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ESTIMATE OF CONSUMPTION OF SUGARCANE BAGASSE AS A COMPLEMENT IN THE FUEL BLEND IN A BIOMASS BOILER

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Abstract. *This work presents an estimate of consumption of sugarcane bagasse as a complement in the fuel blend in a biomass boiler. Elemental analyzes of biomasses (coffee grounds, eucalyptus wood chips and sugarcane bagasse) were obtained in the literature. Reaction parameters such as composition of the biomass blend, moisture and excess air were adopted in the formulation. A thermodynamic modeling was proposed for the combustion process, presenting the lower heat value (LHV), enthalpy of combustion products, air-fuel ratio, biomass exergy and combustion products exergy. All these parameters were evaluated in relation to the addition of wet cane bagasse in the biomass blend. Thus, it was possible to estimate the biomass consumption values for various bagasse moisture values. It is expected that the results and conclusions presented in this work can assist the operation of biomass boilers.*

Keywords: LHV, biomass, combustion, sugarcane bagasse, coffee grounds

1. INTRODUCTION

Brazilian soluble coffee (the world leader in production and export) was exported to exactly 100 countries, generating revenues of just over US $ 500,000,000.00 only in the first 10 months of 2017, even with the drop in the volume of coffee bags in exports compared to 2016 (ABICS, 2018). This can be explained by the considerable increase in the value of soluble coffee in the international market. Brazilian hegemony is threatened by Asian producers, especially Vietnam. In order to cope with the great Asian competition, Brazilian industries must invest in their process in order to reduce the production costs of soluble coffee.

One of the major inputs to the soluble coffee production chain is steam, with about 25% of all energy consumed in the process being used in the form of steam, according to the Nestlé Sustainability Report of 2014. According to the same report, 97% of the production reject (coffee grounds) is used together with eucalyptus wood chip for burning in the boiler, which eliminates some costs related to the disposal of this waste and decreases the environmental impact, estimating that for each ton of coffee are generated 480 kg of coffee grounds, Soares *et al*., 2014.

Given this scenario, the industry has many opportunities to improve its steam generation processes in order to reduce its cost of production. According to VIOTTO, 1991, the use of coffee grounds with excess moisture in the combustion process causes an increase in operating costs, since larger amounts of fuel complement (eucalyptus wood chip) are required. In this context, the use of other fuels in the blend with the coffee grounds can be a good economical option. Thus, sugarcane bagasse presents a great potential as a complementary fuel to the coffee grounds or its blend with eucalyptus.

In this work, a biomass combustion boiler, burning coffee grounds and eucalyptus wood chips is analyzed globally. The combustion of coffee grounds, eucalyptus wood chips and sugarcane bagasse is modeled as a function of their elemental components, moisture, excess air and biomass concentration. With this model, analyzes of first and second laws of thermodynamic laws applied to the biomass boiler (coffee grounds and eucalyptus wood chip) were carried out, and an estimate of the consumption of sugarcane bagasse is presented considering the possibility of use in the same boiler a biomass blend, coffee grounds, eucalyptus wood chips and sugarcane bagasse.

2. MATHEMATICAL MODELLING

According to Torrent *et al*., 2016, a complete combustion reaction of biomass using atmospheric air can be expressed by the following chemical reaction:

$$CH_yO_z+\varepsilon(O_2+3.76N_2)\rightarrow CO_2+\frac{y}{2}H_2O+3.76aN_2 \tag{1}$$

where C, H, O, and N represents, respectively, carbon, hydrogen, oxygen and nitrogen, with the coefficients y, z, and ε related by the following expression:

$$\varepsilon=1+\frac{y}{4}-\frac{z}{2} \tag{2}$$

(Keating, 2007) proposed the following combustion reaction for coal and other solid fuels:

$$n_CC_s+n_HH_2+n_OO_2+a(O_2+3.76N_2)\rightarrow bCO_2+cH_2O+dN_2 \tag{3}$$

where C_s, H_2, O_2, and N_2 represents, respectively, solid carbon, hydrogen gas, oxygen gas and nitrogen gas. The symbols n_C, n_H, n_O, a, b, c e d are the stoichiometric coefficients of the combustion reaction.

In order to identify the stoichiometric coefficients of the combustion reaction it is necessary to perform an elemental analysis of the biomass (coffee grounds, eucalyptus wood chips and sugarcane bagasse). In this analysis, values of $C(\%)$, $H(\%)$, $O(\%)$, $N(\%)$ and $S(\%)$ are presented, where N and S are considered negligible in biomass.

The elemental composition and physical-chemical characteristics of the coffee ground and eucalyptus wood chips in a dry base are showed in the Tab. 1, where the subscript *w* refers to moisture:

Table 1 – Biomass characteristics

	$C(\%)$	$H(\%)$	$O(\%)$	Ash (%)	Moisture (%)
Coffee ground (1)	60.849	7.465	31.396	0.290	73.3 (4)
Eucalyptus wood chips (2)	49.320	5.910	44.266	0.504	45 (4)
Sugarcane bagasse (3)	48.20	6.65	45.15	2.5	55

(1) Silva *et al*., 1997
(2) Macedo, 2006
(3) Hugot, 1969
(4) Values observed in boiler operation

The stoichiometric coefficients of Eq. (3) can be obtained using the expressions given in Tab. 2 and numerical values given in Tab. 1:

Table 2 – Stoichiometric coefficients

	Addition of moisture (kg)	Ashless (kg)	Molar mass (kg/kmol)(5)	Stoichiometric coefficient (kmol)	Molar fraction
C	$C_w=C-C\cdot\frac{w}{100}$	$C_A=\frac{C_w}{100-Ash_w}$	12.01	$n_C=\frac{C_A}{12.01}$	$y_C=\frac{\overline{C}_A}{\overline{C}_A+\overline{H}_A+\overline{O}_A+}$
H	$H_w=H-H\cdot\frac{w}{100}$	$H_A=\frac{H_w}{100-Ash_w}$	2.016	$n_C=\frac{H_A}{12.01}$	$y_H=\frac{\overline{H}_A}{\overline{C}_A+\overline{H}_A+\overline{O}_A+}$
O	$O_w=O-O\cdot\frac{w}{100}$	$O_A=\frac{O_w}{100-Ash_w}$	32.00	$n_C=\frac{O_A}{12.01}$	$y_O=\frac{\overline{O}_A}{\overline{C}_A+\overline{H}_A+\overline{O}_A+}$
Ash	$Ash_w=Ash-Ash\cdot\frac{w}{100}$	–	–	–	–
Water	–	$w_A=\frac{w}{100-Ash_w}$	18.02	$n_C=\frac{w_A}{12.01}$	$y_w=\frac{\overline{w}_A}{\overline{C}_A+\overline{H}_A+\overline{O}_A+}$

(5)Moran *et al*., 2018

From the stoichiometric coefficients and molar fractions given in Tab. 2, it is possible to rewrite the combustion equation, Eq. (3), in a more general way, considering ash-free biomass with moisture:

$$y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 \tag{4}$$

Coffee grounds and eucalyptus wood chips are burned at the same time, so it is necessary to rewrite Eq. (4) by adding the two biomasses and their respective proportions:

$$\alpha\left(y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O\right)_{C.G.} + \beta\left(y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O\right)_{E.C.} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 \tag{5}$$

where the indices C.G. and E.C. refers to the coffee grounds and eucalyptus wood chips and α and β are the biomass proportions in the combustion reaction. The coefficients a, b, c and d can be determined by the stoichiometric balance of the reaction:

$$a = \frac{\left[(2b + c) - \left(2\alpha y_{O,C.G.} + \alpha y_{O,C.G.} + 2\beta y_{O,E.C.} + \beta y_{O,E.C.}\right)\right]}{2}$$

$$b = \alpha y_{C,C.G.} + \beta y_{C,E.C.}$$

$$c = \frac{\left(2\alpha y_{H,C.G.} + \alpha y_{H,C.G.} + 2\beta y_{H,E.C.} + \beta y_{H,E.C.}\right)}{2}$$

$$d = 3.76a$$

In normal operation conditions of the boiler, only coffee grounds and eucalyptus wood chips are burned, so the possibility of adding sugarcane bagasse to the biomass blend can be verified, according to schematic diagram of the boiler, Fig. (1). In this work, the production of steam will not be analyzed and the energy charged by the ashes is considered negligible.

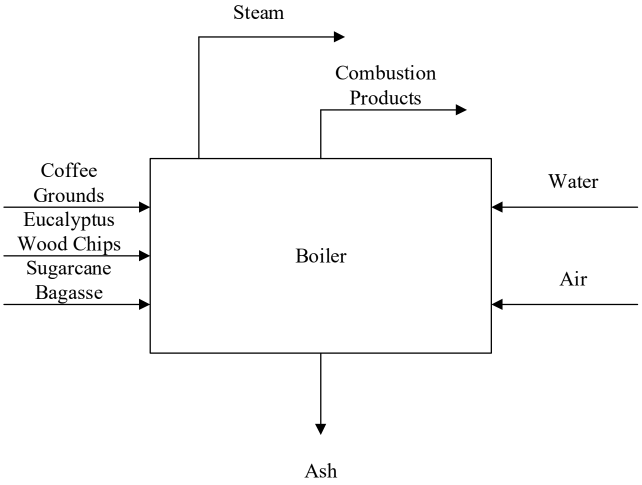

Figure 1. Schematic diagram of the boiler.

Therefore, Eq. (5) and its coefficients must be rewritten in the following form:

$$\alpha\left(y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O\right)_{C.G.} + \beta\left(y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O\right)_{E.C.} + \upsilon\left(y_C C_s + y_H H_2 + y_O O_2 + y_w H_2O\right)_{S.B.} + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2 \tag{6}$$

being S.B. sugarcane bagasse and υ the proportion of sugarcane bagasse. Using the stoichiometric balance of the combustion reaction given by Eq. (6), we obtain:

$$a=\frac{\left[(2b+c)-\left(2\alpha y_{O,C.G.}+\alpha y_{O,C.G.}+2\beta y_{O,E.C.}+\beta y_{O,E.C.}+2\upsilon y_{O,B.C.}+\upsilon y_{O,B.C.}\right)\right]}{2}$$

$$b=\alpha y_{C,C.G.}+\beta y_{C,E.C.}+\upsilon y_{C,E.C.}$$

$$c=\frac{\left(2\alpha y_{H,C.G.}+\alpha y_{H,C.G.}+2\beta y_{H,E.C.}+\beta y_{H,E.C.}+2\upsilon y_{H,B.C.}+\upsilon y_{H,B.C.}\right)}{2}$$

$$d=3.76a$$

The excess air can be added to the combustion reaction. Thus, we obtain the following combustion reaction:

$$\begin{aligned}&\alpha\left(n_C C_s+n_H H_2+n_O O_2+n_w H_2O\right)_{S.C.}+\beta\left(n_C C_s+n_H H_2+n_O O_2+n_w H_2O\right)_{E.C.}\\&\quad+\upsilon\left(y_C C_s+y_H H_2+y_O O_2+y_w H_2O\right)_{S.B.}+\lambda a(O_2+3.76N_2)\rightarrow eCO_2+fH_2O+gN_2+hO_2\end{aligned}\qquad(7)$$

being λ the air excess coefficient and e, f, g and h coefficients that can be determined by the stoichiometric balance of the combustion reaction:

$$e=\alpha y_{C,C.G.}+\beta y_{C,E.C.}+\upsilon y_{C,E.C.}$$

$$f=\frac{\left(2\alpha y_{H,C.G.}+\alpha y_{H,C.G.}+2\beta y_{H,E.C.}+\beta y_{H,E.C.}+2\upsilon y_{H,B.C.}+\upsilon y_{H,B.C.}\right)}{2}$$

$$g=3.76a\lambda$$

$$h=\frac{\left(2\alpha y_{O,C.G.}+\alpha y_{w,C.G.}+2\beta y_{O,E.C.}+\beta y_{w,E.C.}+2\upsilon y_{O,B.C.}+\upsilon y_{w,B.C.}\right)+2a\lambda-2e-f}{2}$$

2.1 Energy Analysis

The heating value is one of the main thermochemical properties of a solid fuel, having two variations, that is, higher heating value (HHV) and lower heating value (LHV). The LHV assumes that the water produced by the reaction remains in the vapor phase, whereas the HHV considers that it is in the liquid phase (Madanayake *et al*., 2017). The HHV can be calculated by the following empirical equation (Friedl *et al*., 2005):

$$HHV=3{,}55C^2-232C-2230H-51{,}2\cdot H\cdot C+131N+20600\qquad(8)$$

However, Eq. (8) is valid for values of elements in the dry base and without ashes. Thus, using the values of the elemental analysis contained in Tab. 1, Eq. (8) can be rewritten as:

$$\begin{aligned}HHV=&-3{,}55\left(\frac{C\cdot 100}{100-Ash}\right)^2-232\left(\frac{C\cdot 100}{100-Ash}\right)-2230\left(\frac{H\cdot 100}{100-Ash}\right)-51{,}2\left(\frac{H\cdot 100}{100-Ash}\right)\left(\frac{C\cdot 100}{100-Ash}\right)\\&+131\left(\frac{N\cdot 100}{100-Ash}\right)+20600\end{aligned}\qquad(9)$$

To determine the LHV values of the moist biomass the following empirical equation can be used (Rendeiro *et al*., 2008):

$$LHV_w=(1-w)\cdot(HHV)-\left(\frac{9\cdot(1-w)\cdot H}{100}\cdot 2442.3\right)-w\cdot 2442.3\qquad(10)$$

The $LHV_{w,blend}$ can be calculated by the following equation (Mehmood, 2012):

$$LHV_{w,blend} = \alpha \cdot LHV_{C.G.} + \beta \cdot LHV_{E.C.} + \upsilon \cdot LHV_{B.C.} \tag{11}$$

The specific enthalpy of the combustion products can be determined by the following equation:

$$HCP = e\left[\Delta\bar{h}(T)\right]_{CO_2} + f\left[\Delta\bar{h}(T)\right]_{H_2O,g} + g\left[\Delta\bar{h}(T)\right]_{N_2} + h\left[\Delta\bar{h}(T)\right]_{O_2} \tag{12}$$

Using the JANAF thermochemical tables, presented by Keating, 2007, it is possible to create a polynomial for the specific enthalpy and specific entropy as a function of combustion reaction temperature. The polynomials below are valid for a temperature range of 500 K to 2000 K, with units of $\Delta\bar{h} = cal/gmole$ and $\Delta\bar{s} = cal/gmole \cdot K$:

$$\Delta\bar{h}_{CO_2} = -6 \cdot 10^{-7} T^3 + 3.3 \cdot 10^{-3} T^2 + 8.1512T - 2844 \tag{13}$$

$$\Delta\bar{s}_{CO_2} = 12.982\ln(T) - 76.152 \tag{14}$$

$$\Delta\bar{h}_{H_2O} = 1.3 \cdot 10^{-3} T^2 + 7.1785T - 2285.6 \tag{15}$$

$$\Delta\bar{s}_{H_2O} = 10.095\ln(T) - 54.636 \tag{16}$$

$$\Delta\bar{h}_{N_2} = 5 \cdot 10^{-4} T^2 + 6.7299T - 2107.2 \tag{17}$$

$$\Delta\bar{s}_{N_2} = 7.8653\ln(T) - 45.479 \tag{18}$$

$$\Delta\bar{h}_{O_2} = 5 \cdot 10^{-3} T^2 + 7.3491T - 2367.5 \tag{19}$$

$$\Delta\bar{s}_{O_2} = 8.344\ln(T) - 48.349 \tag{20}$$

2.2 Exergy Analysis

The chemical exergy charged by the coffee grounds or eucalyptus wood chips can be calculated by the following equation (Szargut and Steward, 1988):

$$\varepsilon = \frac{\left\{1.042 + 0.2160\left(\frac{H_w}{C_w}\right) - 0.2499\left(\frac{O_w}{C_w}\right) \cdot \left[1 + 0.7884\left(\frac{H_w}{C_w}\right)\right] + 0.0450\left(\frac{N_w}{C_w}\right)\right\}}{1 - 0.3035\left(\frac{O_w}{C_w}\right)} \tag{21}$$

Once calculated ε the chemical exergy of coffee grounds or wood chips can be determined by the following equation (Szargut and Steward, 1988):

$$A_{ch} = \varepsilon \cdot \left(2442 \cdot w + LHV_w\right) + w \cdot A_{H_2O} \tag{22}$$

where A_{H_2O} is the chemical exergy of water. The specific exergy biomass blend can be calculated by the following equation:

$$A_{ch,blend} = \alpha \cdot A_{ch,C.G.} + \beta \cdot A_{ch,E.C.} + \upsilon \cdot A_{ch,B.C.} \tag{23}$$

Chemical exergy of the combustion products can be obtained by following equation (Moran *et al.*, 2018):

$$A_{ch,CP} = R \cdot T_0\left[e \cdot \ln\left(\frac{yCO_2}{yeCO_2}\right) + f \cdot \ln\left(\frac{yH_2O}{yeH_2O}\right) + g \cdot \ln\left(\frac{yN_2}{yeN_2}\right) + h \cdot \ln\left(\frac{yO_2}{yeO_2}\right)\right] \tag{24}$$

The physical exergy calculation is based on the difference of pressure and temperature between the system of analysis and the environment in which it is inserted. In this study, the pressure considered is the atmospheric pressure, in such a way that the physical exergy is referring to the temperature difference between the input and output components of the system and the environment. Thus, the physical exergy of combustion gases can be calculated by the following equation (Moran *et al.*, 2018):

$$A_{ph,CG} = e\left\lfloor \Delta h(T_i)_{CO_2,in} - T_0 \Delta s(T_i)_{CO_2,in} \right\rfloor + f\left\lfloor \Delta h(T_i)_{H_2O,in} - T_0 \Delta s(T_i)_{H_2O,in} \right\rfloor \\ + g\left\lfloor \Delta h(T_i)_{N_2,in} - T_0 \Delta s(T_i)_{N_2,in} \right\rfloor + h\left\lfloor \Delta h(T_i)_{O_2,in} - T_0 \Delta s(T_i)_{O_2,in} \right\rfloor \quad (25)$$

2.3 Estimate of consumption

The boiler in analysis burns biomass, in this case a blend of eucalyptus coffee grounds and wood chips. Due to its physical characteristics and the offer of sugarcane bagasse in the market, the opportunity arose to add bagasse to the blend. It is important to note that the equipment under analysis burns coffee grounds, which is a reject of the soluble coffee manufacturing process. Its mass flow rate is equal of 92.75 ton/day, and the eucalyptus wood chips are bought from loggers. Thus, assuming that the burning conditions are the same, the energy flux of the "ground-chip" blend should be equal to the energy flux of the "ground-chip-bagasse" blend:

$$\dot{m}_{G.C.} \cdot LHV_{G.C.} = \dot{m}_{G.C.B.} \cdot LHV_{G.C.B.} \quad (26)$$

where $\dot{m}_{G.C.}$ and $\dot{m}_{G.C.B.}$ are the mass flow rates of the ground-chip and ground-chip-bagasse blend, respectively, being $\dot{m}_{G.C.}$ given by $\dot{m}_{G.C.} = \dot{m}_\alpha + \dot{m}_\beta$ and $\dot{m}_{G.C.}$ given by $\dot{m}_{G.C.B.} = \dot{m}_\alpha + \dot{m}_\beta + \dot{m}_\upsilon$, and $LHV_{G.C.}$ and $LHV_{G.C.B.}$ are the lower heat value of the ground-chip and ground-chip-bagasse, respectively. To obtain the $LHV_{G.C.}$ the following parameters were used: $\alpha = 0.25$, $\beta = 0.75$, $w_{C.G.} = 0.733$ and $w_{E.C.} = 0.733$, getting $LHV_{G.C.} = 7940\, kJ/kg$ and $\dot{m}_{G.C.} = 0.5787\, kg/s$ (Moscato and Oliveira, 2017).

Using Eqs. (9-11), it is possible to determine the consumption relation between the sugarcane bagasse and the eucalyptus wood chips, since the coffee grounds consumption is fixed, according to Eq. (27). For this analysis it was assumed that the biomass moisture values do not change, while the moisture content of the sugarcane bagasse is taken into account:

$$\dot{m}_\beta = 3.204 - 1.979\dot{m}_\upsilon + 2.251\dot{m}_\upsilon \left(\frac{w_{B.C.}}{100} \right) \quad (27)$$

where $\dot{m}_\beta$ and $\dot{m}_\upsilon$ are the mass flow rates of eucalyptus wood chips and sugarcane bagasse, respectively. The concentrations of each biomass in the blend can be written in terms of the mass flow rates:

$$\alpha = \frac{\dot{m}_\alpha}{\dot{m}_{G.C.B.}} \quad (28)$$

$$\beta = \frac{\dot{m}_\beta}{\dot{m}_{G.C.B.}} \quad (29)$$

$$\upsilon = \frac{\dot{m}_\upsilon}{\dot{m}_{G.C.B.}} \quad (30)$$

being:

$$\alpha + \beta + \upsilon = 1 \quad (31)$$

3. RESULTS AND DISCUSSION

The parameters for construction of the curves presented in this work are the following: $\dot{m}_\alpha = 0.5787$ kg/s, $\lambda = 1.28$, and $T_0 = 300K$. For $\dot{m}_\upsilon = 0$, it is understood to burn coffee grounds and eucalyptus wood chips only ("ground-chip").

The behavior of the LHV as a function of the bagasse mass flow rate can be seen in Fig. (2). Two different conditions can be verified in Fig. (2). Firstly, for bagasse moisture values above 45%, the values of LHV decrease as the bagasse mass flow rate increase. Secondly, for conditions that the bagasse moisture is below 45%, the values of LHV increase as the bagasse mass flow rate increase.

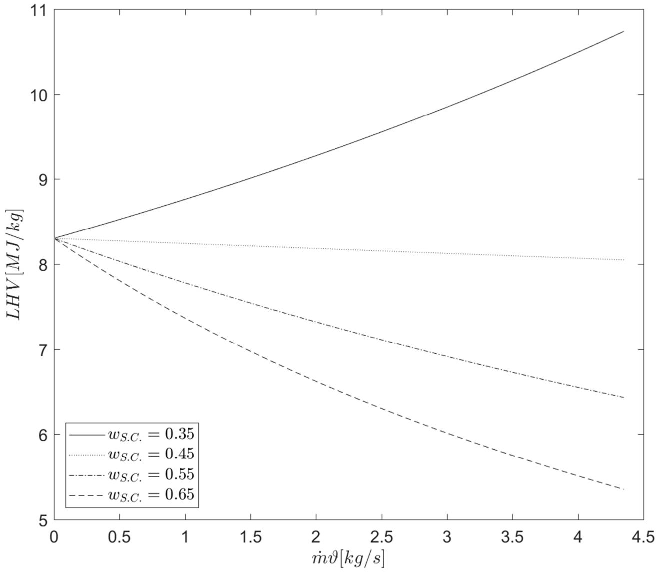

Figure 2. LHV as a function of bagasse mass flow rate for various values of bagasse moisture.

Figure 3 shows the consumption or mass flow rate of the biomasses that are burned in the boiler. Observing the behavior of the mass flow rate of eucalyptus wood chips, it can be seen that the increase of the mass flow rate of sugarcane bagasse causes a decrease in the mass flow rate of eucalyptus wood chips while the mass flow rate of coffee grounds remains constant, since this is a production residue and must be burned in its entirely. The increased moisture content of the bagasse causes an increase in the eucalyptus wood chips consumption as well as an increase in the mass flow rate of the total biomass that must be burned in the boiler.

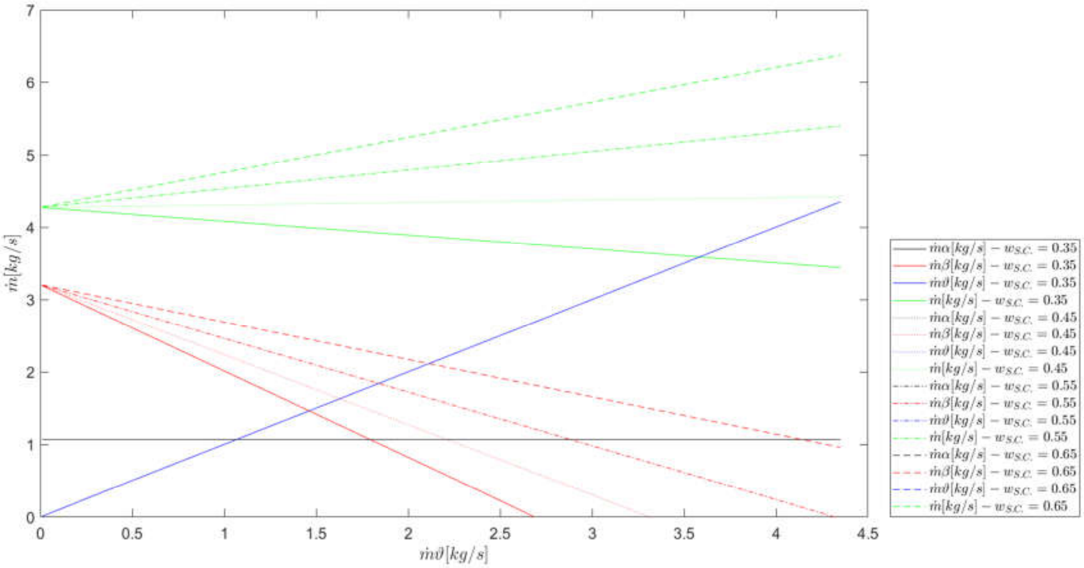

Figure 3. Biomass mass flow rate as a function of bagasse mass flow rate for various values of bagasse moisture.

Comparing Figs. 2 and 3 it can be seen that for 45% of moisture there is just a slight variation in the values of LHV and of $\dot{m}$. With this result, it can be suggested that to maintain the conditions of burning of coffee grounds and eucalyptus wood chips, the moisture of sugarcane bagasse burned should have a moisture content closer to 45%. In this case, the total biomass consumption will be closer to the initial conditions, as well as the LHV.

Analyzing the behavior of biomass proportions as a function of cane bagasse mass flow rate in Fig. 4, it can be seen that an increase of cane bagasse moisture causes a decrease in the concentration of coffee grounds and eucalyptus wood chips, besides increasing the concentration of sugarcane bagasse. The moisture content of sugarcane bagasse causes a decrease in LHV, so, in order to maintain LHV levels, more bagasse is required. As the cane bagasse mass flow rate increase, the eucalyptus wood chips concentration decrease while the concentration of coffee ground shows a slight decrease.

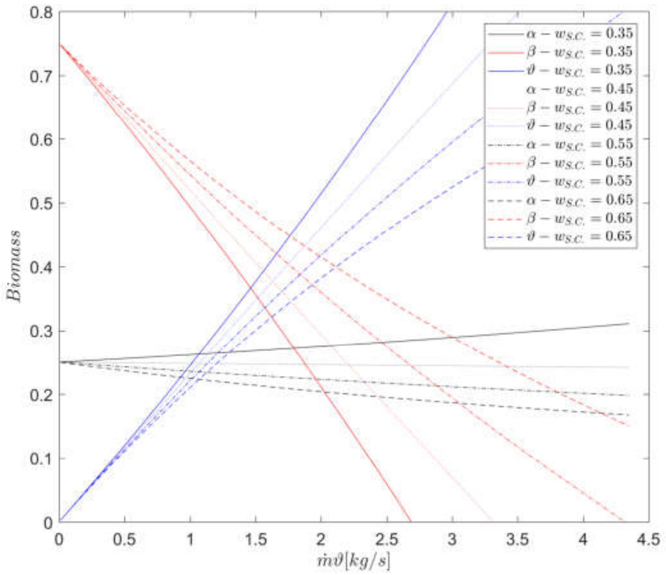

Figure 4. Concentration of biomass as a function of bagasse mass flow rate for various values of bagasse moisture.

It can be seen from Fig. 4 that for moisture curves of 45% bagasse (shown in Figs. 2 and 3 as an ideal value to maintain the initial operation conditions) the biomass proportion would be approximately 25% of coffee grounds, 37.5% of wood eucalyptus chips and 37.5% of sugarcane bagasse. The same behavior of the LHV shown in Fig. 2 can be seen in Fig. 5 for the chemical exergy of the biomass as a function of the mass flow rate of the sugarcane bagasse. Values above approximately 45% moisture of the bagasse causes a decrease in the chemical exergy of the biomass, while values above 45% causes an increase in the biomass chemical exergy. Again, it can be seen that the moisture of the bagasse next to 45% promotes similar initial operation conditions (grounds-chips).

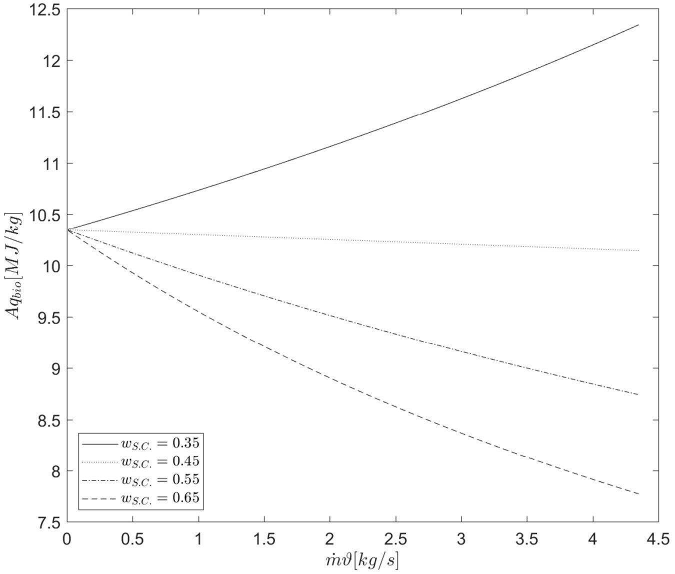

Figure 5. Chemical exergy of biomass as a function of bagasse mass flow rate for various values of bagasse moisture.

The air-fuel ratio as a function of the mass flow rate of sugarcane bagasse can be seen in the Fig. 6. It can be seen that values below 55% of moisture causes an increase in the volume of air required for biomass burning, while values above 55% of moisture causes a decrease in this ratio. This occurs because the biomass blend is drier, i.e., in place of water there is more biomass to be burned causing an increase in the amount of air required for the combustion to occur completely.

The enthalpy of the combustion products can be seen in Fig. 7. With similar behavior to the exergy and LHV, the enthalpy of the combustion products increase with values of cane bagasse moisture equal of 45%, and decrease for values above this line. It was noticed again that moisture values close to 45% maintain the initial firing conditions.

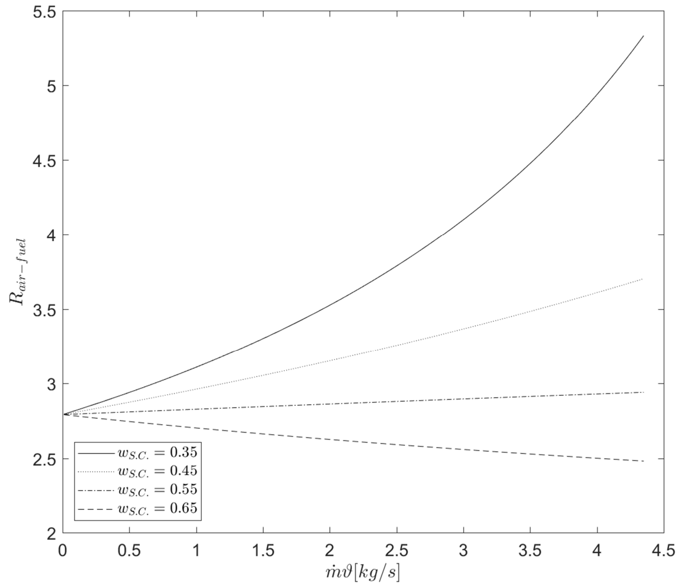

Figure 6. Air-fuel ratio as a function of bagasse mass flow rate for various values of bagasse moisture.

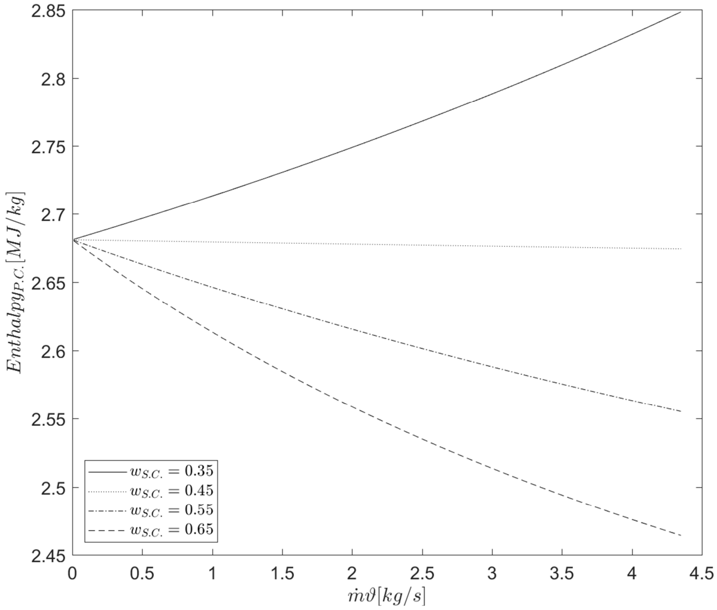

Figure 7. Combustion products enthalpy as a function of bagasse mass flow rate for various values of bagasse moisture.

With the sum of the chemical and physical specific exergy of the combustion products, the specific total exergy behavior of the combustion products can be obtained as a function of the mass flow rate of cane bagasse, Fig. 8. The increase in the moisture content of sugarcane bagasse, as well as previous figures, causes a decrease in the exergy of the combustion products. Values closer to 45% of moisture maintain the exergy levels of combustion products from the burning of coffee grounds and eucalyptus wood chips. By reducing the moisture content of the bagasse (<45%) it can be seen an increase in the specific exergy of the combustion products.

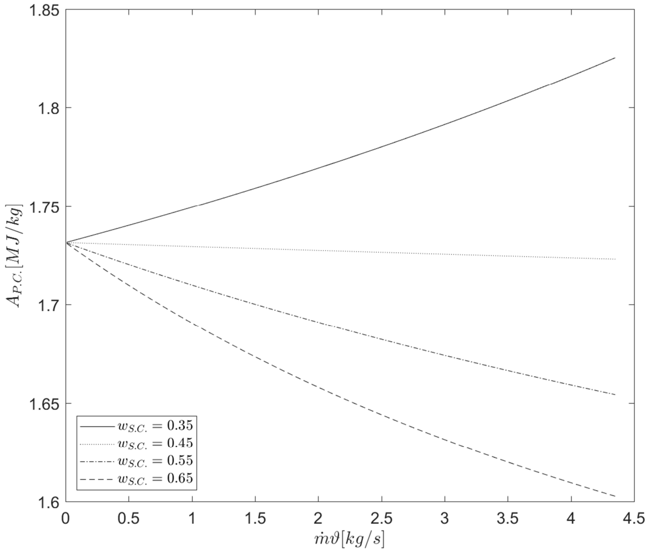

Figure 8. Specific total exergy of the combustion products as a function of bagasse mass flow rate for various values of bagasse moisture.

4. CONCLUSIONS

This work presents an estimate of sugarcane bagasse consumption as a fuel complement in a biomass boiler. A combustion reaction model based on the first and second laws of thermodynamics was proposed using the following parameters: air excess, biomass composition and moisture. The model was based on the elemental analysis of coffee grounds, eucalyptus wood chips and sugarcane bagasse. Analytical expressions were obtained for LHV and exergy of both the biomass and the products of combustion, chemical and physical.

It was verified that an increase of the mass flow rate of the sugarcane bagasse with values higher than approximately 45% in the biomass blend decreases the LHV, the exergy of the biomass and the exergy of the combustion products, while values lower than 45% increases the LHV, the exergy of the biomass and the exergy of the combustion products.

When the consumption of eucalyptus wood chips and sugarcane bagasse were studied, with the increase of the bagasse moisture, the eucalyptus wood chips consumption also increase. However, the total biomass consumption increase with moisture values above 45%. For moisture values lower than 45% a reduction of the total bagasse consumption has been observed. As the coffee grounds is a production residue, its consumption cannot be changed.

The boiler usually burns coffee grounds and eucalyptus wood chips. In order to use the sugarcane bagasse in this blend, the LHV of the "ground-chips" must be at least equal to that of the "ground-chip-bagasse". In this sense, bagasse moisture seems to be suitable for values closer to 45%, as it maintains the values of enthalpy of combustion products, biomass exergy and combustion products.

It is expected that the proposed model and its results may be useful to understanding of the combustion of biomass, mainly the combustion of a several biomasses blend, in this case coffee grounds, eucalyptus wood chips and sugarcane bagasse.

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6. REFERENCES

ABICS, 2018. "Relatório Café Solúvel do Brasil, Novembro 2017". 8 Jan. 2018 < http://www.abics.com.br>.

Nestlé, 2018. "NESTLÉ NA SOCIEDADE, Relatório 2014 criando valor compartilhado". 8 Jan. 2018< https://www.nestle.com.br>

Cabral, M.S. and Moris, V.A.S, 2010. "Reaproveitamento da borra de café como medida de minimização da geração de resíduos". In *Proceedings of the XXX Encontro nacional de engenharia de produção, São Carlos.*

Viotto, L.A., 1991. *Projeto e avaliação econômica de sistemas de secagem de borra de café.* Campinas: UNICAMP.

Torrent, J.G., Ramírez-Gómez A., Fernandez-Anez, N., Pejic, L.M. and Tascón, A., 2016. "Influence of the composition of solid biomass in the flammability and susceptibility to spontaneous combustion". *Fuel,* Vol. 184, p. 503.

Keating, E.L., 2007. *Applied combustion*, CRC, Boca Raton, 2nd edition.

Silva, M.A., Nebra, S. A., Silva, M. J. M. and Sanchez, C. G., 1998. "The use of biomass residues in the Brazilian soluble coffee industry". *Biomass and Bioenergy*, Vol. 14, p. 457.

Macedo, J.C.F., 2006. *Análise Térmica e Ambiental da Queima do Lodo Primário da Fabricação de Papel e Celulose em Caldeira de Biomassa à Grelha.* Itajubá: Universidade Federal de Itajubá.

Hugot, E., 1969. *Manual da Engenharia Açucareira- Vol. I.* Mestre Jou, São Paulo, 1st edition.

Moran, M.J., Shaprio, H.N., Boether D. D. and Bailey, M. B.,2018. *Fundamentals of thermal engineering*, LTC, São Paulo, 8th edition.

Madanayak, B. N., Gan, S., Eastwick, C., Ng, H. K., 2017. "Biomass as an energy source in coal co-firing and its feasibility enhancement via pre-treatment techniques". *Fuel Processing and Technology*, Vol. 159, p. 287.

Friedl, A., Padouvas, E., Rotter, H., Varmuza, K., 2005. "Prediction of Heating Values of Biomass Fuel from Elemental Composition". *Analytica Chimica Acta*, Vol. 544, p. 191.

Rendeiro, G., Nogueira, M.F.M. Brasil, A.C.M., Cruz, D.O.A., Guerra, D.R.., Macêdo, E. N. and Macêdo, J.A., 2008. *Combustão e gasificação de biomassa sólida*. Brasília: Ministério de Minas e Energia, 1st edition.

Mehwood, S., Reddy, B.V. and Rosen, M.A., 2012. "Energy Analysis of a Biomass Co-firing Based Pulverized Coal Power Generation System". *Sustainability,* Vol. 4, p. 462.

Szargut, J., Morris, D.R., Steward, F.R., 1988. *Exergy Analysis of Thermal, Chemical and Metallurgical Processes.* Hemisphere, New York.

Moscato, A., L., S., and Oliveira, S., D., R., 2017. "Estimation of LHV, released heat and exergy of a combustion reaction of spent coffee and eucalyptus wood chips". In *Proceedings of the 24th International Congress of Mechanical Engineering -COBEM2017*. Curitiba, Brazil.

7. RESPONSIBILITY NOTICE

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