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Exergoeconomic analysis in a food industry boiler: a case study

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Abstract

This study aims to apply the SPECO method in a firetube steam generating unit located in a food industry to measure the cost and to suggest actions that will increase its efficiency. In the current global scenario, re-searches for alternatives of the cost reduction and increased sustainability are more and more on the agenda in companies. Therefore, the present work develops a study to make possible the energy losses minimization *in biomass boilers located in Saudali food industry, Ponte Nova (Minas Gerais, Brazil). The used methodology was developed from the exergoeconomic analysis using the Specific Exergy Costing (SPECO) method. To possibilitate this procedure it was necessary to map all the exergetic flows and to find its thermodynamic values. Regarding the fuel calorific potential, it was necessary the measurement of its average humidity, measured in (25 ± 1%), approximately, in order to obtain a Lower Calorific Power of 15960 kJ.kg-1. The massic and exergy flow rates values were defined using measurement equipments, thermodynamic tables and company's information. The obtained results for exergetic efficiency, steam cost and fuel cost were, respectively, 51.74%, 0.0446 R$.(kWh)-1 and 0.01490 R$.(kWh)-1. These results evidenced a cost ratio between product and fuel of 1.99, which represents a product cost two times superior to the fuel cost, approximately. It is concluded that SPECO method application in Saudali industry evidenced important and often disregarded points, as the moisture interference in biomass available exergy and great variance between steam and fuel costs.*

Keywords: Thermal System, Exergy, Exergoeconomic, SPECO.

1. Introduction

Boilers appeared in the 18th century aiming to solve problems created by heat generation with coal burning in the factories (Bazzo, 1995). Therefore, the useful energy could be created for a central unit and be distributed to the entire installation through steam pipes.

Boilers are thermal machines created to capture the energy liberated by the fuel in a furnace and to distribute it through all industry's locations where there was a demand for this thermal energy. Over time, these steam generators elements became indispensable in the country's industrial activity. Therefore, it developed different types of boilers, for example the Firetube and Acuotubular boilers with distinct characteristics and applications.

The boiler's fundamental aspect is the First and Second Law efficiency analysis. Through the First Law, it is pointed to the percentage of energy liberated from fuel that is transformed in steam, characterizing the boiler's energetic efficiency. The Second Law emphasizes the maximum performance and the factors that prevent from obtaining it, it evaluates the boiler performance based on an exergetic efficiency concept (Moran et al., 2013; Çengel and boles, 2007; Yourong and Shuangying, 2000).

Kotas (1985) defines the exergy of a substance constant flow as being equal to the maximum quantity of work that can be obtained when the flow variates from its initial to its dead state through processes which flow can only interact with the environment. Therefore, the exergy of a substance flow is a two states property, flow and environment stage.

Cavalcanti (2016) adds the equilibrium of environment final and output state must be mechanical (pressure), thermical (temperature), chemical (chemical concentration), kinetic (null velocity in system or minimum velocity in flow, to secure the flow), minimum potential energy (minimum height) and other.

According to Dincer and Çengel (2001), with the exergy use it is possible to surpass the First Law of Thermodynamics limitations which is based on energy conservation. This statement is supported by the fact the exergy is based on the First and Second Law of Thermodynamics and therefore, it supplies the energy losses localization and the real condition where the energy is transferred to the process.

In this context, the searches for more efficient processes that consequently consume less fuel and engender savings for industries are always present in the academic and professional sphere. Thereby, the exergoeconomic analysis becomes necessary to clearly provide the financial cost associated with the exergy flow.

Lazzaretto and Tsatsaronis (2006) report the exergoeconomic accounting methods use business administration concepts. They emphasize the cost balances are explicitly formulated and the used sources in the production process are computed in the cost which they were bought or generated. This information is used in the formulation of an auxiliary cost equation.

For a satisfactory system analysis is necessary to obtain and to interpret the exergoeconomic indicators that will define the process viability. Bejan et al. (1996) presented the goals of this analysis to support the engineers when making decisions regarding thermal systems, to allow the components betterment, to improve specific variables and to understand how the system costs and flows work. Hence, the referred researcher defines thermoeconomy as the engineering branch combining the exergetic analysis with economic principles, aiming to provide the system designer or operator the information not available at conventional thermodynamic and economic analysis, but crucial for a system economic project and operation.

The exergetics and economics analysis integration have an important role in the project's idealization to optimize processes. Hereby, these techniques can be largely used in boilers or in other components, aiming a greater efficiency and, consequently, cost analysis that provides a process quality to supply the main areas of interest of the industrial sector.

In this context, the two strands working with the same purpose, although they have their bases substantiated in different areas of knowledge. This work aims to elaborate an exergoeconomic analysis for a firetube boiler in a food industry to identify costs and possible improvement in energy generation process through SPECO (Specific Exergy Costing) method.

2. Materials and Methods

2.1 Case study

The exergy and exergoeconomic method were applied in a firetube boiler model CAF-CF-8000, as represent in Figure 1, of a dairy company located in Ponte Nova (Minas Gerais, Brazil), city near to Viçosa (Minas Gerais, Brazil). Ponte Nova is 402 meters above sea level, at coordinates 20º 24' 46 S and 42º 33' 50" W. The annual average temperature variates between 24º and 33 ºC. The relative humidity is between 60 and 70%.

Figure 1 - Firetube boiler model CAF-CF-8000.

The boiler, according to the Saudali company's necessities, is a machine manufactured by CTA Equipamentos e Serviços. The equipment uses biomass as fuel, preferably wood chip, however it has been powered with eucalyptus logs due its greater viability in the region. The boiler production capacity is 8000 kg of steam hourly.

The used methodology in this work is a combination of economics and thermodynamics coefficients of a thermal component, the exergoeconomic analysis. This analysis is based on the Second Law of Thermodynamic concept. Therefore, to evaluate the boiler performance, it was focused on the maximum available thermodynamic efficiency, exergetic efficiency and the irreversibility minimum, entropy production, combined with the economic performance of the referred equipment. Thus, in economic terms of the equipment, the study focus is the cost analysis of the available energy, exergy, and not the energy.

Boiler operating data were collected with direct contact with the engineers responsible for the company maintenance. Furthermore, a technical visit was carried out in the company for a better comprehension of the machine operation. These data were:

1. Steam mass flow
2. Fuel Lower Calorific Power, LCP.
3. Water supply conditions.
4. Steam outlet condition.
5. Used fuel.
6. Air intake state.
7. Gases outlet conditions.
8. Operation pressure.

In the technical visit, it was noticed water enters at room temperature in the cycle and, after the mixture with purge water, it reaches 80 ºC, in accordance with Figure 2. This fact is due to this boiler storage of condensed water inside the tubing, the purge water, for reutilization. Therefore, this water is mixed in a tank with room temperature water and it increases the process efficiency.

Figure 2 - Boiler water supply tank.

Air enters at room temperature and passes by exhaust gas heat reuse, aiming to reuse the exhaust gas heat energy through a set of heat exchangers tubes, extracting a heat portion that would be released in the environment, reaching a temperature of 120 ºC, approximately, as exposed in Table 1.

Table 1 - Parameters supplied by the studied company.

Boiler parameters	Operation pressure (Pa)	Temperature (°C)	Mass flow ($kg.s^{-1}$)	LCP ($MJ.kg^{-1}$)
Operation pressure	784.50	-	-	-
Fuel (firewood)	-	-	0.24	13.30
Air supply	-	120	-	-
Water supply	-	80	-	-
Exhaust gas	-	180	-	-
Steam	784.50	198.32	2.22	-

As this boiler has some automated processes as regulation of engine operation, exhaust hoods, among others processes, its working properties can alternate according to the industry demand. To accomplish the study, it was considered the machine works on permanent regime with the collected data in the specific moment. The company has a data acquisition system where it was supplied the average values of a set of measurements performed in several periods.

Other information obtained during the technical visit was regarding the steam produced at 198.32 ºC, saturated steam, with a mass flow of 2.22 $kg.s^{-1}$ and exhaust gas at 180 ºC, as exposed in Table 1.

For the eucalyptus firewood, the boiler's fuel, it was informed by the boiler operator the feed is about 1 cubic meter per hour of firewood. Being the standard cubic meter of 850 kg in accordance with Alves (2017), approximately, the fuel mass flow is 0.24 $kg.s^{-1}$, as described in Table 1.

The dead state for this system is when the boiler was at room temperature, about 300 K, for all exergy analysis.

The dada necessary to obtain the thermodynamic properties were acquired through water, steam, exhaust gas and air thermodynamic tables. For the LCP fuel, the eucalyptus firewood, it was calculated according to Nogueira (2005). Regarding the exhaust gas, it adopted the hypothesis of ideal gas behavior.

Furthermore, regarding the LCP fuel, it was performed 24 measurements in random points of the wood, the extremes and the center of the eucalyptus wood in the company courtyard, to obtain a moisture of (25 ± 1) %. This value is the average of 24 measurements. For this analysis, it used a moisture meter model MD812. The equipment precision is ± 1%, according to the manufacturer. This electric current meter is composed of two tips that are injected in wood. When the equipment is switched on, an electric current goes through a tip to another and, the form this current electric behaves is interpreted by the device. Therefore, the equipment is going to supply the present moisture percentage of the wood. According to Nogueira (2005), the LCP for this moisture, (25 ± 1) %, is equal to an LCP of 13.3 $MJ.kg^{-1}$, as exposed in Table 1.

2.2 Exergetic and Exergoeconomic Analysis

Exergy is a property that allows to determine the useful work potential of a determined energy quantity in a specific state. In this situation, when having access to an energy source, it is not sufficient to verify if there is a lot of available energy in the system, but it is necessary to verify if the available energy will really perform the work (Çengel and Boles, 2007). Exergy is always evaluated as a standard or reference state, the dead state (Caliskan *et al.*, 2011).

Through the company information, it was possible to calculate the exergetic rate flow, the destroyed exergy and the boiler exergetic efficiency during the process.

The exergetic rate flow, $\dot{E}$, in the boiler input and output was calculated with the supplied information of Table 1, in accordance with Cavalcanti (2016), Szargut *et al.* (1988) and Kotas (1985), dividing in different components as followed:

$$\dot{E} = \dot{E}_c + \dot{E}_p + \dot{E}_f + \dot{E}_{ch} \quad (1)$$

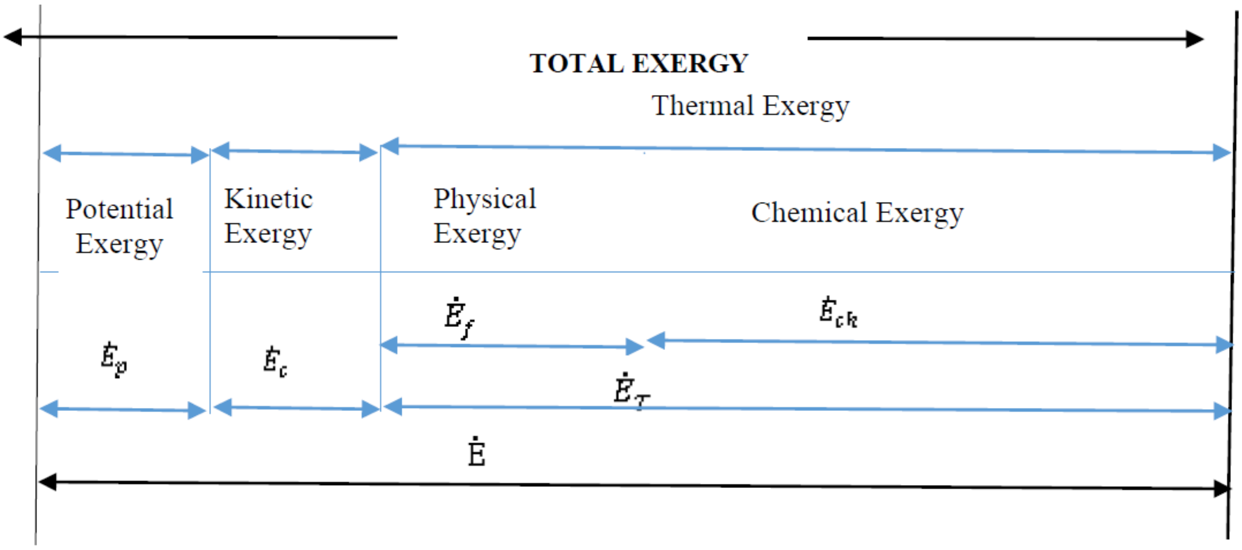
Where $\dot{E}_c$ is kinetic exergy, $\dot{E}_p$ is potential exergy, $\dot{E}_f$ is physical exergy and $\dot{E}_{ch}$ is chemical exergy. Therefore, the total exergy, $\dot{E}$, is the sum of kinetic, potential, physical or thermomechanical and chemical exergies, as illustrated in Figure 3.

The potential and kinetic exergies were considered minimum when compared to other exergies, being disregarded from the boiler analysis.

Equation 1 can be rewritten in terms of specific exergy, E:

$$E = \dot{E}/\dot{m} \quad (2)$$

Figure 3 - Representation of the exergy portions, adapted from Szargut *et al.* (1988).



2.3 SPECO Method

This method is based on the specific exergy and auxiliary equations and it can be divided in three stages: energy flows identification, product and fuel definition and cost equations (Cavalcanti, 2016).

In the first stage, it must define if the components will be evaluated using the total exergy or separately as thermal, mechanical and chemical exergies. It is recommended to evaluate it separately since the results will be more precise.

In the second stage, the product and fuel exergies are defined considering the aimed result produced by the component and source consumed to reach the result. The product is defined by the authors with all output exergy values and all input and output exergy increase that are in accordance with the purpose of the flow component that receives exergy. However, fuel is defined as all values of input exergy summed to all reduced exergy between input and output and decreased of all exergy increase that is not in accordance with the component purpose.

The third stage associates the thermal system cost with its environment and inefficiencies sources, and as usually, there is a great number of flow then a component number. Auxiliary equations are developed to complete the information (Cavalcanti, 2016).

3. Results and discussion

The water and air dead state was considered at room temperature, 300 K, approximately, only temperature differences than that will be considered in the calculations. The standard reference values for exhaust gases, as Table 2, were considered equal to the air one at ideal gas situation. Moran *et al.* (2013) adopted the same procedure when auxiliating the exergy of exhaust gas in an internal combustion engine. Thermodynamic data for flows are obtained in thermodynamic tables, in accordance to Moran *et al.* (2013). These data are exhibited in Table 2. Through the given data of Table 2, Equation (10) exposed in referential makes possible the attainment of specific exergies, according to Table 3.

Through the calculations of Tables 2 and 3, with support of Equations (4, 6), it was possible to obtain the boiler's exergetic efficiency as well the exergy destroyed in the process, as presented in Table 4. The destroyed exergy characterizes the boiler irreversibility. Table 5 exhibits the exergetic flows rates balance.

Table 2 - Boiler Thermodynamic Parameters.

Flow	Enthalpy ($kJ.\ kg^{-1}$)	Entropy ($kJ.kg^{-1}.K^{-1}$)	Temperature (K)	Mass Flow ($kg.\ s^{-1}$)
Water supply	334.91	1.075	353.15	2.22
Steam	2768.70	6.666	471.32	2.22
Exhaust gas	451.80	**2.116***	453.20	12.00
Air supply	390.98	**1.966***	396	2.00
Air Dead Environment	300.19	1.700	300	-
Water Dead Environment	104.89	0.367	300	-

***This value is due to absolute entropy in the standard reference state (s^o) for exhaust gases.**

Table 3 - Flows specific exergy

Flow	Direction	Specific Exergy ($kJ.\ Kg^{-1}$)
Water	Entrance	19.24
Steam	Exit	878.20
Gases	Exit	27.38
Air	Entrance	12.15

Table 4 - Exergetic efficiency data.

Exergetic Efficiency			
Input Exergy (kW)	Steam output Exergy (kW)	Destroyed Exergy (kW)	Exergetic efficiency (%)
3768.00	1949.60	1813.40	51.74

The calculated exergetic efficiency value, as exposed in Table 4, demonstrated that 51.74% of the potential to produce work through the fuel is really incorporated to the boiler work fluid.

Table 5 - Exergetic rates balance

Flow	Exergy output rate (kW)	%
Steam	1949.60	85.60
Gases	328.56	14.40
Total exergy	2278.16	100.00

In the study elaborated by Ramos *et al.* (2019) in a boiler of 70,000 $kg.h^{-1}$ of superheated steam, also supplied with biomass, the global exergetic efficiency found was 42.47%. For Behbahaninia, Ramezani and Hejrandoost (2017), the exergetic efficiency found was 53.70% in a plant with a total capacity of 1,300 MW, water reaching 545 °C, 165 bar and gaseous fuel supply.

However, the steam generating machine supplied with eucalyptus of Costa *et al.* (2019) reported an exergetic efficiency between 30 and 33%, according to the moisture variations between 55 and 40%. In Pambudi, Lauresia, Wijayanto, Perdana, Fasola, Imran, Saw and Handogo (2017) study, it was developed an exergetic analysis in process of alcohol production using biogas and the calculated evaporator exergetic efficiency was 45.97%. The destroyed exergy has increased, but Saudali Alimentos's boiler have a great efficiency standard. This fact can be explained for the several elements of energies reuse that it has.

To increase the boiler income, the rise of the available exergy in the furnace through woods with bigger LCP, can be performed. This measure can be performed by building a shelter for this material, so it does not stay exposed to climate changes and accumulate moisture. This waste is not considered in the exergetic balance, where the calculations take to account only the exergy flow injected in the boiler and it do not consider measurements to increase this value. It is important to consider the great losses of exhaust gases, even with the reuse the gases are eliminated at 180 ºC, temperature superior to 150 ºC, which is the one the gases are expelled (Costa *et al.*, 2019).

It disregarded the exergies introduced by water and air with temperature below the dead state, because this process might be reported as interns to the studied control volume, the air and water enter at room temperature and they are heated, extracting the energies that would be lost during the cycle. Besides, the exergy rate of two flows would represent only 1.8% of the fuel exergetic flow, a small value that would not interfere in the result.

An interesting study to complement this work is the performed by Cavalcanti *et al.*, (2019), where the authors search to identify where the greatest exergetic losses for the biomass boiler stage. It was concluded that a bigger portion is destroyed by the fuel exergy chemical transference, reaching an exergetic efficiency of 16.89%, due the high eucalyptus impurity, mixture of non-contributing materials for the combustion process.

To develop the exergoeconomic analysis, it was used the SPECO method. The aim of this strategy is to measure the costs and the possibility to take efficient measurements that could correct these questions. The basic costs values involved boiler are presented in Table 6.

Table 6 - Basic costs involved boiler.

Parameter	Value (R$)
Water (m^3)	4.20
Firewood (m^3)	56.00
Energy (kWh)	0.51
Maintenance (Year)	9,000.00

The flow costs related with time (seconds and hourly) were exposed in Table 7, for comparison. Therefore, it is possible to observe which factors contribute more with the operation cost.

Table 7 - Cost per unit of boiler time.

Parameter	Cost (R$. s^{-1})	Cost (R$. h^{-1})
Exhaust gases	0.0014	5.04
Water	0.0092	33.12
Steam	0.0242	87.02
Firewood	0.0156	56.16
Maintenance	0.0003	1.08
Destroyed Exergy	0.0062	22.32
Fuel	0.0142	51.12
Product	0.0150	54.00

Table 8 represents the cost per unit of each flow, this is the value used to perform the exergoeconomic efficiency study. This Table was elaborated with support of Equations (13, 14).

These data are fully coherent and meet the study expectations. Initially, it is noticed that the conclusions of the F principal were fulfilled, the fuel pays the losses bill and, as confirmed in Table, proving these flows have the same unit costs. Another data that presents the study veracity is the steam having unit cost superior to all other flows, which is the product desired by the machine. All expenditure is performed aiming to promote this generation, and therefore, the most expensive parameter must be the steam.

Table 8 - Unit costs of each flow.

Flow	Unit cost R$. $(kWh)^{-1}$
Firewood	0.0149
Water	0.7825
Steam	0.0446
Exhaust gases	0.0149
Destroyed exergy	0.0149

It is also noticed the steam cost, 0.0446 R$. $(kWh)^{-1}$ is superior to the firewood cost, 0.01490 R$. $(kWh)^{-1}$. This evidence shows the steam leads several expenditures besides the fuel, as maintenance, water and other costs. Furthermore, the water cost is low and its unit cost is elevated when compared to other measurements due the unit cost relation with the exergy rate cost, which for water is smaller.

Souza et al. (2019) developed a SPECO method in an acuotubular boiler to produce electricity. The unit cost per fuel time of his studied boiler was 3.11 R$. s^{-1}, value superior to the found in this work, 0.0156 R$. s^{-1}. This fact can be due to: increased cost of this fuel, lower boiler efficiency and, mainly, the higher fuel consumption due the greater machine size. When comparing the fuels unit costs, there are 0.179 R$. $(kWh)^{-1}$ for the boiler where the researcher developed his method, being different from the 0.0149 R$. $(kWh)^{-1}$ found in this study.

4. Conclusion

The presented results pointed, through its analysis and discussion, the followed conclusions about the exergoeconomic methodology: 1) the used methodology is enough to represent the unit cost of fuels, products and equipment; 2) the methodology combines accounting concepts with auxiliary cost equations and thermodynamic laws; 3) the used methodology can be used for other equipment, besides the boiler; 4) the used methodology creates forms so engineers can analyze the machine real situation and, therefore, taking more effective attitudes aiming a more lean and economic operation; 5) some important points and, sometimes disregarded, were exposed, among them there is the energy cost of the machine operation and the spends with water treatment to supply the equipment. These are expenses not commonly cited, although they have great influence in the cost.

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