Optimization of blast furnace through reducing coke consumption and CO_2 emission using HSC software

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Abstract

In this paper, a comprehensive evaluation of the charged materials, energy consumption and CO_2 emissions of blast furnace (BF) is done by relating the operating data from the Esfahan steel company (ESCO) with the established static process models. The mass and energy balance calculations were performed using the HSC software. This model is capable of predicting 16 independent variables of the 150 total variables at the same time. The model was verified by comparing the results with the ESCO BF No. 3 off gas, slag and dust composition and were found in 8% deviation from the operating data. The model indicated that increasing the hot air blast temperature and CH_4 injection, reducing coke ash level and slag volume in the product improved the plant productivity. Compared with a convectional BF, the results of optimization showed that the energy consumption, CO_2 emission and coke consumption were reduced by 3% (~183 Gj/THM), 16% (~0.56 kg/THM) and 15% (~79.5 kg/THM), respectively. The energy efficiency was calculated at 81.84% and was increased by about 5% in the optimizing conditions.

Keywords: Blast Furnace; Mass and Energy Balance; HSC Software; CO_2 Emission; Energy Consumption.

1. Introduction

The BF process is one of the major methods of producing cast iron. The BF is charged continuously with iron-bearing burdens, slag formers, and coke [1)]. The coke makes the basic source of energy and acts as a carbon reductant. The preheated air or oxygen-enriched air brings an important amount of heat to the process [2)]. The coke reacts and produces CO_2 and heat in front of the tuyeres to increase the temperature. The CO_2 reacts again with excess carbon to produce CO gas. The gas reduces the iron oxides and other charge materials by indirect reduction at temperatures of 750 to 1150 ℃ [3)]. The final reduction reaction is the direct reduction of iron ore by solid carbon that occurs in a high-temperature region at the lower part of the furnace. The reduced iron is melted and carburized simultaneously and then is collected as a hot metal (HM) at the hearth of the furnace [4)]. The BF has continuously been improved to decrease energy and carbon consumption, reduce CO_2 emission and change the regime of raw materials [5)]. Also, the BF is becoming competitive because of the increasing process efficiency. The mass and energy analysis are essential accessible tools in checking the efficient operation of the BF [6)]. The performance of the feed charge and predicting its optimal conditions may be enhanced by applying the mass balance calculations [7)]. Also, estimating the thermal conditions of the BF is necessary for various reasons such as facilitating the operation, maintaining a stable furnace condition and predicting the required heat

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for the furnace[8]. A significant aim of the transition to a sustainable energy system is to progressively decarbonize the conventional energy systems in all sectors including the metals and mining industry. For instance, the target in Europe is the reduction of greenhouse gas emissions by 80-95% until 2050 in comparison with the level in 1990. A great producer of greenhouse gas emissions, in particular CO_2, is the steel industry [9]. Steel production makes high energy consumption and CO_2 emissions [10]. The production of about 1869 million tons of crude steel in 2020 resulted in 3.6×10^{11} GJ of energy consumption and 3050 million tons of CO_2 emissions, according to the World Steel Association [11]. It was shown that the energy consumption of the ironmaking process can be decreased significantly by adopting commercially available energy-saving technologies for BF [12]. The share of the steel industry in the global CO_2 emissions is about 7-9%, the main reason being the use of coke as a reductant in the BF, according to World Steel Association [13].

The CO_2 emission can be minimized by different methods. A comparative evaluation has been done for the relative effects on the emission and also expected effects on the operational features at the BF by a static heat and mass balance model [14-17]. Although many researchers [18-22] have studied the BF operation over the past years, many problems have been remained unsolved with the operating mechanism of the BF. The work has done by Prakash et al.[21] was modeled the BF considering different zones of BF employing 1-D, 2-D and 3-D steady-state and computational fluid dynamics-discrete element method modeling. Besides this, the research conducted by Hashimoto et al.[5] was nonlinearly modeled the BF to provide operators with appropriate control actions while minimizing the influence of process disturbances. The model was validated and shown to successfully reduce the variance of hot metal temperature by 1.9°C. Similarly, the research conducted by Castro et al.[22] was modeled the mini BF using the multiphase multicomponent modeling approach to investigate the high rates of pulverized charcoal injection and hot hydrogen injections. In this study, the rate equations were also considered to propose a new simulated scenario. Accordingly, the model results for the actual operation were compared with the industrial data and shown to be capable of modeling the BF performance for cleaner hot metal production with the lowest carbon intensity.

The main reason is the complexity and variety of the chemical and physical processes occurring simultaneously in the furnace. The furnace efficiency can be predicted by an appropriate heat balance and any excessive fuel wastages can be eliminated [21]. However, to the best of our knowledge, no studies have been conducted on the energy consumption optimization of the BF considering the chemical reactions using the HSC software. The chemical reactions and processes were simulated by the HSC Chemistry software on a thermochemical basis. HSC software, developed by Metso-Outotec Company is a chemical reaction and equilibrium software that is known worldwide among the thermochemical software with a versatile flowsheet simulation module. HSC is designed for various kinds of chemical reactions and equilibrium calculations as well as process simulation. With HSC it is possible to carry out thermodynamic and chemical processing calculations on a personal computer easily. HSC provides an essential software toolkit for process design and development. The HSC software has various applications in research, industry and scientific education. Thus, the focus of the present study is to determine the energy consumption and CO_2 emission of ESCO BF using mass balance and heat balance modules of HSC software. These modules were used to evaluate the process data provided by ESCO. In doing this, a process calculation model was used to estimate the optimizing condition for charged materials. In this model, by changing the input and output parameters such as the components' fraction of the mass of each stream, the quantity of any unknown component can be calculated and then optimized by minimizing the energy consumption. This model is capable of predicting 16 independent variables of the 130 total variables at the same time with about 8% deviation from the BF No. 3 operating data. In this research, a detailed analysis of energy consumption, CO_2 emission, the heat efficiency of the BF in optimizing conditions and operating processes were performed by a combination of the operating data from the ESCO steel plant with established static process models.

2. Methodology

2.1. Mass balance

The steel plant requires a determined quality of HM and the amount of the slag should be selected for the optimum fluidity and desulphurizing capacity. The calculation uses the chemical composition and the weight of the various materials as the input parameters. The input charge analysis and the output analysis of ESCO BF No. 3 are shown in Tables 1 to 3. It is noteworthy that the air injected into the BF is normal air consisting of 79% N_2 and 21% O_2 with a rate of 3043 m^3/min. Furthermore, 2.8 g/m^3 H_2O is injected into the BF associated with air.

The total number of variables, the stream weights, and the components weight fractions in BF No. 3 were measured to be 130. Regarding the balance equations for each component, elements, and inert components (i.e., Fe, C, Si, Ti, N_2, Mn, P, S, CaO, Al_2O_3, MgO, K_2O, Na_2O, ZnO, PbO and O) and one equation for the total mass equation, the total number of independent equations is 16. The independent mass balance equations are obtained using the component mass balance equation (Eq. 1) [23] and the total mass balance equation. The degrees of freedom are the number of independent variables that must be specified for solving the mass balance equations. These numbers are determined by Eq. (2).

$$\sum_{in} m_i \times w(x)_i = \sum_{out} m_j \times w(x)_j \qquad \text{Eq. (1)}$$

Where m_i and m_j are the mass of input and output materials for 1 ton of produced hot metal, kg; $w(x)_i$ and $w(x)_j$ are the mass fraction of x in material i and j.

$$F = \sum_{n=1}^{N} C_n - C \qquad \text{Eq. (2)}$$

Where F is the degree of freedom, Cn is the total number of variables and C is the number of mass balance equations. It is tried to analyze the output streams of the furnace including the HM, slag composition, top gas, dust, and sludge composition. Despite the components that are present in many streams, some components are present in the only single input stream and single output stream. These are named as tie components, for which solving all the mass balance equation is not necessary. A good example of these components is nitrogen. Nitrogen does not react in the BF, so it enters together with the blast air stream and escapes unchanged throughout the top gas. According to Eq. (1), the top gas volume can be calculated with a nitrogen balance as follows:

- Mass of the input air: 2101.78 kg/THM
- Mass of nitrogen in input air: 78% × 2101.78 =1639.38 kg/THM
- Mass percentage of nitrogen in output gas: 54.80 %
- Mass of output gas: 2991.5 kg/THM

Table 1. Composition (%) of input charge for ESCO BF No. 3.

	Iron ore	**Pellet**	**Sinter**	**Coke**	**Quartz**	**Manganese**
Mass (kg/THM)	333.00	250.50	1038.50	470.70	4.00	9.50
C	-	-	-	84.79	-	-
Fe_2O_3	69.83	75.60	68.30	-	-	-
FeO	15.96	15.50	9.27	1.62	2.42	12.60
Mn	0.09	0.12	1.08	-	-	41.28
P	0.09	0.01	0.01	0.03	-	0.04
S	0.06	0.02	0.04	0.17	-	0.02
CaO	2.70	0.78	9.99	0.54	4.98	10.93
SiO_2	5.05	2.35	6.56	6.90	86.54	26.76
Al_2O_3	0.71	1.04	1.29	4.99	3.92	5.14
MgO	2.57	1.44	2.13	0.16	0.58	1.06
TiO_2	0.19	2.91	0.51	0.16	0.26	0.29
K_2O	0.13	0.09	0.08	0.48	1.17	0.96
Na_2O	0.12	0.11	0.08	0.14	0.14	0.68
ZnO	0.03	0.01	0.01	-	-	0.05
PbO	-	-	-	-	-	0.18

Table 2. Composition (%) of output charge for ESCO BF No. 3.

	Hot Metal	**Slag**	**Dust**	**Sludge**
Mass (kg/THM)	1000.00	342.50	12.00	10.00
Fe	93.68	-	-	-
C	4.43	-	25.10	-
Si	0.53	-	-	-
Ti	0.08	-	-	-
Mn	0.90	1.44	0.68	20.15
Al_2O_3	0.02	11.46	1.62	1.72
CaO	-	38.58	5.44	5.22
MgO	-	7.87	11.28	3.67
SiO_2	-	37.79	10.36	11.38
TiO_2	-	2.07	0.12	0.77
ZnO	-	-	0.12	1.56
PbO	-	-	0.12	1.12
K_2O	-	1.16	0.89	0.62
Na_2O	-	0.70	0.43	0.09
P	0.30	0.03	0.12	0.08
S	0.06	1.37	0.40	0.03
FeO	-	0.47	43.32	32.01

Table 3. Gas composition (%) for ESCO BF No. 3.

Component	N_2	O_2	H_2	CO_2	CO	CH_4
	54.8	0.00	6.50	15.60	23.00	0.10

2.2. Energy balance

The model covers all the energy generated as sensible heat by the input and output materials and the energies generated from exothermic and endothermic reactions. The mass of the variables that have been used in the calculations was obtained from the mass balance section. The reactions in the BF are discussed in three different zones of the BF, as proposed in the Biswas theory [24]. The reduction of Fe_2O_3 to Fe_3O_4 is thermodynamically favorable. According to experimental data presented by Bhattacharya [2] based on the gas analysis and kinetics of reactions, the reduction in the BF is 60% indirect with CO gas, 35% direct with carbon, and 5% by H_2 gas. The raw materials entering BF No. 3 were calculated by using Table 1. Table 4 shows the generated heat for each reaction. All the thermodynamic calculations in Table 4 were performed using the HSC chemistry toolbox. The water vapors formed during the reactions at the bottom of the BF go to the upper part of the furnace and convert to H_2 at the temperature of 1000 K according to Eq. (6). The oxygen entering the bottom of the BF at 1700K causes the carbon to burn according to Eq. (19). The water vapor that enters the BF with air, reacts with the carbon at 1700 K, and produces CO and H_2 gas in Eq. (15).

Considering the operational data, the temperature of material for preheated air, HM, slag, BF gas, dust and sludge are 1358, 1713, 1763, 453, 1400 and 900 K, respectively. According to the first law of thermodynamics, the heat of a closed system is calculated by the following formula [23]:

$$\sum_{in} m_i\, w(x)_i . h_i + \sum_{in} m_i . q_i = \sum_{out} m_j\, w(x)_j . h_j + \sum_{in} m_j . q_j + H_l \qquad \text{Eq. (20)}$$

Where h_i, h_j are the enthalpy of the chemical reaction, kJ/THM; q_i, q_j are the sensible heat (Eq. 21), kJ/THM; and H_l is the enthalpy of loss.

$$q = \int_{T_1}^{T_2} C_p \, dT \qquad \text{Eq. (21)}$$

Sensible heat for each component is presented in Table 5.

Table 4. The heat values for each reaction occurred in BF No. 3.

Eq. (No)	Reaction	T	Total heat
(5)	$3Fe_2O_3 + CO = 2Fe_3O_4 +$	1000	-149548.75
(6)	$H_2O + CO = CO_2 + H_2$	1000	-39429.57
(7)	$Fe_3O_4 + CO = 3FeO + CO_2$	1200	29188.52
(8)	$FeO + CO = Fe + CO_2$	1200	-142849.74
(9)	$3Fe_2O_3 + H_2 = 2Fe_3O_4 +$	1200	-922.74
(10)	$Fe_3O_4 + H_2 = 3FeO + H_2O$	1200	10182.04
(11)	$FeO + H_2 = Fe + H_2O$	1300	12580.60
(12)	$C + CO_2 = 2CO$	1300	284352.55
(13)	$3Fe_2O_3 + C = 2Fe_3O_4 + CO$	1400	317220.13
(14)	$Fe_3O_4 + C = 3FeO + CO$	1400	295837.84
(15)	$H_2O + C = CO + H_2$	1700	27019.52
(16)	$FeO + C = Fe + CO$	1700	665042.80
(17)	$TiO_2 + 2C = Ti + 2CO$	1700	11759.56
(18)	$SiO_2 + 2C = Si + 2CO$	1700	135364.81
(19)	2C + O2 = 2CO	1700	-3371924.82

Table 5. Sensible heat for components of BF.

Component	Sensible Heat (kJ/THM)
Air	2829421.56
H_2O*	8323.60
CH_4*	326483.76
Hot Metal*	2918307
Slag*	577018.16
BF Gas	321720.84
Dust	11697.44
Sludge	2999.42

*2.8 g/m^3 H_2O and 58 kg/THM natural gas inject with air at 1358K

*C_p for HM [2] = 2.06 kJ.kg^{-1}.K^{-1}

*C_p for slag [25] = 1.15 kJ.kg^{-1}.°C^{-1}

An experimental formula has been developed by the International Institute of Iron and Steel Standards [26] to calculate BF heat losses:

Eq. (22)

$$h_{loss} = \frac{5.4\times10^3\times\text{Hearth dia.}+0.85\times10^3\times\text{number of tuyeres}}{\frac{\text{pig iron production per hour}}{55.85}\times\frac{\text{pig iron Fe\%}}{100}} =$$

497.10 kJ/THM

2.3. Energy efficiency

Based on the energy balance calculations performed above, for BF No. 3, the energy efficiency compared to the first law of thermodynamics can be calculated according to Eq. (23).

Eq. (23)

$$\eta = \frac{\text{Energy Contents of Useful Products}}{\text{Energy Input}}\times100\%$$

A comprehensive energy consumption per ton of steel was calculated according to the energy balance of a BF by the value of energy equivalent for each energy substance [27]. The main input energy substances into the system include injection of the input charges which enter the BF with temperatures greater than 273 K and output materials with temperatures less than 273 K and exothermic reactions.

2.4. CO_2 emission

According to the World Resources Institute & World Business Council for Sustainable Development guidelines, the indirect CO_2 emissions, the direct CO_2 emissions and the CO_2 credit were used to calculate the net CO_2 emissions by the following equations [28]:

$$CE = \mathrm{CE_d} + \mathrm{CE_i} - \mathrm{CE_c} \qquad \text{Eq. (24)}$$

$$\mathrm{CE_d} = \frac{(\mathrm{CE_{in}} - \mathrm{C_p} - \mathrm{C_{byp}})}{12} \times 44 \qquad \text{Eq. (25)}$$

Where CE, CE_d, CE_i, CE_c are the net, direct, indirect, and credit of the CO_2 emissions (kg/THM), respectively. The C_{in}, C_p, C_{byp} are the total carbon input to the system, the carbon fixed in the product, and the carbon fixed in the byproduct (kg/THM), respectively.

3. Results and Discussion

3.1. Validation of the model

According to Table 1, the BF charge contains many impurities associated with iron oxides. The affinity for oxygen of the impurities can be illustrated within the Ellingham diagram plotted by the HSC software (Fig. 1). Na_2O, K_2O, and PbO are more easily reduced with CO and H_2 gases in the upper part of BF and escape together with the off-gas. Besides, MnO, SiO_2, and TiO_2 can be partially reduced by carbon in the higher temperature zones. Finally, Al_2O_3, MgO, and CaO are generally not reduced in the BF and are called inert compounds.

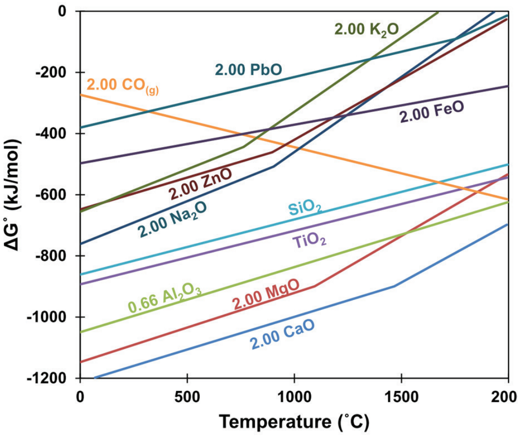

Fig. 1. Ellingham's diagram drawn with HSC software for the compounds in BF No. 3.

To validate the model, as an example, the slag, BF gas and dust compositions could be calculated according to the mass balance equation. The results were then compared with the available analysis data, which proved the validity of the procedure. Using the mass balance equations, the composition of the required input and output materials can be accurately calculated according to the demand of the industry and furnace operator. The accuracy of the mass balance equations is validated by comparing the results in the model with the available analysis of the BF. In Table 6, the slag composition, BF gas, and flue dust of the furnace are compared with the model results. The data used in the below example were achieved from the ESCO's metallurgical department (analysis of the charged materials, coke, HM, and slag) and ESCO BF No. 3 control room (all temperature, pressures, and air-related parameters). As is seen, the estimated values using the model were close to the plant operating data with a variation of about ±8%. The variation could be due to several unknown variables that are usually present in any complex system such as BF. Another source of variation could be due to the time difference between the input time and the output time charge difference. Since this model can calculate all other unknown variables, the variables were validated accordingly. This mass analysis model of the BF system indicates useful information on the BF performance. This means that where and how the charged materials have been consumed.

3.2. Energy saving, coke consumption and CO_2 emission

The operation of BF can be improved by combining various changes in the operating parameters including the change of the blast temperature, the level of coke ash and the burden charge. One of the features of the HSC is the graphical capabilities the software has in the optimization of different variables. This capability may be used in the optimization of one or a few variables when other variables are changing. The effects of the air temperature, the ash content of the coke, natural gas volume, and slag weight on the consumption of coke and volume of the blast air were evaluated. As shown in Fig. 2, with an increase in the air temperature by 150 K, the amount of the required blast air can decrease by 102 m^3/THM, which saves about 250 MJ of energy.

Table 6. Measured and calculated data for dust, slag and BF gas compositions.

Wt%	Dust		Slag		BF Gas	
	Measured	Model	Measured	Model	Measured	Model
FeO	43.32	44.50	0.47	0.47		
CaO	5.44	5.80	38.58	35.30		
SiO_2	10.36	11.53	37.79	36.11		
MgO	11.28	11.67	7.87	8.77		
C	25.10	26.50				
Mn			1.44	1.36		
P			0.03	0.02		
S			1.37	1.32		
Al_2O_3			11.46	12.76		
TiO_2			2.07	2.10		
K_2O			1.16	1.14		
Na_2O			0.70	0.65		
N_2					54.80	54.60
CO					23.00	23.40
CO_2					15.60	15.55
H_2					6.50	6.45

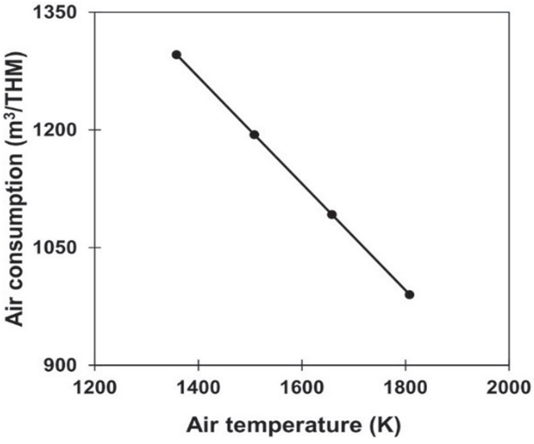

Fig. 2. The effect of air temperature on air consumption.

According to the model prediction, the effect of different operational parameters on coke consumption was shown in Fig. 3. According to Fig. 3 (a), increasing the temperature of the blast air by every 100 K decreases the coke consumption by 40 kg/THM. This is equal to the energy saving of about 500 MJ/THM. One of the most important factors in the rate of coke consumption is the ash content of the coke. According to Fig. 3 (b), reducing the coke ash by 2% reduced the coke consumption by 50 kg, which is equal to about 1400 MJ/THM of energy. So, millions of joules of energy can be saved in the BF by selecting a low ash coke. Fig. 3 (c) shows that by increasing the volume of natural gas by 20 m^3, 45 kg less coke is consumed, which is equal to 650 MJ of energy. Besides, Fig. 3 (d) shows the effect of slag volume on coke consumption. By reducing 20 kg of slag, 35 kg/THM (equivalent to 100 MJ of energy) less coke will be used. The use of higher-grade ferrous charge reduces the production of slag and thus reduces the consumption of coke. Although the reduction in the coke rate in exchange for a reduction in slag volume is not very large, the use of suitable load-bearing materials makes this reduction practical and cost-effective. The calculated energy efficiency for BF No. 3 was 81.84%. The energy content of the useful products to the total amount of energy input was compared using the first law efficiency.

According to the effect of the parameters on the amount of coke consumption mentioned in the previous section, the optimal point of the system for coke consumption can be calculated. Taking into account all the conditions and the ascending and descending effect of the variables on coke consumption, the optimal point of the system, which shows the lowest coke consumption was calculated. Minimum coke for BF No.3 is about 330 kg/THM, for this consumption, air temperature is 1600 K, slag volume is 280 kg/THM, the natural gas volume is 130 m^3/THM and ash content in coke is 8 %. Therefore, the performance of BF will improve in this condition.

According to the model predictions, it can be seen how CO_2 emissions levels and energy consumption are strongly influenced by coke rate, burden composition and temperature. The net CO_2 emissions in BF No. 3 and the optimizing condition decreased from 3.49 kg/THM to 2.93 kg/THM. Moreover, the energy consumption for BF No. 3 and the optimizing condition decreased from 6153.10 MJ/THM to 5969.10 MJ/THM. The calculated energy efficiency for BF was 81.84%, while in the optimizing condition, the energy efficiency decreased to 86.10%. The reason was related to the direct effect of coke consumption on the net CO_2 emissions.

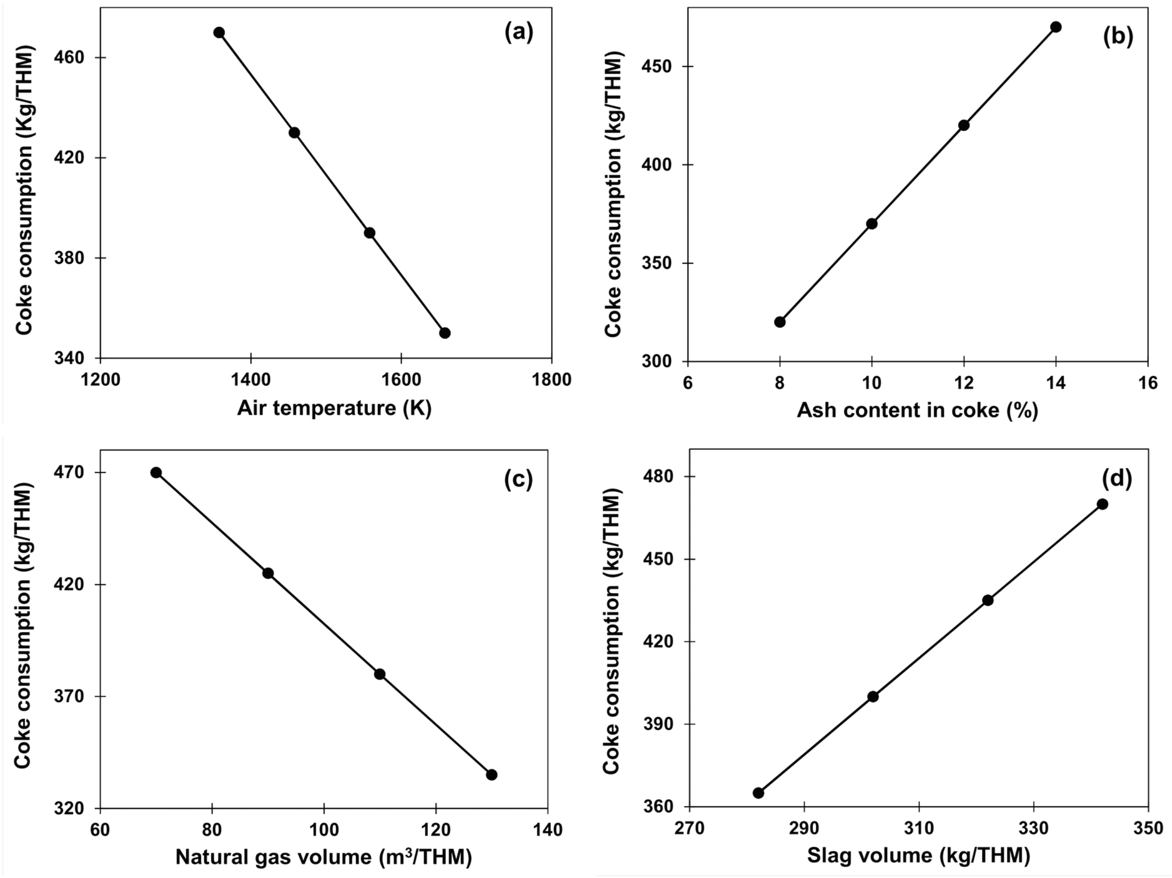

Fig. 3. Effect of (a) air temperature, (b) ash content in coke, (c) natural gas volume and (d) slag volume on the coke consumption.

4. Conclusions

In this study, the impact of operating parameters on the plant efficiency and CO_2 emissions of BF No. 3 of ESCO has been investigated. The efficiency improvement was identified as a function of CO_2 emissions and consumption of coke and energy. The results of this study are summarized as follows:

- The operating variables can be controlled by the model using the correlated parameters to increase the furnace efficiency, reduce the specific energy consumption, and estimate the heat loss of a furnace.
- Any increase in the ash content of coke and the slag volume has negative effects on energy consumption. Moreover, enhancing the air temperature and the natural gas volume decreases energy consumption.
- An optimal set of operating conditions can be identified by the employment of the model optimization tool which leads to a minimization of coke consumption.
- The results of optimizing indicated that the energy consumption, CO_2 emission and coke consumption were reduced by 3% (~183 Gj/THM), 16% (~0.56 kg/THM) and 15% (~79.5 kg/THM), respectively.
- The energy efficiency was calculated at 81.84% and was increased by about 5% in the optimizing condition.

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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