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EXERGY ANALYSIS OF THE ELECTRICITY GENERATION PROCESS IN THE REUSE OF BLAST FURNACE GASES IN A STEELMAKING COMPANY

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Abstract. *In the present work, using the tools and the concepts of energy and exergy for the steelmaking process, a detailed study of the electric energy generation system (Cogeneration) in a non-integrated steel mill coupled with a thermoelectric plant was carried out, where the production process of this steel industry, which is located in a city in the Midwest region of Minas Gerais (Brazil), was analyzed. A pig iron producer that sells in the internal and external markets, this steel industry is continuously seeking to increase its competitiveness in the steel sector and to become an ecologically sustainable company. The intention is to propose a better utilization of the gases generated in the production of pig iron in a charcoal blast furnace. That is, since the gas flow from the blast furnace, which serves as fuel in the combustion process in the boiler, does not have a regular or constant flow, it is necessary to monitor the air/fuel ratio almost in real time, in order to obtain the highest power in the turbo-generator set of the steam system. Through the energy and exergetic analyses performed for each of the components of the energy generation cycle of the steel mill, improvement proposals are suggested to increase the energy and exergetic efficiency of the components and, consequently, of the cycle as a whole.*

Keywords: *Steel Making Company, Cogeneration, Blast Furnace Gases, Energy, Exergy.*

1. INTRODUCTION

The development and optimization of energy conversion systems are linked to industrial progress, everyday life, and human well-being. The growing demand for electricity and other forms of energy encourages their development and the search for more efficient systems with lower fuel consumption. Decision making and resource allocation are not always easy. For this, there are several tools to aid decision making. Depending on the type of system to be analyzed, one can make use of optimization techniques, exergoeconomic analysis, as well as the use of the theoretical concepts of energy and exergy, as is the objective of the present work.

The energy analysis is based on the First Law of Thermodynamics or, as it is also known, Energy Conservation, and focuses on a quantitative study of energy. The energy analysis also contributes to the understanding of the concept of energy use in different parts of the process, highlighting its efficiency and enabling the identification of processes that are more energy inefficient in the system. One of the limitations of this method is the lack of available information about the energy degradation that occurs in the process, as well as the quality of the energy contained in the process flows (Moran *et al.*, 2013).

Exergy analysis, according to (Kotas (2013); Bejan *et al.* (1996); Dincer and Rosen (2007)), overcomes the limitations of the First Law (of energy analysis), and can then, in an energy process, quantify and point out energy degradation and calculate the real magnitude of exergy losses. According to Kotas (2013), exergy is the maximum work in which one can obtain from a given form of energy, using environmental parameters as the reference state.

An exergetic analysis involves mass, energy and exergy balances for all plant components (control volumes), and definition of exergetic efficiency for each of them. The following equations represent the mass, energy and exergy balances in the control volumes. Kinetic and potential energy/exergy are not considered.

Mass balance:

$$\sum_{i=1}^n \dot{m}_{in} - \sum_{i=1}^n \dot{m}_{out} = 0 \quad (1)$$

Energy balance:

$$\sum_{i=1}^n \dot{Q}_{vc} - \dot{W}_{vc} + \sum_{i=1}^n \dot{m}_{in} h_{in} - \sum_{i=1}^n \dot{m}_{out} h_{out} = 0 \quad (2)$$

Exergy balance:

$$\sum_{i=1}^n \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) - \dot{W}_{vc} + \sum_{i=1}^n \dot{m}_{in} e_{in} - \sum_{i=1}^n \dot{m}_{out} e_{out} = \dot{I}_{vc} \quad (3)$$

The variable “e” represents the specific exergy of the flow and can be defined by:

$$e = (h - h_0) - T_0(s - s_0) + e_{ch} \quad (4)$$

where the subindex “o” represents the reference environment, and “ e_{ch} ” the chemical exergy.

The combination of these analyses is focused on enabling the optimization of the system, allowing the study of each component that makes up the power generation cycle, identifying the energy losses that occur during the processes and, consequently, enabling their reduction, contributing to the improvement of the project with the achievement of better efficiency.

Using the tools and the concepts of energy and exergy for the steelmaking process, a detailed study of the electric energy generation system (Cogeneration) in a non-integrated steel mill coupled with a thermoelectric plant was carried out, where the production process of this steel industry, which is located in a city in the Midwest region of Minas Gerais, was analyzed (Fig. 4). A pig iron producer that sells in the internal and external markets, this steel industry is continuously seeking to increase its competitiveness in the steel sector and to become an ecologically sustainable company. Furthermore, the company where the study was carried out has a blast furnace in operation and a deactivated one, and a thermoelectric plant designed to operate with the surplus gases from the two blast furnaces.

1.1 Steel Mills and Energy Cogeneration

Steel mills can be integrated, semi-integrated and non-integrated. The integrated steel mills acquire the raw materials in their raw state, carry out all the phases of the industrial process and sell the finished products, that is, they operate the three basic phases of steel production: reduction, refining and rolling.

In the semi-integrated mills, in turn, there are two stages, refining and rolling. The semi-integrated mills buy pig iron from other mills to transform it into steel. The non-integrated steel mills, which were the object of the study, are those that only produce pig iron. They only carry out the process of reducing the iron ore in the blast furnace, which is sold to foundries and steel mills.

Pig iron is a first-melting product obtained from the reduction of iron ore in a blast furnace. In the production process of pig iron in blast furnaces, flue gases are formed, which are called blast furnace gas (BFG). The analysis of the chemical composition is important to evaluate the operational aspects of using the waste gases generated during the pig iron production process.

The average values of the gas composition are presented in Tab. 1. The gases were collected from the blast furnace of the partner company and analyzed in a chromatograph equipped with molecular sieve and porous polymer columns, in addition to thermal conductivity and flame ionization detectors.

Table 1. Blast Furnace Gas Composition

Blast Furnace Gas Composition (%weight)					
CO	H ₂	H ₂ O	CH ₄	N ₂	CO ₂
22,15	5,46	9,88	1,02	46,73	14,76

Source: Steel Mill

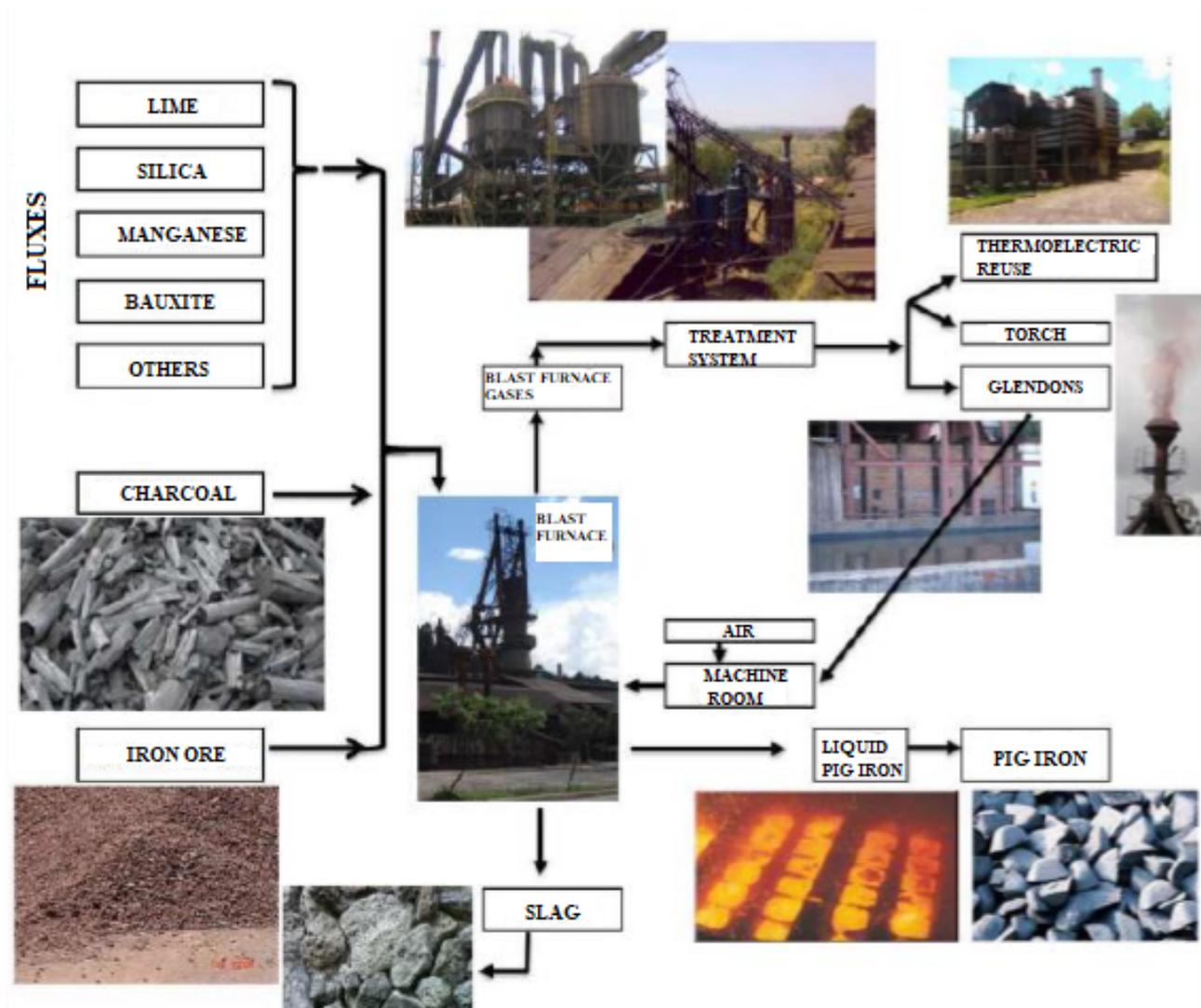


Figure 1. Production process flowchart for a blast furnace of a non-integrated steel mill.

The calorific value of a fuel is given by the number of calories expended in burning it. One calorie is one unit of heat required to raise one gram of pure water from 14.5°C to 15.5°C under normal atmospheric pressure (Linerio, 2008).

The calorific value of the blast furnace gas (BFG) was analyzed together with the gas composition, obtaining an approximate value of 3,842.5 kJ/Nm³, which is within the range of the Higher Heating Value (HHV) and Lower Heating Value (LHV), presented in Tab. 2. These values were obtained from the partner company.

Table 2. Calorific value of BFG

Blast Furnace Gas (BFG)	
	Specific Energy (kJ/Nm ³)
LHV	3.768
HHV	3.919

Source: Steel Mill

Besides being used in the blast furnace air preheating systems, this gas which is emitted in the production of pig iron can also be used to generate electricity. After the blast furnace emissions treatment system and the use of part of the gases in the heat recoverers, the viability of using the rest of the BFG to generate electric energy is a path of enormous importance for the steel mills, taking into consideration the energy waste when opting for the disposal of BFG into the atmosphere.

It is at this point that the concept of energy cogeneration in steel mills arises. The concept of cogeneration can vary according to the focus of the process. Nevertheless, Energy Cogeneration can be defined as a thermodynamic process in which occurs the simultaneous and sequential production of electrical or mechanical energy, and useful thermal energy, from a single energy source.

Therefore, as previously mentioned, the gas generated in the production of pig iron can be used in the production of electricity, thus supplying part or all of the electrical energy consumption of the steel mill and helping to reduce the operational cost of the process. However, it is important that they are used in the best possible way, that is, providing the highest level of efficiency possible (Carpio, 2000).

2. METHODOLOGY

The methodology employed consisted of an energy and exergetic analysis, using the equations presented previously for each piece of equipment that is part of the energy generation system when using blast furnace gas (BFG) as fuel.

It is worth mentioning that the priority of a non-integrated steel company is that the Blast Furnace Gas (BFG) primarily serves the Glendons. The purpose of this equipment is to heat the air that enters the blast furnace. The rest of the blast furnace gas (BFG), between 45% and 50%, goes to the production of electricity.

With a range from 45% to 50% and a non-uniform composition of the blast furnace gas (BFG), it is important to build an energy and exergy model by performing mass, energy and exergy balances.

The model was built and solved using the programming language *Spyder - Python v.4.2.5* (Free Software), together with the tool *CoolProp v. 6.4.1* (Free Software for thermodynamic properties). It is worth mentioning that this analysis was performed:

- Energy calculation for each element of the Power Cycle of Energy Generation (*Ciclo Rankine*): Boiler, Steam turbine, Condensation System.
- Exergetic calculation for each element of the Power Cycle of Energy Generation (*Ciclo Rankine*): Boiler, Steam turbine, Condensation System.
- Energetic and exergetic analysis when there is variation in the blast furnace gas flow (BFG).

For the solution of the analysis model elaborated using the programming language *Spyder - Python v.4.2.5*, some data from the steel mill in question were necessary. The data we used were obtained by contacting the company under analysis, shown below in Tab. 3:

Table 3. Steelmaking data

	Pressure	Temperature	Flow
Boiler Steam	21 <i>kgf/cm²</i>	300°C	20 <i>t/h</i>
Boiler Feedwater	26, 25 <i>kgf/cm²</i>	90°C	18, 6 <i>t/h</i>
Turbine	21 <i>kgf/cm²</i>	300°C	20 <i>t/h</i>

In addition to the data in Tab. 3, some data about the flue gases in the boiler and some information about the condenser and the power consumption of the plant were also obtained.

There are a few ways to calculate the exergy of a system. Among them, one can use the equation (Moran *et al.*, 2013):

$$B = \dot{m} \cdot [(h - h_o) - T_o \cdot (s - s_o)] \quad (5)$$

2.1 Boiler

To perform the calculations for the boiler, we must first analyze the fuel, in this case, the Blast Furnace Gas - BFG. Table shows the elemental composition of the fuel, considering an analysis by weight, along with other information.

Table 4. Elemental Composition of Fuel

	<i>CO</i>	<i>H₂</i>	<i>H₂O</i>	<i>CH₄</i>	<i>N₂</i>	<i>CO₂</i>
% weight	22,15	5,46	9,88	1,02	46,73	14,76
M.M	28	2	18	16	28	44
<i>y_i</i>	0,2215	0,0546	0,0988	0,0102	0,4673	0,1476

Where:

- *MM* is the molar mass of each element
- *y_i* represents the fraction of each term, given by: $y_i = \frac{n_i}{n_t}$

With this information it is then possible to perform the stoichiometric balance for a combustion reaction. However, before this, it is common to use an extra percentage of Oxygen in the combustion reactions to ensure that all the fuel present is properly utilized.

The equations required for the exergetic calculation differ depending on the type of fuel that is used. They vary in the case of solid, liquid or gaseous fuels. Considering gaseous fuel, the exergy of gases will be the sum of chemical exergy and physical exergy, given by the following equation (Kotas, 2013):

$$B_g = n_{mg} \cdot b_{mg}^{\circ} + (T_g - T_o) \cdot \sum_k (n_{gk} \cdot Cp_{gk}^b) \quad (6)$$

Where:

$$b_{mg}^{\circ} = \sum_k (y_{gk} \cdot b_{gk}^{\circ}) + R \cdot T_o \cdot \sum_k (y_{gk} \cdot \ln y_{gk}) \quad (7)$$

The values of *Cp* and *b_{mg}^o* are obtained for the reactants and products using thermodynamic tables for the elements that are part of the combustion equation.

The thermal efficiency can be obtained through the following equation (Silva, 2002):

$$\eta = \frac{\dot{m}_v \cdot (h_v - h_c)}{\dot{m}_c \cdot PCI} \quad (8)$$

Where:

- *h*: is the enthalpy of the vapor or condensate
- *PCI*: Fuel's Lower Calorific Value

The exergetic efficiency is given by (Silva, 2002):

$$\psi = \frac{P}{R} \quad (9)$$

Where:

- *P* (products): Steam Exergy
- *R* (resources): Exergy from condensate, fuel and electrical energy

And irreversibility, which shows how much exergy is lost, is calculated by:

$$I = P - R \quad (10)$$

2.2 Steam Turbine

A steam turbine is considered to be a control volume in a permanent regime, where its main purpose is to produce work or electrical power. The heat transfer of turbines in general is negligible ($\dot{Q} \approx 0$), since they are well insulated. Potential energy variations are also negligible in steam turbine analyses ($\Delta ep \approx 0$). The flow velocities in most turbines are very high, and the fluid undergoes a significant variation in its kinetic energy. However, this variation is generally very small with respect to the enthalpy variation and can therefore be neglected (Çengel and Boles, 2013).

As such, the equations for energy and mass balance of a steam turbine are given by (Dincer and Zamfirescu, 2016):

$$\text{Mass Balance Equation : } \dot{m}_1 = \dot{m}_2 = \dot{m} \quad (11)$$

$$\text{Energy Balance Equation : } \dot{W} = \dot{m}\Delta h \quad (12)$$

Regarding the exergy balance, the net exergy associated with the flow at the inlet and outlet of the steam turbine is obtained by (Dincer and Zamfirescu, 2016):

$$\dot{E}x_{cons} = \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2)] \quad (13)$$

The exergy destruction rate can be determined by subtracting the power produced (\dot{W}) from the net exergy rate of the turbine (Dincer and Zamfirescu, 2016):

$$\dot{E}x_d = \dot{E}x_{cons} - \dot{W} \quad (14)$$

Furthermore, it is possible to determine the total exergy rate available in the turbine, considering the output state to be the dead state. The total exergy available can be calculated using Eq. (5).

The isentropic efficiency of a turbine is given by the following equation (Dincer and Zamfirescu, 2016):

$$\eta = \frac{\dot{W}}{\dot{W}_s} = \frac{\dot{m}(h_1 - h_2)}{\dot{m}(h_1 - h_{2s})} \quad (15)$$

The exergetic efficiency of a turbine can be obtained by (Dincer and Zamfirescu, 2016):

$$\psi = \frac{\dot{W}}{\dot{E}x_{cons}} \quad (16)$$

2.3 Condensation System

A condensation system (cooling tower) can be considered to be a heat exchanger operating on a permanent basis, in which two moving fluid streams exchange heat with each other. The principle of conservation of mass applied to a heat exchanger operating under steady state conditions requires that the sum of the incoming mass flows equals the sum of the outgoing mass flows. Heat exchangers typically do not involve work interactions ($w = 0$), and kinetic and potential energy variations are negligible ($\Delta ec \approx 0$, $\Delta ep \approx 0$) for each fluid stream (Çengel and Boles, 2013).

As such, the equations for energy and mass balance of a cooling tower are given by (Dincer and Zamfirescu, 2016):

$$\text{Mass Balance Equation : } \dot{m}_{1h} = \dot{m}_{2h} = \dot{m}_h \quad \text{and} \quad \dot{m}_{1c} = \dot{m}_{2c} = \dot{m}_c \quad (17)$$

$$\text{Energy Balance Equation : } \dot{m}_h(h_{1h} - h_{2h}) = \dot{m}_c(h_{2c} - h_{1c}) \quad (18)$$

Regarding the exergy balance:

$$\dot{E}x_{IN} = \dot{m}_h[(h_{1h} - h_0) - T_0(s_{1h} - s_0)] + \dot{m}_c[(h_{1c} - h_0) - T_0(s_{1c} - s_0)] \quad (19)$$

$$\dot{E}x_{OUT} = \dot{m}_h[(h_{2h} - h_0) - T_0(s_{2h} - s_0)] + \dot{m}_c[(h_{2c} - h_0) - T_0(s_{2c} - s_0)] \quad (20)$$

Where the prefix “h” indicates the hot fluid and the prefix “c” indicates the cold fluid. Thus, the exergy destruction rate can be obtained by:

$$\dot{E}x_d = \dot{E}x_{IN} - \dot{E}x_{OUT} \quad (21)$$

The exergetic efficiency of a cooling tower can be obtained by (Dincer and Zamfirescu, 2016):

$$\psi = \frac{\dot{E}x_{OUT}}{\dot{E}x_{IN}} \quad (22)$$

2.4 Programming

Based on the need to assist in the calculations of the project and the fuel stoichiometric balance, programming in *Python* was used, which has several libraries that facilitate and favor its use.

To obtain the enthalpy and entropy values, the library *CoolProp v. 6.4.1*, which has information about the properties of some substances, was used. Then, the equations that were mentioned above were written in *Spyder - Python v.4.2.5*. A graphical interface was created in order to improve the interaction with the user. As shown in (Fig. 4)

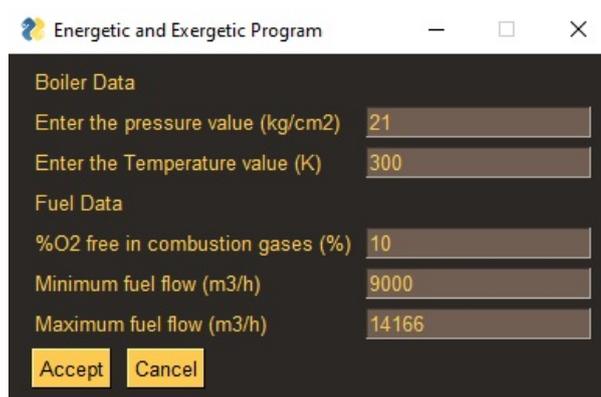


Figure 2. Graphical interface of the Energetic and Exergetic Program.

3. RESULTS AND DISCUSSIONS

From the definitions and the data shown above, the energy, mass and exergy balance calculations for the boiler, the steam turbine and the condensation system were then performed through Python programming. The main results will be shown in the following topics.

3.1 Boiler

The results that were obtained for the boiler are shown below in Tab. 5. By analyzing the results in the table it can be seen that there is a huge difference between the energy efficiency and the exergetic efficiency of the boiler.

Table 5. Results - Boiler

Definition	Value
Exergy Balance	
Fuel exergy	14.626 kW
Flue gas exergy	9.403 kW
Efficiencies	
Energy Efficiency	85,73%
Exergetic Efficiency	37 %
Irreversibility	
Resources	15.212 kW
Products	5.629,29 kW
Irreversibility	9.582 kW

3.2 Steam Turbine

Table 6 contains the main results obtained in the energy and mass balance and exergy balance calculations for the Steam Turbine.

Analyzing Tab. 6, one can notice the power produced in the Steam Turbine of approximately 1,8 MW and its isentropic efficiency of 64%. In addition, it is worth noting the calculations made in the exergetic balance of the turbine, where an exergy destruction rate of approximately 790 kW and an exergetic efficiency around 70% was obtained.

3.3 Condensation System

Table 7 contains the main results obtained in the energy and mass balance and exergy balance calculations for the Condensation System.

Analyzing Tab. 7, the exergy rates entering and leaving the cooling tower through the water and air flows are high-

Table 6. Results - Steam Turbine

Definition	Value
Input enthalpy (h_1)	3022, 48 kJ/kg
Output enthalpy (h_2)	2692, 22 kJ/kg
Input entropy (s_1)	6, 7526 $kJ/kg \cdot K$
Output entropy (s_2)	7, 2295 $kJ/kg \cdot K$
Energy and Mass Balance	
Power Output (\dot{W})	1834, 77 kW
Isentropic efficiency	64, 34 %
Exergy Balance	
Net exergy rate entering	2624, 65 kW
Exergy destruction rate	789, 88 kW
Exergetic efficiency	69, 91 %
Total available exergy rate (Exit State as Dead State)	5631, 89 kW

Table 7. Results - Condensation System

Definition	Value
Input enthalpy of water (h_{1h})	2688, 08 kJ/kg
Output enthalpy of water (h_{2h})	335, 05 kJ/kg
Input entropy of water (s_{1h})	8, 7791 $kJ/kg \cdot K$
Output entropy of water (s_{2h})	1, 0755 $kJ/kg \cdot K$
Input air enthalpy (h_{1c})	47, 04 kJ/kg
Output air enthalpy (h_{2c})	117, 67 kJ/kg
Input air entropy (s_{1c})	0, 1685 $kJ/kg \cdot K$
Output air entropy (s_{2c})	0, 4058 $kJ/kg \cdot K$
Exergy Balance	
Exergy rate entering	122, 35 kW
Exergy rate leaving	48, 83 kW
Exergy destruction rate	73, 51 kW
Exergetic Efficiency	39, 91 %

lighted, where an exergy destruction rate of approximately 73.5 kW was obtained, as well as an exergy efficiency around 40%.

3.4 Energetic and exergetic analysis when there is variation in the blast furnace gas flow (BFG).

Calculations were performed when the blast furnace gas (BFG) used as fuel flow varies. This directly affects the generation of electrical energy. The blast furnace gas (BFG) range is shown in the Table 8. The data were obtained from the partner company.

As mentioned above, there is a range of blast furnace gas from 45% to 50% used as fuel. This is why it is important to carry out an energetic and exergetic analysis when this variation exists. The (Fig. 4) shows the direct relationship between the variation of the blast furnace gas flow in and the generation of electrical energy. The greater the flow of blast furnace

Table 8. Blast Furnace Gas (BFG) Variation

Blast Furnace Gas (BFG) used as fuel	
	(Nm ³ /h)
Minimum fuel flow	9000
Maximum fuel flow	14000

gas (BFG), the greater the generation of electricity.

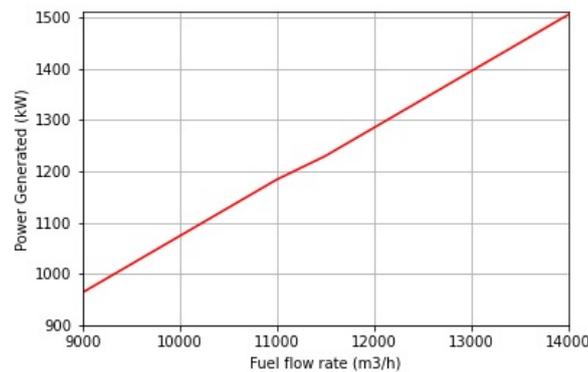


Figure 3. Variation of the blast furnace gas flow *versus* generation of electrical energy.

The (Fig. 4) shows the relationship between gas flow and exergetic efficiency in the Boiler. We can observe that exergy destruction must be considered during exergetic analysis. It can be seen that we have a maximum exergy efficiency in the Boiler of 34% for a flow of 12.500 m³/h.

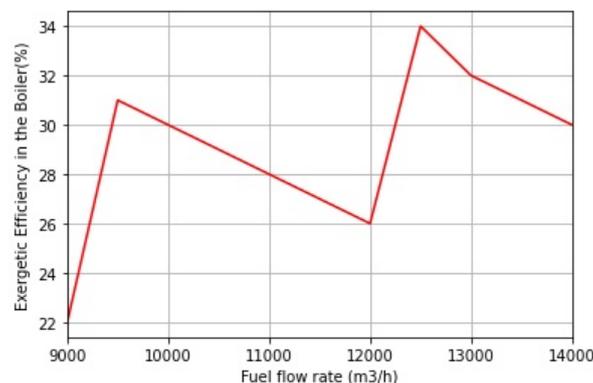


Figure 4. Variation of the blast furnace gas flow *versus* Exergetic Efficiency in the Boiler.

4. CONCLUSION

It can be observed, that the processes in steel mills are complex. To achieve greater efficiency, it is always common to try to use the inputs in the best way possible, distributing them throughout the industry.

In the present work, it was approached in two moments. The first being an analysis when the blast furnace gas (BFG) flow rate was fixed. In a second moment, it was analyzed when the blast furnace gas has variations, as happens in a steel industry.

The results show that it is important to perform an exergetic analysis, with the purpose of observing which equipment has the largest losses, in order to reduce them.

We can observe that the boiler is the equipment where the greatest irreversibility occurs. When the Blast Furnace gas flow rate (BFG) is fixed, an efficiency of 86% was obtained, using the first law, without considering the losses that occur in this type of equipment. However, when performing the exergetic calculations, an efficiency of 37% was obtained, a much lower value than that obtained in the previous analysis. When we perform the variation of the blast furnace gas flow (BFG), as shown in Figure 4, we can prove that there is a great destruction of energy during the steam generation process.

This destruction of exergy is associated with the temperature and pressure parameters of the equipment. We can conclude that it is very important to maintain the fuel flow

The turbine is the equipment that has the lowest energy and exergetic losses, according to table 6, it has an exergetic efficiency of 69.91 %. It is able to transform steam into mechanical energy which is transformed into electrical energy through the generator, as shown in Figure 3.

The condenser, as well as the boiler, is an equipment that has higher energy and exergetic losses, according to Table 7 it reaches 73.51% of exergetic destruction.

One of the conclusions that we can observe in a steel mill industry is that it is necessary to stabilize the flow of the blast furnace gases (BFG) that serve as fuel in the boiler furnace. Avoiding heat losses which are important for the generation of electrical energy. It is worth mentioning that nowadays the cost of electricity is increasingly high, and the steel industry needs electricity for the production process of pig iron.

Finally we can mention that a database search was carried out in order to find papers with a similar approach. We found more works that address an energy and exergetic analysis of the blast furnace and not the generation of energy when using blast furnace gases (BFG).

It is hoped that this work will be of help to the non-integrated steel industries that produce pig iron.

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