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EFFICIENCY ANALYSIS OF SUGARCANE BAGASSE BOILERS THROUGH THE FIRST AND SECOND LAW OF THERMODYNAMICS

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Abstract. *This work shows the efficiency analysis of bagasse sugar cane boilers through the first and second law of thermodynamics. The calculation methodology for the first law uses the Efficiency Energy Balance Method (the losses method) due to the great difficulty of making correct measurements of bagasse flow. Furthermore, this methodology offers the possibility of identifying specific points of system improvements. The indirect method is found in the most recent standards established for boilers efficiency calculation: ASME PTC 4-2008 and EN 12952-15:2003. In these standards, it was necessary to make adaptations for bagasse since there are no specific standards for this type of fuel. Additionally, an analysis of the efficiency through the Second Law of Thermodynamics was made. Current Brazilian industrial boilers, which were assessed in performed tests, were used to get the data in order to offer an outlook of the industry.*

Keywords: *Bagasse, Efficiency, Exergy.*

1. INTRODUCTION

Boiler efficiency is currently the most important parameter in cogeneration systems, to perform a good efficiency calculation allows the optimization and identification of faults during system operation. Current bagasse boilers have development technologies based in that used for other solid fuels, as coal, therefore, the methodology to determine their efficiency is adequate was based in reference standards developed for coal boilers (ASME PTC 4-2008) and (BS EN 12952-15: 2003) with the necessary adaptations, once the bagasse has a high moisture content unlike coal.

The performance of a boiler is commonly quantified by three parameters, Efficiency, Capacity and Output, where efficiency is given by the ratio of energy output to input, the capability is described as the maximum mass flow rate of steam produced under certain operational conditions and the output is the energy absorbed by the working fluid, with the exception of that energy recovered by elements within the steam generating system.

“The performance tests allow obtain the efficiency and actual operating parameters of a boiler, and thus, make appropriate adjustments to the working regime” (Beaton & Lora, 1991).

Several authors found in the literature as the case of Beaton and Lora (1991) recommend the use of Lower Heating Value (LHV) as a basis for calculation of efficiency, but others, such as Acosta (1995), calculated it using as basis the Higher Heating Value (HHV) of bagasse. Sosa Arnao (2006a) discusses the use of the two proposals and concludes that due to the high moisture content of bagasse, it is more appropriate an efficiency calculation based on the Higher Heating Value.

A second law analysis or exergetic analysis for bagasse boilers can be found in various works at the literature (Prieto and Nebra, 2004, Sosa-Arnao et al. 2006a; Sosa-Arnao and Nebra 2006b and 2007), but since this analysis uses the method of the inputs and outputs, does not identify the irreversibilities associated with the various processes occurring in the steam generation system. Therefore, works published like Lozano, (1987), Cortez and Gomes, (1998), Kamate and Gangavati, (2010) aim to identify and correct the various irreversibilities of the system.

The second law analysis is one of the most important analyses because it permits a quick characterization of the available mechanical energy in the steam, compared to the energy input.

2. CALCULATION METHODOLOGY

The methodology for calculating bagasse boiler efficiency is based on adaptations of the two main technical standards (ASME PTC 4-2008) and (BS EN 12952-15, 2003), on the specific issue of steam generation from coal. Besides the use of standards, other references were used, which treat specifically of boilers using bagasse as fuel, Beaton and Lora (1991), Sosa Arnao (2007), and Sosa-Arnao and Nebra(2011).

Fig. 1 shows the application of thermodynamic analysis to a bagasse boiler. The first law analysis uses two methods: i) method of the inputs and outputs and ii) energy balance method (losses method), where both can be applied based on the Lower or Higher Heating Value as calculation basis. The second law is applied based on the input and output method, using data obtained from the first law analysis.

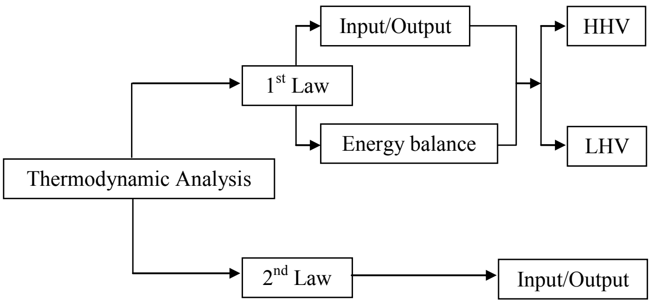

Figure 1: Thermodynamic analysis applied to bagasse boiler.

3. ANALYZED SYSTEM

The measurements were conducted in a boiler constituted by a steam generator, an economizer and an air pre-heater. This work was carried out with data collected from a real performance test, which is part of a cogeneration system that operates in a factory sited in the state of Sao Paulo - Brazil. Due to privacy policies of the companies involved in the efficiency analysis they have requested not to be mentioned in this paper.

For the analysis of the system, the reference system proposed by Szargut et al. (1988) is adopted, that is 25ºC, 1 atm and the standard chemical exergies proposed by these authors.

4. EFFICIENCY FOR THE FIRST LAW OF THERMODYNAMICS

Inputs – outputs method:

The inputs-outputs method for a steam generator is based on the direct measurement of parameters (inputs) of energy entering the boiler, which is the energy contained in the fuel, and the outputs, which is the energy contained in the exit working fluid.
First Law efficiency is given by the Eq. (1):

$$\eta^{I} = \frac{Output}{Input} \times 100 \tag{1}$$

This method requires direct measurement of the output energy in the working fluid and direct measurement of the fuel flow, which, in the case of bagasse boilers is a great difficulty.

Losses Method:
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The energy balance method (losses method) combines the inputs and outputs with the energy balance equation which is given by Eq. (2):

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$$Input = Output + Losses \tag{2}$$

Dividing the above expression for the energy input to the boiler, the Eq. (3) is obtained:

$$\eta^{II} = 1 - \left[\frac{Losses}{Input} \right] \times 100 \tag{3}$$

The calculation of the efficiency by this method requires the identification and calculation of all the losses that occur in the boiler.

For the calculation of the boiler efficiency it is necessary to carry out various laboratory tests, and some primary measurements, among which are:

* Fuel ultimate analysis (Carbon content, Hydrogen and Nitrogen)
* Proximate analysis of fuel (Fuel moisture, volatile material, fixed carbon and ash)
* Determining the flow temperatures in the inlet and outlet of the boiler (air and flue gases)
* Measurement of the composition of the combustion gases and unburned materials entrained by gases
* Presence of unburned matter in the ashes

4.1 1st law efficiency based on Lower Heating Value (LHV)

In the analysis based on the Lower Heating Value (LVH), the absorbed energy to evaporate the water due to the moisture content of the bagasse and the water formed by the oxidation of hydrogen contained in the fuel is discounted.

The efficiency by the method of inputs and outputs in Lower Heating Value basis is given by the Eq. (4):

$$\eta_{LHV}{}^{I} = \left| \frac{\dot{m}_s (h_{s,out} - h_{w,in})}{Qd_{LHV}} \right| \times 100$$

(4)

What if combined with the Eq. (5), determines the efficiency of the boiler based on Lower Heating Value:

$$\eta_{LHV}{}^{II} = 100 - (q_g + q_{CO} + q_C + q_T + q_a + q_b) \tag{5}$$

where:

q_g: energy loss with the combustion gases
q_{CO}: energy loss due to the incomplete combustion of CO (chemical causes)
q_C: energy loss due to non-combustion of C (mechanical causes)
q_T: energy loss to the environment through the walls
q_a: energy loss with the hot ashes
q_{bs}: energy loss due to the bleeding of the boiler

The available heat (Qd) based on the Lower Heating Value is calculated using the Eq. (6):

$$Qd_{LHV} = LHV_b + Cp_b (T_b - T_r) \tag{6}$$

The equations used for calculating the different losses q_g, q_{CO}, q_C, q_T, q_a, q_{bs}, are presented below:

i) Energy loss by the flue gases (q_g), it is considered the most important energy loss and depends on the temperature at which the gases leaving the boiler. (Beaton and Lora, 1991). The Eq. (7) is used for the calculation:

$$q_g = \frac{m_g \left(h_{g,out} - h_{g,r} \right)}{Qb_{LHV}} \times \left(100 - q_C \right) \tag{7}$$

Where: m_g: is the ratio between the flue gases flow and the fuel flow; $h_{g,out}$; $h_{g,r}$:are the specific enthalpy of flue gases at boiler outlet and the reference state respectively (kJ/kg); *Qd*: available heat of bagasse – LHV (kJ/kg).

(ii) Energy loss due to incomplete combustion of CO (q_{CO}),. As the combustion of bagasse is made with air excess, the possible presence of elements such as H_2, SO_2 and CH_4 are not taken into account, because their contribution is very small, therefore these losses are assumed equal to zero. It is calculated by Eq. (8):

$$q_{CO} = \frac{-m_{CO}\left(h_{fCO2} - h_{fCO}\right)}{Qb_{LHV}} \times 100 \tag{8}$$

iii) Heat loss by incomplete combustion due to mechanical causes (q_C): it corresponds to unburned fuel particles constituted by pure carbon,that go out mixed with the ashes, or are carried by the exit gases. It is calculated by Eq. (9):

$$q_C = \left(\frac{x_{gr} c_{gr}}{100 - c_{gr}} + \frac{x_{ah} c_{ah}}{100 - c_{ah}} + \frac{x_{wh} c_{wh}}{100 - c_{wh}} \right) \times \frac{HV_{f,ash} m_{ash}}{Qb_{LHV}} \tag{9}$$

Where: x_{gr} ;x_{ah} ;x_{wh}: are fraction of ashes contained in the bagasse that are carried by the gases till the stoker, air heater and scrubber, respectively (%); c_{gr} ;c_{ah}; c_{wh} : carbon contained in the ashes at stoker, air heater and scrubber, respectively (%); m_{ash}: is the ratio between the ashes flow and the fuel flow and $HV_{f,ash}$: Heating Value of fuel (pure carbon) contained in the ashes (28300 kJ/kg – Szargut et al. 1998).

iv) Heat losses due to surface radiation and convection (q_T) were calculated using the Abma Standard Radiation Loss Chart (ASME PTC 4.1, 1964). This chart uses the HHV as calculation basis and need to be converted to LHV calculation basis. The calculation of the losses by radiation and convection using the chart, is a function of the steam mass flow, therefore the steam energy is calculated, and this value is applied to the chart to obtain the value of losses, as a percentage.

v) Heat losses by slag and ash (q_a): are referred to sensible heat lost by slag and ash. According to Beaton and Lora (1991), this fraction is responsible for a very small loss of heat available, depending on boiler operation this loss can be neglected. but in our case this loss will not be neglected because its value is not so small. The calculation of losses (qa) is given by the Eq. (10).

$$q_a = \left[\frac{x_{gr} Cp_{ash}\left(T_{ash,gr} - T_r\right) + x_{ah} Cp_{ash}(T_{ash,ah} - T_r) + x_{wh} Cp_{ash}(T_{ash,wh} - T_r)}{Qb_{LHV}} \right] \times 100 \tag{10}$$

vi) Heat losses due to bleeding in the boiler (qb) can be considered as 2% of the steam mass flow, according to Acosta (1995), but for real performance tests they were assumed as 3% of the steam mass flow. The heat losses by bleedings in the boiler are given by the Eq. (11):

$$q_b = \frac{m_{bs} \cdot \left(h_{s,bleeding} - h_{w,in}\right)}{m_b \cdot Qb_{LHV}} \times 100 \tag{11}$$

Where: m_{bs}, m_b: are the bleeding flow and the fuel flow; $h_{s,bleeding}$; $h_{w,r}$: *are* the specific enthalpy of the bleeding steam and and reference state respectively (kJ/kg); *Qd*: available heat of bagasse – LHV (kJ/kg).

4.2 1st law efficiency based on Higher Heating Value (HHV)

This analysis uses the HHV as the calculation basis, and considers the same energy losses that were calculated on the LHV basis in terms of q_{CO}^*, q_C^*, q_T^*, q_a^*, q_b^*, only with different calculation basis.

However, there is a difference in the analysis of the energy loss with the flue gases of the boiler, q2 losses, which was considered on the LHV basis and represents the largest energy losses, it is calculated again but now is subdivided into three major losses:

- Energy losses due to dry gases.
- Energy losses due to the evaporation of water formed from the hydrogen contained in the fuel.

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- Energy losses due to evaporation of moisture from the bagasse.

Eq. (12), determines the efficiency of the boiler based on the higher calorific value:

$$\eta_{HHV}{}^{I} = \left[\frac{\dot{m}_s (h_{s,out} - h_{w,in})}{Qd_{HHV}} \right] \times 100$$

(12)

What if combined with the Eq. (13), determines the efficiency of the boiler based on Higher Heating Value:

$$\eta_{HHV}{}^{II} = 100 - (q_{gs} + q^{*}_{CO} + q^{*}_{C} + q^{*}_{T} + q^{*}_{a} + q^{*}_{b} + q_{hb} + q_{mb}) \tag{13}$$

where:

q_{dg}: energy losses due to dry gases.
q_{CO*}: energy losses by the non-combustion due to CO (chemical causes)
q_{C}^{*}: energy losses due to non-combustion of C calculated on HHV basis (mechanical causes)
q_{T*}: energy losses to the environment through the walls by a temperature difference
q_{a*}: energy losses with the ashes
q_{bs*}: energy losses due to the bleeding of the boiler
q_{hb}: energy losses due to the evaporation of water formed from the hydrogen contained in the fuel.
q_{mb}: energy losses due to evaporation of moisture from the bagasse.

The available heat (Qd) based on the Higher Heating Value is calculated using the Eq. (14):

$$Qd_{HHV} = HHV_b + Cp_b (T_b - T_r) \tag{14}$$

The equations used for calculating the different losses q_{dg}, q_{hf}, q_{mf}, are presented below:

(i) Heat losses due to dry gases (q_{dg}), represents the energy of the dry flue gases due to the sensible heat carried by these when leaving the boiler and can be calculated by Eq. (15).

$$q_{dg} = \frac{m_{dg} \left(h_{dg,out} - h_{dg,r} \right)}{Qb_{HHV}} \times \left(100 - q^{*}_{C} \right) \tag{15}$$

where: m_{dg} : is the ratio between the dry flue gases flow and the fuel flow; $h_{dg,out}$;$h_{dg,r}$: are the specific enthalpy of dry flue gases at boiler outlet and reference state respectively (kJ/kg) ; *Qd:* available heat of bagasse – HHV (kJ/kg).

(ii) Heat loss due to evaporation of water formed from hydrogen in fuel (q_{hb}): it corresponds to the energy loss due to the evaporation of water formed in the combustion of hydrogen contained in the fuel, which leaves the boiler with the flue gases. The Eq. (16) is used for the calculation:

$$q_{hb} = \frac{m_{hb} \left(h_{hb,out} - h_{hb,r} \right)}{Qb_{HHV}} \times 100 \tag{16}$$

Where: m_{hb}: is the ratio between the water vapor mass flow formed from hydrogen contained in the fuel and the fuel flow; $h_{hb,out}$;$h_{hb,r}$: are the specific enthalpy of the water vapor formed from hydrogen contained in the fuel at boiler outlet and reference state respectively (kJ/kg); *Qd:* available heat of bagasse – HHV (kJ/kg).

(iii) Heat loss due to water evaporation bagasse moisture content (q_{mb}): this corresponds to the most significant heat loss due to the high moisture content of the bagasse (about 50%). This loss can be reduced when bagasse dryer is used in the boiler (Sosa-Arnao and Nebra, 2009). The Eq. (17) is used for the calculation:

$$q_{mb} = \frac{m_{mb}\left(h_{mb,out} - h_{mb,r}\right)}{Qb_{HHV}} \times 100 \tag{17}$$

Where: m_{mb}: is the ratio between the water vapor mass flow formed from moisture contained in the fuel and the fuel flow; $h_{mb,out}$;$h_{mb,r}$: are the specific enthalpy of the water vapor formed from moisture contained in the fuel at boiler outlet and reference state respectively (kJ/kg); *Qd:* available heat of bagasse – HHV (kJ/kg).

5. EFFICIENCY FOR THE SECOND LAW OF THERMODYNAMICS

Although the application of the Second Law of analysis is very important, in bagasse boilers is unusual. This analysis can be done through two methods: input / output and exergy balance. The first is commonly used in the analysis of the boiler, and can be applied because important information is obtained from the analysis of the first law, such as the bagasse flow, necessary for this analysis.

5.1 Input / Output Method

In this paper, the second law analysis was performed by the Input / Output method. The boiler efficiency is determined by the Eq. (18):

$$\xi = \left[\frac{\dot{m}_s (b_s - b_w)}{\dot{m}_b \, b_b}\right] \times 100 \tag{18}$$

Where: m_s , m_b : mass flow of steam and bagasse, respectively (kg/s); b_s, b_w, b_b: specific exergy of steam, water and bagasse, respectively (kJ/kg).

5.1.1 Exergy of Sugar Cane Bagasse:

There are two methods to determine the exergy of bagasse: The first is proposed by Szargut et al. (1988) for the calculation of exergy of wood and the second by Wittwer, (1991). Although the exergy of bagasse is an adaptation of exergy calculation for wood, the Szargut et al. methodology is as adequate as Wittwer's (1991) methodology which was specifically developed for bagasse, according Sosa-Arnao and Nebra (2005). Therefore, Szargut, et al. (1998) methodology was adopted. Bagasse exergy calculation is determined by the following equations:

$$\beta = \frac{1{,}042 + 0{,}2160\frac{x_{H2}}{x_C} - 0{,}2499\frac{x_{O2}}{x_C}\left(1 + 0{,}7884\frac{x_{H2}}{x_C}\right) + 0{,}0450\frac{x_{N2}}{x_C}}{1 - 0{,}3035\frac{x_{O2}}{x_C}} \tag{19}$$

Where: x_{H2}, x_C, x_{O2}, x_{N2}, are mass fractions of hydrogen, carbon, oxygen, nitrogen, respectively.

$$b_b = \beta\left(LHV + \lambda x_w\right) + 9683 x_s + b_{ash} x_{ash} + b_w x_w \tag{20}$$

Where b_b: specific chemical exergy of cane bagasse (kJ/kg); λ : water vaporization heat (kJ/kg); x_w, x_s, x_{ash}: Mass fraction of water, sulfur and ash in fuel; b_{ash}, b_w, : specific chemical exergy of ash and water respectively (kJ/kg).

5.1.2 Chemical Composition of Dried Bagasse:

The average values reported by the plant were used, where: 47.30% carbon, 6.26% hydrogen, 0.30% nitrogen, 39.75% oxygen, 0.09% sulfur and ash 6.30 %.

Due to the low fractions of nitrogen and sulfur obtained in the bagasse analysis, the losses due to these components were not taken into account.

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6. RESULTS

The different parameters, such as, mass flow, pressure, temperature, of system currents are presented in the Table 1. for the system operational conditions.

The values shown correspond to the input and output of the control volume, where the different processes that take place within the volume were considered.

Table 1. Real operating parameters of the bagasse boiler, measured by the staff.

Description	**UNITS**	**VALUE**
Steam flow	kg/s	55,79
Steam output temperature	ºC	507,09
Steam output pressure	kPa	6572
Water inlet pressure	kPa	8574
Water inlet temperature	ºC	116,14
Steam drum pressure	kPa	7032
Environment air temperature	ºC	38
Radiator air temperature	ºC	85,80
Outlet temperature of the flue gases	ºC	189,48
Air excess	%	38,44
CO (in the flue gases)	ppm	2716,35
Fixed carbon in the ashes at the stoker	%	0,103
Fixed carbon in the ashes at the bottom of the drum	%	0,265
Fixed carbon in the ashes at the scrubber	%	0,439
Ashes temperature in the stoker	ºC	181,44
Ashes temperature in the scrubber	ºC	84,07
Ashes temperature in the bottom of the drum	ºC	69,75
Bagasse Lower Heating Value (LHV)	kJ/kg	6800
Bagasse Higher Heating Value (HHV)	kJ/kg	8700
Bagasse moisture	%	54

Fig. 3 and 4 shows the Sankey's diagram for the real bagasse boiler efficiency, analyzed by the first law of thermodynamics based on the lower heating value (LHV) and higher heating value (HHV) respectively.

The analysis based on the lower calorific value is shown in Figure 2 where are presented the different losses, and that it can be seen, for this case, the loss due to flue gases is the most important. The first law boiler efficiency based on LHV is the highest of the calculated efficiencies, since in this analysis does not take into account the energy used to evaporate the water formed by the hydrogen contained in the fuel, and the energy used to evaporate the water presents as moisture in the fuel.

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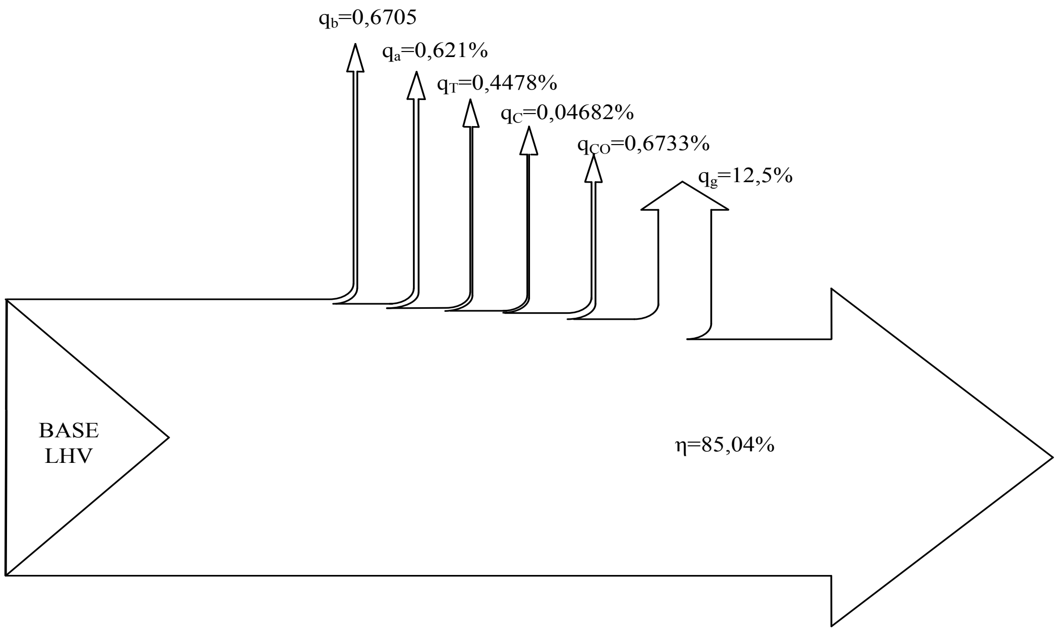

Figure 2. Sankey's diagram for the bagasse boiler efficiency (LHV as calculation base).

The analysis based on the higher heating value (HHV) shown in Figure 3 shows a big difference in the calculation of boiler efficiency because this analysis takes into account the energy used to evaporate the water formed by the hydrogen contained in the bagasse and the energy used to evaporate the moisture contained in the bagasse. In this analysis the loss due to the energy carried by the combustion gases is subdivided into three major losses:

q_{dg} -Energy losses due to dry gases.
q_{hb} -Energy losses due to the evaporation of water formed from the hydrogen contained in the fuel.
q_{mb} -Energy losses due to evaporation of moisture from the bagasse.

which represent the largest energy loss in the boiler, as shown.

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q_C=0,04682%

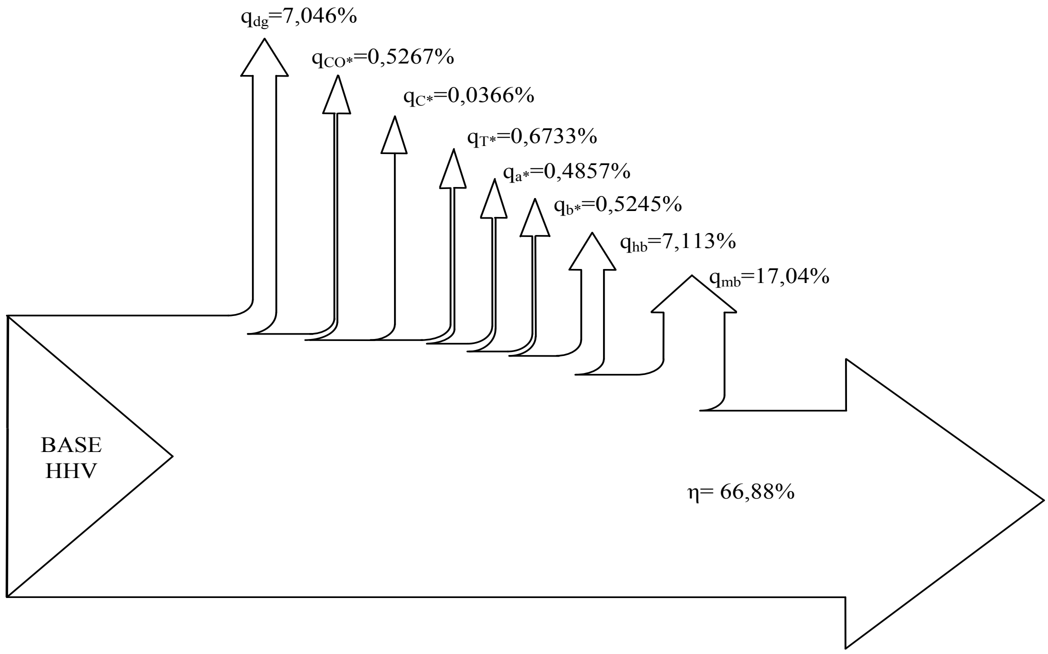

Figure 3. Sankey's diagram for the bagasse boiler efficiency (HHV as calculation base).

The second law efficiency or exergetic efficiency presented in the equation(18), calculated by the method of inputs and outputs, , using the results of the first law analysis on the fuel current and the exergy of bagasse (Eq. 19 and 20) was calculated as:

$$\xi = 27{,}2\%$$

As it is very well known, this low value is due fundamentally to the steam temperature and pressure values.

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