ENERGETIC ESTIMATION OF HEAT-RECOVERY COKE OVEN

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ABSTRACT

Worldwide, steel production insistently seeks energy strength, pointing out the precision of application of all energy from the raw material with the objective of increasing production with quality and economically viable. In this sense, the energy assessment is the basis adopted to decide on the manufacture of coke in the industry. With this argument, this paper presents an energy analysis of Heat Recovery furnaces through calorific value, a method specified by the Energy Research Company of Brazil and the Brazilian Association of Metals and Materials for application in calculations in a productive environment. The data of the basic raw materials for the production of coke, the technological analysis and the energy estimation in the manufacture of coke in Coke Ovens Heat Recovery can be found in the proposed method. The present work presents results that demonstrate that the active and efficient use of the calorific value of metallurgical coal produces an energy quality coke for the manufacture of pig iron in the blast furnace.

Keywords: Heat-recovery coke oven, calorific value, energetic estimation

INTRODUCTION

The steel industry in the current social scenario represents an essential pillar in the chain of energy and primary inputs in the demand of various sectors of production, its task is based on production with quality, competitiveness, safety and environment. Worldwide, steel producers pursue energy excellence with emission reduction programs and autonomous energy production. Therefore, it is important to operate the furnaces with energy efficiency of the inputs, optimizing losses and the use of raw material, effective in the management of the steel plant (Coelho, 2003).

Energy is the basis for productive activities, in all sectors of the industrial process, with the objective of achieving products with competitive prices, high quality and low cost, thus enabling entry into the competing market (EPE, 2005). The statistical study of energy assessment is crucial in the application of energy in industries. However, there is a scarcity of scientific studies addressing energy assessments in coke manufacturing.

Currently, conceptual surveys of studies of energy in the manufacture of coke are carried out as in Coke Plants Heat Recovery, enabling innovations in energy calculations in metallurgy.

Routes of the Steelmaking Process

Steel plants are characterized through the stages of execution of production and sale of raw material. Plants that process all phases of the industrial process, from the raw state to the sale of products, are classified as integrated.

An integrated steel mill is made up of the following phases: Raw Materials Yard, where the materials for the manufacture of coke, pig iron and steel are stored; the Coke Plant where coke is produced, fuel to reduce iron for the transformation of pig iron; Sintering, where the manufacture of flux pellets, which are composite materials in pig iron, takes place; the Blast Furnace, responsible for the production of pig iron; the Steelworks, which transforms pig iron into liquid steel, and finally Continuous Casting where the liquid steel is solidified and transformed into steel plate.

In general, obtaining steel requires the processing of raw materials, iron ore, fluxes and mineral coal. The agglomeration of these natural products in sintering reduces energy consumption and increases efficiency in the blast furnace process. The Coke Plant, specifically, is responsible for the generation of the fuel called coke in an integrated plant, so it is relevant in the reduction of gas emissions to the environment and energy cost (Larsson, 2006).

Coke

Coke is produced for the steel industry; its manufacture is of an unparalleled complexity because it involves the pyrolysis of metallurgical coal in ovens. Coal is a mineral that comes from wood and substances under high pressures and temperatures for many years. It has four stages: peat, lignite, coal and anthracite. Peat has a lower carbon level and anthracite has a high carbon level. Its constitution is essentially carbon, hydrogen, sulfur, nitrogen, oxygen and halogens in smaller percentages. (Moraes Junior, 2010).

The analyzes of the coals are carried out in two types: immediate and elementary. In the immediate analysis, the content of the percentage of volatile matter, the percentage of humidity, ash rate and the fixed carbon rate are verified. According to standard NBR 8290 of the Brazilian Association of Technical Standards, ABNT, defines the result of volatile material in coal from combinations of carbon, hydrogen and other gases. Coals can be qualified by the volatile matter content being low volatile, medium volatile; and high volatile. In elemental analysis, it defines the proportions of carbon, hydrogen, nitrogen, sulfur, ash and oxygen assessment. The total percentage of carbon is the sum of the carbons in the coal. At a given time during combustion, volatile materials can be gasified and be releasing or absorbing energy from coal. The ash from this process influences the heat generation system, with an ideal point occurring between the ash chemistry and the thermal system (Moraes Junior, 2010).

Among the process variables directly affected by volatile matter content are flame size and combustion stability. An increase in calorific value can be expected due to the higher volatile content of up to 20%. Above these values, there is a decrease (Moraes Junior, 2010).

The Greek philosopher Theophrastus (371 BC) is the first known reference in the manufacture of coke. (Araújo, 1997). At the same time, this process is carried out through a mix of metallurgical mineral coals in ovens at an average temperature of 10,000 C located in the Coke Plant.

This fuel is part of the Blast Furnace load with iron ore, sinter and pellets, having in its composition volatile matter from coal. The presence of volatile matter is essential and influences the control of coking in the pressure regulation of coke batteries. (Ulhoa, 2003).

Its use consists of being part of the reduction and permeabilizer in the Blast Furnace load and also a carbon supplier for liquid pig iron (Gallo, 2004).

Coke Manufacturing Process

Coke is manufactured in coke batteries, where ovens are constructed of refractory materials. Coking technologies are defined as conventional coking, Non-Recovery coking and Heat-Recovery coking.

- **Conventional coking**

It is the type of manufacture widely used by Coke plants worldwide. In this type of manufacturing, some chemical products and coke oven gas are also produced. This gas is used to heat the furnace itself and other furnaces in the steel mill (Gallo, 2004).

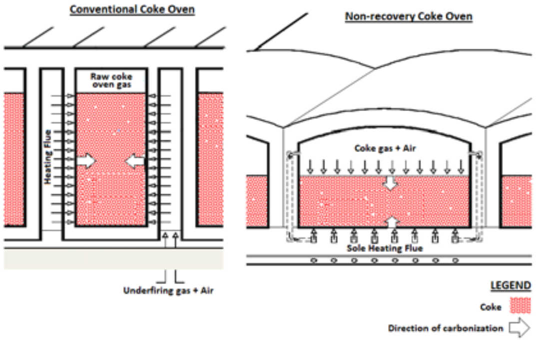

Figure 1 - Conventional coke oven and Non-recovery Coke oven (Takano, 2013)

Figure 1 shows a conventional battery of ovens, the heating of the coal in the oven is indirect, that is, the heat is produced in the heating pipes that are inside the walls of the ovens. Coking of the combination of coals heated to 1100°C, in a refractory compartment with no air with an upper opening, through which the volatiles are drained, which are collected, for their added value. This capture causes the release of gases and the appearance of a residue composed of carbon called coke (Takano, 2013; Hardarshan, 2019).

- **Non-recovery coking**

Figure 1 also illustrates the non-recovery coke oven. Coke production takes place in vertical ovens called “Beehive”, whose chemical products produced in the process undergo direct combustion in the equipment. Therefore, there is no need for external heat and its gases are not used to feed boilers, for energy use.

In Non-recovery ovens, the material is crushed in a hammer mill. This material is then conveyed by trolleys on top of the kilns. The coal undergoes carbonization and is distilled between 1200 °C to 1500 °C. In coking, volatiles are present in the air emission, as shown in Figure 2 (Gautam, 2011).

Figure 2 - Non Recovery Oven (Gautam, 2011)

- **Heat-recovery coking**

Using Beehive technology, ovens called Jewell-Thompson were created, where in the manufacture of coke the volatiles are partially burned in chambers located at the bottom of the oven and the supply of metallurgical coal is carried out in the middle part of the equipment. The technology of ovens has this name because the thermal energy of the burned volatiles is used for the production of electric energy (Ulhôa, 2009; Ulhôa, 2011).

Figure 3 - Heat Recovery Oven (Tiwari, 2012)

Figure 3 shows the carbonization of coal. It starts at about 1100ºC. The energy for carbonization is produced by the ignition of volatiles released from the coal, using air through channels. The gas formed is transported through tubular passages in the wall to the bottom of the oven. Other channels supply the necessary amount of air to complete the coke making (Kim, 2014).

The amount of air supplied to it is controlled using a fan or natural suction. In the middle and inner part of the furnace, energy is transferred to the coal mass, mainly by radiation through the refractory walls and by convective hot gases, which are products of partial combustion of volatiles. The energy produced in the lower part of the furnace is transferred by conduction to the coal mixture. This process requires around 48 to 72 hours until the material is decomposed into coke. The final combustion gases are CH_4, CO_2, CO, O_2, H_2O and N2 The internal combustion of hydrocarbons in the furnace reduces emissions due to the negative pressure in the process (Kim, 2014).

Combustion Principle

The science of combustion has become increasingly important due to the voracity for energy, combined with the need for the rational use of energy resources.

Combustion is characterized by exothermic chemical reactions of elements contained in a fuel that react with oxygen, reducing these elements and releasing energy. The oxygen required for this reduction comes from atmospheric air, which has an average of 21% O2 and 79% N_2 by volume, with oxygen being the real element that wakes up with the fuels for the heat to be produced (Francisco, 2012).

There are combustion processes as complete and incomplete. The complete one occurs when all the carbon in the fuel is carbonized to form carbon dioxide, the hydrogen is burned to form water, the sulfur is oxidized to form sulfur dioxide and all other fuel elements are fully oxidized, with the energy released in each reaction called enthalpy. Sulfur does not add anything to the release of heat, but it is a polluting and corrosive source. Incomplete combustion happens when carbon monoxide, unburned carbon, hydrogen and other hydrocarbon like gases are present in the products. This situation occurs due to incomplete mixing, insufficient time for complete combustion, the percentage of air lower than the theoretical amount and other manufacturing factors (Francisco, 2012).

The enthalpy change (ΔH) between the products and reactants of the reaction is determined by the temperature at which the reaction proceeds. If the enthalpy change is negative ($\Delta H < 0$), that is, if heat is generated, the reaction is called “exothermic”. If it is positive ($\Delta H > 0$) it is said to be “endothermic”, it is equivalent to the heat concentrated in the system (Moraes Junior, 2010).

The energy data of the combustion principles consider the energy linked to the fuel flows and air rate, chemical reaction of the combustion, heat transfer to the working fluid and the lost energies constituted by the process gases, ash, partial combustion, purges and heat rate across process equipment boundaries (Francisco, 2012).

The combustion methodology, the level of mixture between fuel and air is a relevant control parameter. However, in reality the amount of air in this process can exceed the ideal or stoichiometric amount of air. Excess air lowers the temperature of the adiabatic flame, postponing ideal combustion, and significant heat losses due to enthalpy of process gases still occur (Francisco, 2012).

Reactants turn into products and these are how reductants turn into fuels in combustion reactions. The mass of the products as well as the reactants is conserved. What differs in this chemical equilibrium are the numbers of moles of each chemical compound in the reactants and products. The temperature and equilibrium of the products are the most important items for the combustion process evaluation. In this system, energy is estimated as heat transferred to the working fluid and its energy loss is the gases, ash, and heat being expelled from the system. All the heat attracted in the reaction is added to raise the temperature of the reaction product, whose temperature is said to be the adiabatic flame temperature (Moraes Junior, 2010).

When there is no interaction of work or transformation in the potential and kinetic energies during this process, the flow of chemical energy is directed to the surroundings of the system in heat or is used in the process to raise the temperature of the combustion products (Francisco, 2012).

Combustion control is essential because it ensures an effective mixture of oxidizer and fuel, at the correct time and at the ideal temperature to ensure complete combustion, thus releasing all the energy contained in the fuel (Moraes Junior, 2010).

In practice, the natural way of fully applying fuel energy is almost impossible. High temperature to start and maintain the burning of the fuel to reach the equilibrium composition of the products, with the proper mixture of air with the fuel and enough time for the combustion to occur are some basic conditions for the combustion to occur efficiently (Moraes Junior, 2010)

Heat Transfer Mechanisms

These mechanisms make it possible to know the conduct of the heat rate, as well as the variation and control of temperature in a thermal system that takes place in the chamber where the coke is made. These energies transfer mechanisms that occur in this type of systems are Conduction, Convection and Radiation.

Conduction is the transport of energy in a medium as a result of a change in temperature. In the atomic view, it can be defined as the transfer of energy from more energetic particles to less energetic ones (Incropera, 2014). In solid materials, energy is transferred by lattice vibration and free electrons. This heat transfer mechanism is driven by Fourier's Law. Convection is the transfer of energy between a surface and a fluid moving over that surface and this transfer is accomplished by the global motion of the fluid and the random molecular motion of the fluid. There are flows of natural convection and forced convection. In natural convection, fluid circulation is given by density differences associated with temperature changes produced by heating or cooling. In forced convection the fluid motion is driven by some external event (Sayma, 2009).

Heat transfers by conduction and convection require the existence of a temperature variation in a material medium, unlike radiation that does not need a physical medium to propagate. Thermal radiation is the energy emitted by matter that is at a temperature above 0 K in electromagnetic waves or photons. This energy can be attributed to changes in the electronic configurations of the atoms or molecules that make up matter (Incropera, 2014).

In the coal coking process, heat transfer occurs between the produced gas and the internal surfaces of the furnace, at the end of the process this gas contains a higher concentration of hydrogen and an average calorific value of 10 KJ. The rate at which the energy transferred per unit area is known as the surface emissive power (E), which is determined by the Stefan-Boltzmann law, representing the flux of radiation emitted by a blackbody, as per the equation $E = \sigma T4$, where σ is the Boltzmann constant and Ts is the absolute surface temperature. The emissivity (ε) is a property of the radiant surface that expresses how efficient the thermal radiation is, which has an average value of $0 < \mathcal{E} < 1$ (Kern, 2010).

The thermal indicators of the Heat Recovery type oven are determined by operating parameters, ideal battery temperature, and controlled combustion of coal volatility. In order for the heat transfer mechanisms in the furnace to occur uniformly and efficiently inside the furnace, one of the most important variables is the thermal conductivity of the refractory walls due to the accumulation of thermal energy of the gases in the circulation inside the furnace (Tiwari, 2017).

Energy estimate in coke manufacturing

The existence of energy information is the fundamental basis for consistent energy policy decisions, both for the identification of current structures, and the historical past that built them, and for the formulation of indicators (EPE 2005).

The primary sources of energy are products from nature, such as oil, coal, hydraulic energy, plant and animal waste, solar energy, wind energy, etc. (EPE 2005).

The inputs in which primary energy bases are summarized in secondary bases in transformation centers such as oil refineries, natural gas plants, gasification plants, coke ovens, among others. Energy products resulting from primary energy, such as coke oven gas, are specified as secondary energy. (EPE 2005).

Initially, the constitution of an energy assessment is the standardization of energy sources and flows, their properties, unit conversions and possibly the energy aspect. Usually the units used are mass, volume, energy or another relevant parameter.

The form of elaboration of this procedure is published by the Energy Research Company of Brazil (EPE, *Empresa Brasileira de Pesquisa Energética*) annually. Its context follows the form used based on international balance sheets by international bodies. This form of processing the National Energy Balance began in 2002 by the lower calorific value of materials (PCI) as a way to efficiently elaborate the origin of energy data, as dictated by the First Law of Thermodynamics. (EPE 2005).

Araújo, 2015, comprehensively cited an energy balance model used by the Brazilian Association of Materials and Metals, using the Energy Research Company procedure, making comparisons with other models used internationally.

MATERIAL AND METHODS

Heat recovery oven energy indicators using the EPE method

In combustion, the higher calorific value (HCV) contains the concentrated heat of water condensation in the form of steam. And the lower calorific value (LCV) has the energy of the products of combustion excluding water.

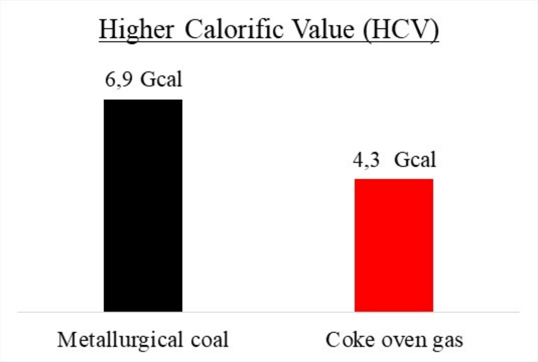

Figure 5 – HCV of coke oven inputs (EPE, 2015; EPE 2021)

Figure 5 shows the graph of calorific values of the basic materials used in the transformation of coke in the Heat Recovery Coke Plant.

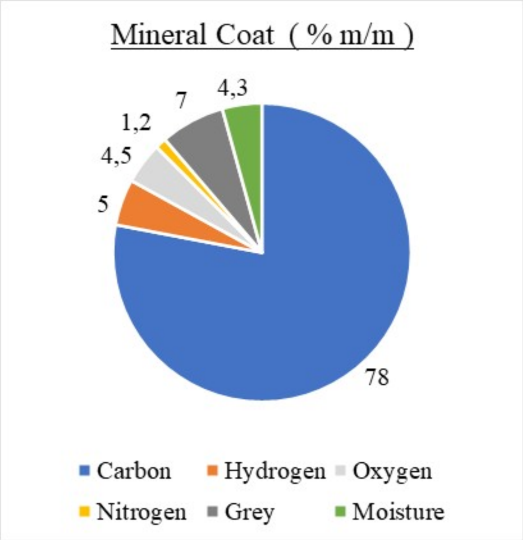

Figure 6. Graph of composition of mineral coal (NPTEL, 2019)

Metallurgical coal is composed of complex organic materials called hydrocarbons, specified in Figure 6. Hydrocarbons are partly the volatile material that with the combustion of coal, is transformed into coke oven gas.

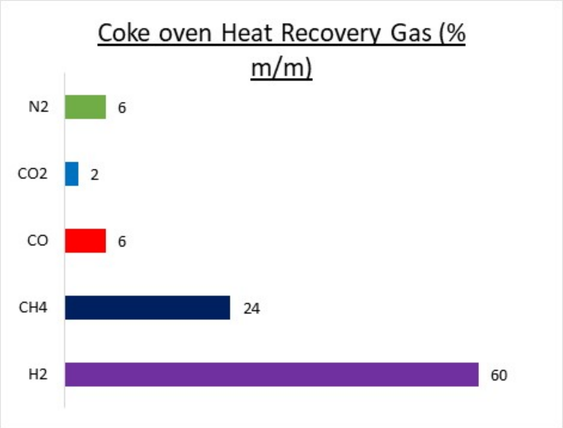

Figure 7. Graph of the gas composition of coal combustion (Seetharaman, 2014)

Figure 7 shows the percentage of gas composition arising from the combustion of coal in a Coke Oven Heat Recovery (Seetharaman, 2014).

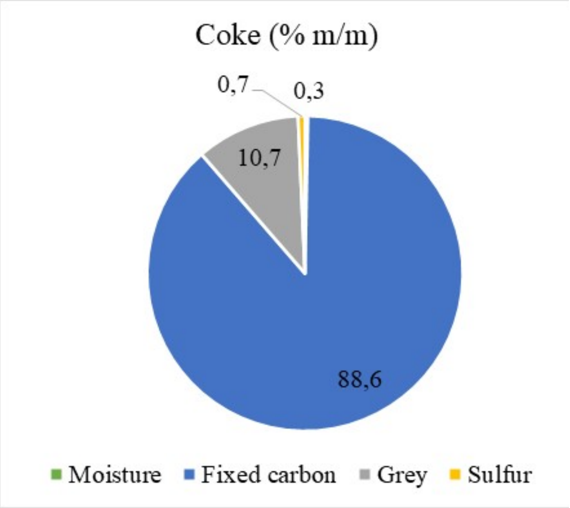

Figure 8. Graph of composition of coke (Coelho, 2003)

For the acquisition of coke with properties for the blast furnace, the characteristics presented must have high levels of carbon and low levels of ash, sulfur and humidity and standardized values of CO_2 and H_2O reactivity. Figure 8 exhibits the composition of a good quality coke in a steel mill (Coelho, 2003).

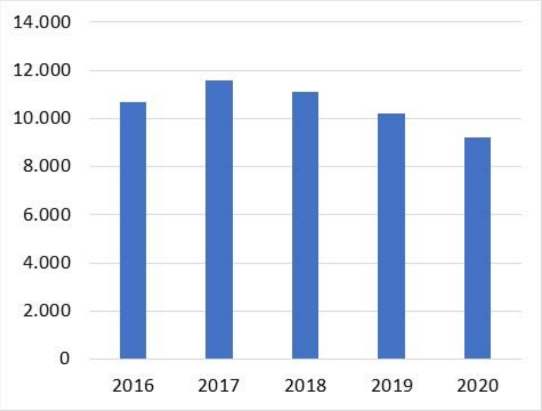

Figure 9. Chart of coal processed in coke plants in Brazil, in millions of tons. (EPE 2021)

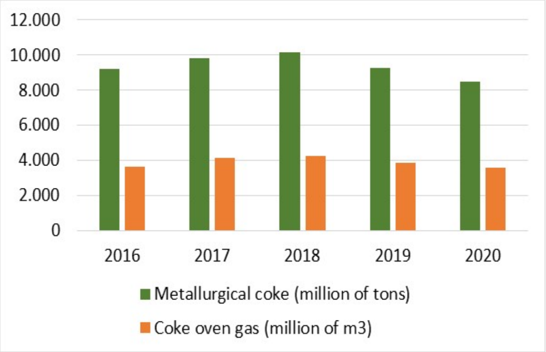

Figure 10. Graph of Brazilian production in coke ovens. (EPE, 2021)

Figures 9 and 10 present graphs with information on the processing of metallurgical coal and the production of coke and coke oven gas in the Steel Plants according to the Final Report of the National Energy Balance - 2021, base year 2020 of the EPE. The year 2020 was marked by the Covid'19 Pandemic that caused major conflicts in the world economy, affecting relevant sectors of the commercial, public and energy economy, this behavior is also observed in the production of coke in the plants.

RESULTADOS E DISCUSSÃO

Energy assessment of a heat recovery oven

According to information from the EPE's National Energy Balance, the assessment of the specific consumption of inputs and products and energy inputs and outputs was carried out through the PCI (Lower Calorific Value) in a Heat Recovery oven. In the study, 1 ton of coke was taken as a basis for calculation, according to the methodology of the Brazilian Association of Metals and Materials (ABM) [EPE, 2017; EPE 2021]

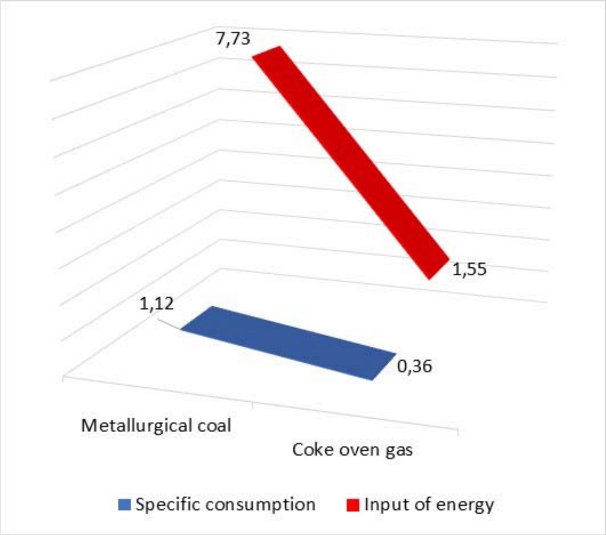

Figure 11. Evaluation of the specific consumption (KN/m3) and the input of energy (Gcal) from metallurgical coal and coke oven gas.

Figure 11 shows that there is agreement between the specific consumption values and the energy input values for both inputs of the Coke oven. A similar result is shown with the products on the output of the coke ovens (Figure 12).

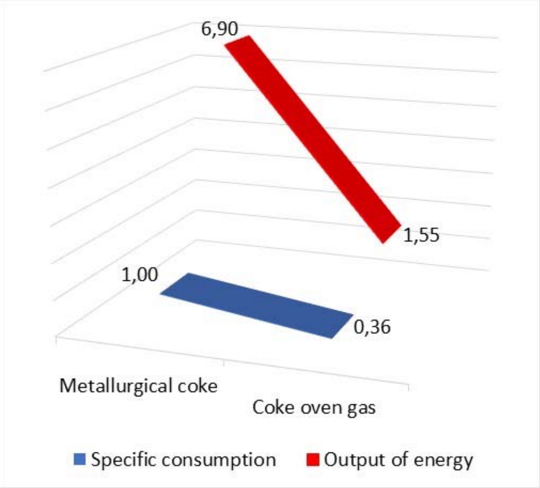

Figure 12. Evaluation of the specific consumption (KN/m3) and the output of energy (Gcal) of products in coke ovens.

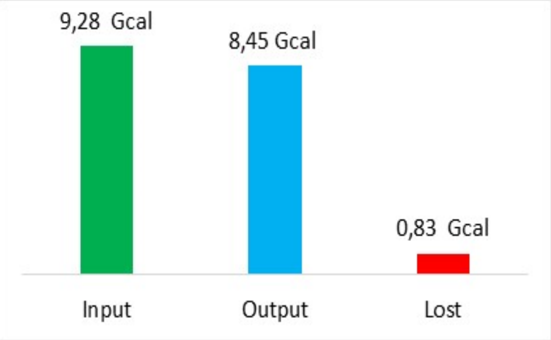

Figure 13. Estimate of energy losses of coke oven based on 1 ton of coke.

Figure 13 shows the energy difference that exists between the inlet and outlet in the coke production furnace in a Heat Recovery coke oven. It is observed that although there is the energetic use of the combustion gases, there are still energy losses in the process.

Study referred to by Lima et.al. 2019, evaluated the influence of different operational parameters on energy efficiency in this type of furnaces, such as fuel moisture, hydrogen combustion, air humidity, the percentage of hydrogen in the fuel and unburned carbon in the ash, among others. The authors have shown that these losses are significantly related to the percentage of oxygen in the coke oven gas.

CONCLUSIONS

The present article intends to show an energetic analysis of the coke production process, with emphasis on the Heat Recovery Coke Plants. The energy efficiency of this type of process was observed in the study by revealing reduced energy losses, mainly influenced by the percentage of oxygen in the COG.

The data and estimates shown encourage companies to plan new investments in the steel manufacturing industry with a focus on energy use, which in the long term brings economic and environmental benefits.

In the future, further studies are suggested regarding the statements of Thermodynamics such as Exergy and Statistical Thermodynamics.

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