	161.23	<0.0001
AB	0.054	1	0.054	10.32	0.0031
AC	0.041	1	0.041	7.70	0.0093
AD	0.34	1	0.34	64.52	<0.0001
AE	0.11	1	0.11	20.94	<0.0001
BC	0.039	1	0.039	7.43	0.0104
BD	0.11	1	0.11	20.94	<0.0001
BE	0.041	1	0.041	7.70	0.0093
CD	0.0001512	1	0.0001512	0.29	0.05961
CE	0.18	1	0.18	34.13	<0.0001
DE	0.22	1	0.22	41.29	<0.0001
A^2	0.88	1	0.88	166.84	<0.0001
B^2	0.052	1	0.052	9.93	0.0036
C^2	0.50	1	0.50	94.51	<0.0001
D^2	0.91	1	0.91	171.73	<0.0001
E^2	0.65	1	0.65	123.90	<0.0001
Residual	0.16	31	0.005275	-	-
lack of fit	0.12	22	0.005448	1.12	0.4509 (Not significant)
Pure error	0.044	9	0.005450	-	-

Table 6. Statistical variables of the model obtained from the variance analysis.

Variable type	Value
standard deviation	0.073
Average	91.77
Coefficient of variation	0.079
The sum of squares of the residual error (Press)	0.55
coefficient of determination (R^2)	0.9901
Adjusted coefficient of determination (Adjusted R^2)	0.9837
Predicted coefficient of determination (Predicted R^2)	0.9664
Adequate Precision	65.111

where the variables A, B, C, D, and E represent furnace bed temperature, process gas CO_2, bustle gas temperature, reformed gas CO_2, and process gas flow/ton, respectively. As observed in Table 5, all the interactions presented in the model are significant because they have a P value of less than 0.05, which shows that the resulting model is very meaningful [11].

Figs. 1. (a-d) shows the normal probability diagrams of the residuals (a), the value of the residuals according to the test number (b), the predicted values according to the actual values (c), and the value of the residuals according to the predicted values (d). According to these graphs, the normality and randomness of the data, the constancy of the residual variance, and the independence of the responses concerning time are visible, representing the appropriateness of the model for the test data [26].

3.2. The effect of the main parameters on the metallization degree

Figs. 2. (a-d) shows the effect of the five main parameters on the metallization degree of the product. As it is observed, the increase of the furnace bed temperature (Fig. 2a.), process gas CO_2 (Fig. 2b.), bustle gas temperature (Fig. 2c.), and process gas flow/ton (Fig. 2e.) caused an enhancement in the metallization degree of the product. The increase of the reformed gas CO_2 (Fig. 2d.) leads to a decrease in the metallization degree of the product has decreased.

On the other hand, according to the F value data presented in Table 5, it is clear that the most influential parameter on the metallization degree is the furnace bed temperature. According to the well-known Arrhenius relation, the increase in the bustle gas temperature and the furnace bed temperature led to an increase in the transformation rate of the oxide pellet (Fe_2O_3) into metallic iron (Fe) [27]. But at temperatures higher than 800 °C, the produced sponge irons form a metal bond with each other, and as a result of this problem, many clusters are formed, which leads to a decrease in the quality (MD) of the product [28]. On the other hand, the increase in the process gas flow caused an improvement in the penetration of the reduction gas in the furnace bed, which led to an enhancement in the metallization degree [29].

The quality of reduction gas in the Midrex process is defined by Eq.(5):

$$\text{Quality of reduction gas} = \frac{CO+H_2}{CO_2+H_2O} \qquad \text{Eq.(5)}$$

The increase of process gas CO_2 up to 17% led to improved methane reforming reactions with CO_2, and as a result, more CO and H_2 gas are produced, and the quality of the reduction gas is increased. This phenomenon caused an increase in the metallization degree of the product. Still, with the rise in reformed gas CO_2 (coming out of the reformer tubes of the Midrex plant), the fraction denominator in Eq.(5) is increased, and the quality of the reduction gas is decreased, followed by a decrease in the metallization degree [3, 10].

3.3. The effect of main parameters interaction on the metallization degree

Figs. 3. (a-j) shows the interaction plots of the main effective parameters. As shown in Fig. 3. there is an interaction between all the main parameters, which are interdependent. The F values in Table 4 show the highest interaction between the furnace bed temperature and reformed gas CO_2. Also, the lowest interaction is observed between the bustle gas temperature and reformed gas CO_2. In all graphs (except the interaction between reformed gas CO_2 and process gas flow/ton), more interaction can be seen in low values of the variables. So, it can be concluded that there is a great dependence between the process parameters in the Midrex process [10].

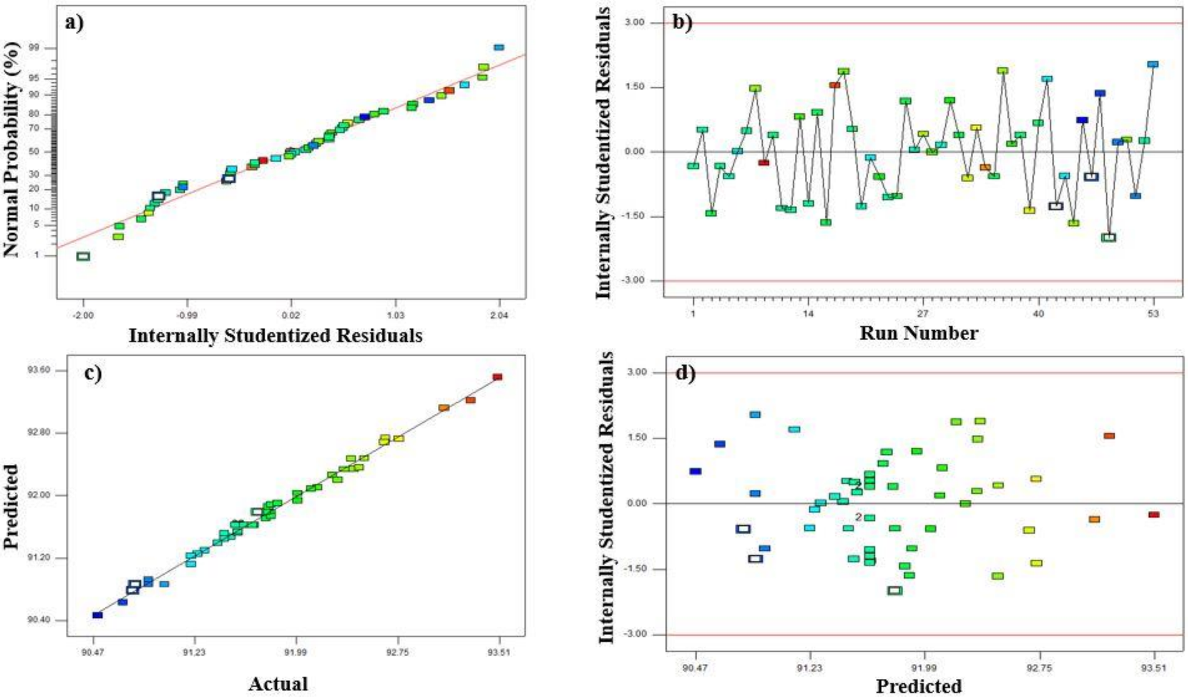


Fig. 1. Diagrams of the normal probability of residuals (a), the value of residuals versus test number (b), predicted values according to actual values (c), and the value of residuals versus predicted values (d).

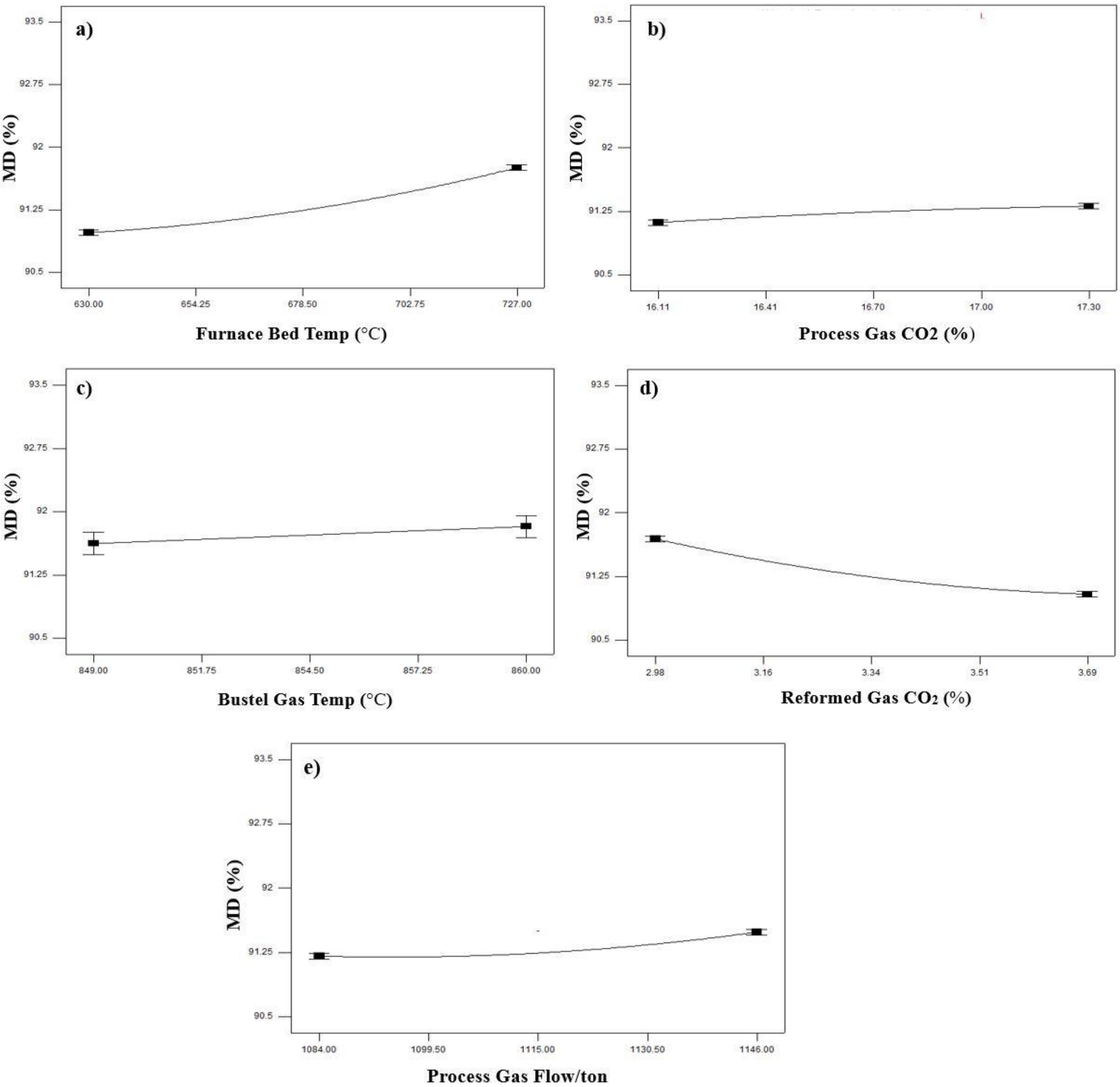
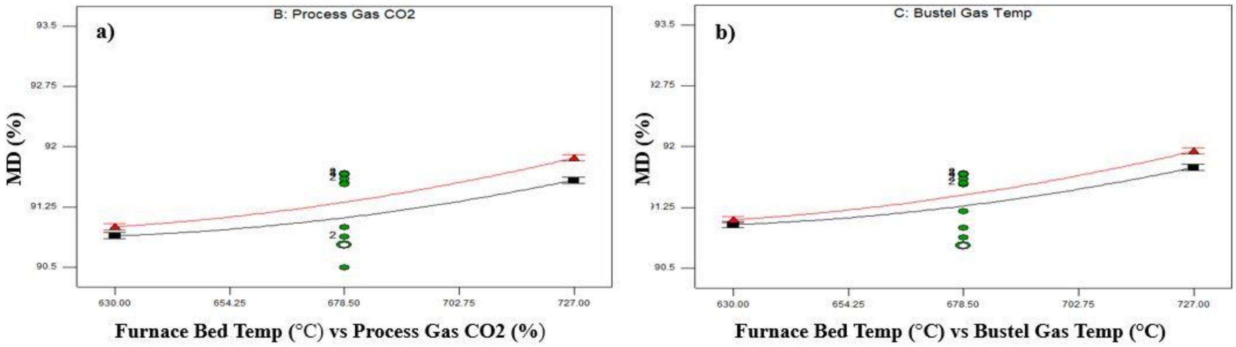
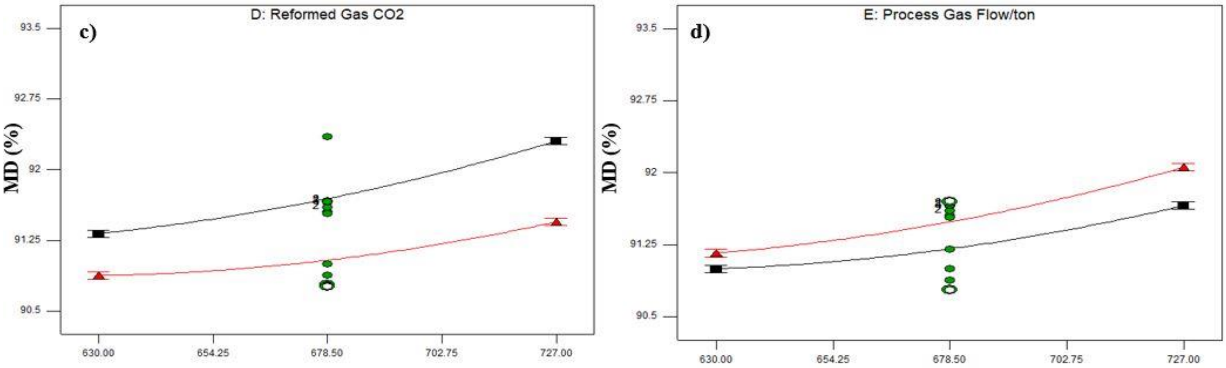
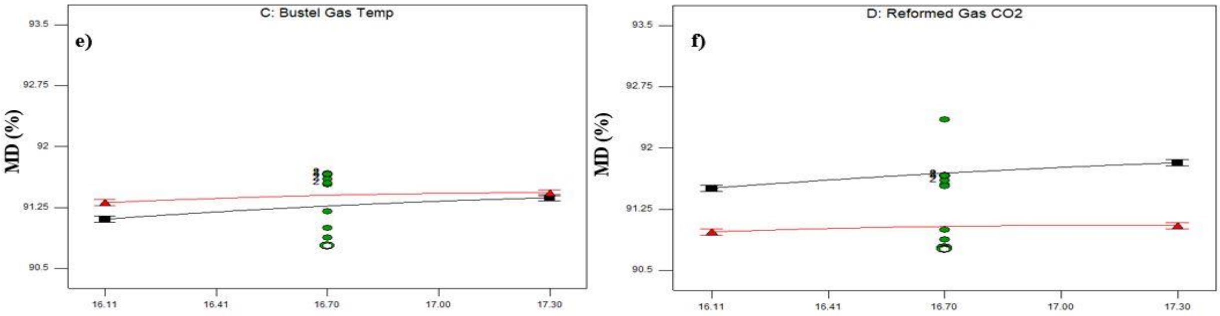


Fig. 2. Effective parameters of furnace bed temperature (a), process CO_2 (b), bustle gas temperature (c), reformed gas CO_2 (d), and process gas flow/ton (e) on quality of the product.

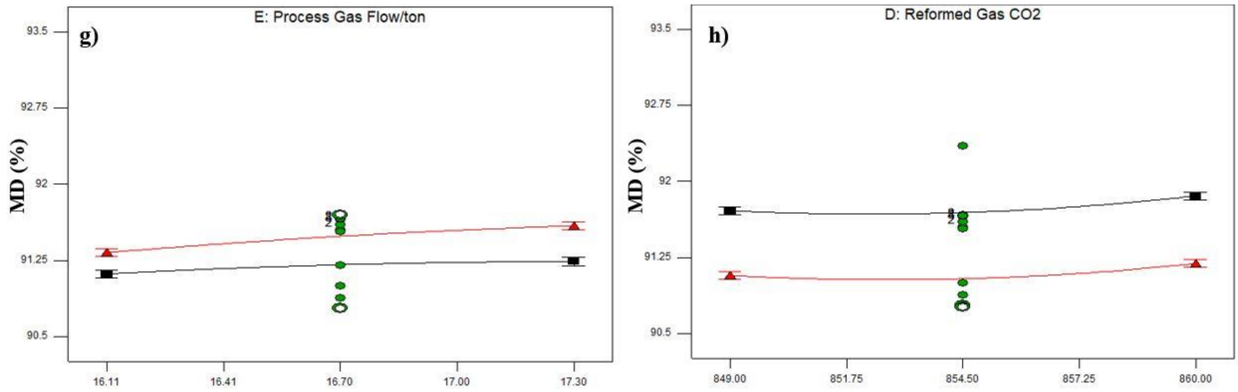




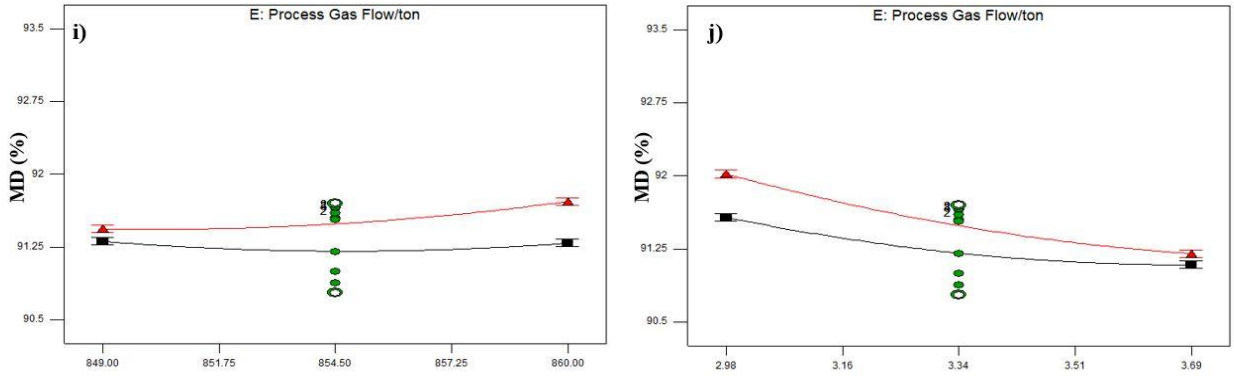
Furnace Bed Temp (°C) vs Reformed Gas CO2(%) **Furnace Bed Temp (°C) vs Process Gas Flow/ton**



Process Gas CO2 (%) vs Bustel Gas Temp (°C) **Process Gas CO2 (%) vs Reformed Gas CO2 (%)**



Process Gas CO2 (%) vs Process Gas Flow/ton **Bustel Gas Temp (°C) vs Reformed Gas CO2 (%)**



Bustel Gas Temp (°C) vs Process Gas Flow/ton **Reformed Gas CO2 (%) Process Gas Flow/ton**

Fig. 3. Interaction curves of the effects of the main variables related to the presented model.

3.4. Contour and three-dimensional diagrams of the main parameters affecting the metallization degree

According to the F value data in Table 5. it was determined that the most important main parameters affecting the metallization degree of the product are furnace bed temperature and reformed gas CO_2. The diagram of the simultaneous influence of these parameters was presented as contour and 3D in Fig. 4. As it is known, increasing the furnace bed temperature causes a decrease in reformed gas CO_2 and improvement of metallization degree. An increase in bed temperature caused an increased reaction rate, decreased the reformed gas CO_2, and improved the reduction of gas quality. So, combining these factors leads to an impressive quality of the produced sponge iron [9, 29].

3.5. Optimization of the metallization degree of sponge iron

A numerical method was used to optimize the metallization degree of the produced sponge iron. For this purpose, the highest metallization degree of the product was selected as the optimization result, and other parameters were optimized based on it. Then, the optimal conditions proposed by the model were examined in real estate, and all the results are shown in Table 7. Based on the obtained results, the best metallization degree of the product (MD: 93) was obtained in the condition that furnace bed temperature of 727 °C, process gas CO_2 of 17.29%, bustle gas temperature of 859.55 °C, reformed gas CO_2 of 2.98%, and process gas flow/ton of 1146 Nm^3/ton.

4. Conclusions

The response surface methodology by the central composite design is a successful and practical method to optimize the parameters affecting the metallization degree of sponge iron in the direct reduction methods of Midrex. In this research, the following results were obtained:

- In the Midrex method, the furnace bed temperature and reformed gas CO_2 are the most influential parameters on the metallization degree of produced sponge iron.
- The effective parameters of the metallization degree are highly dependent on each other in the Midrex process and cannot be considered independently of each other.
- Numerical optimization results showed that the best metallization degree (93) was obtained at the values of furnace bed temperature, process gas CO_2, bustle gas temperature, reformed gas CO_2, and process gas flow/ton are equal to 727 °C, 17.29%, 859.55 °C, 2.98%, and 1146 Nm^3/ton respectively.
- Numerical optimization with experimental design methods can be very close to the real conditions of the Midrex plant and, therefore, widely used in the future.

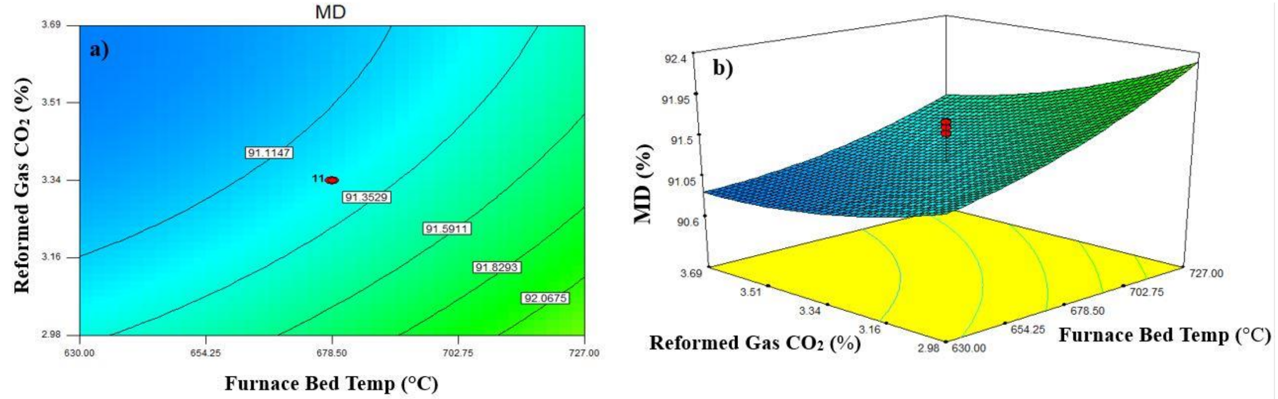


Fig. 4. Contour (a) and three-dimensional (b) diagrams showing the simultaneous effect of furnace bed temperature and reformed gas CO_2 on product quality.

Table 7. Results of numerical optimization of metallization degree.

No.	Furnace bed temperature (°C)	process gas CO_2 (%)	Bustle gas temperature (°C)	reformed gas CO_2 (%)	Process gas flow/ton	MD (%)	
						Actual	predicted
1	727	17.29	859.55	2.98	1146	93	93.07
2	727	17.19	859.43	2.98	1141	92.90	93.05
3	726	17.30	859.99	2.98	1146	92.95	93.02

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