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CO-COMBUSTION OF FLOATED SLUDGE FROM A SLAUGHTERHOUSE WASTEWATER TREATMENT PLANT WITH EUCALYPTUS WOODCHIPS IN A BIOMASS STEAM GENERATOR

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Abstract. *The floated sludge is a residue generated in slaughterhouses wastewater treatment plants, which can be applied in combustion with the main fuel in biomass boilers. In this regard, the present work aims to study the use of the floated sludge in mixture with eucalyptus woodchips in a boiler used for process steam generation. Field tests were performed in the steam generator with nominal capacity of 40 ton/h of saturated steam at 15 bar, considering floated sludge co-firing ratios up to 20% on a mass basis. The efficiency calculation was performed according to the indirect method of ASME PTC 4 (2013) standard. As a result, the efficiency of the steam generating unit increased with increasing the content of sludge mixed with woodchips up to the percentage of 15%. This was mainly caused by the reduction of energy losses associated with the flue gases as well as the reduction of CO emissions. On the other hand, the efficiency related to the 20% co-firing ratio showed a slight reduction due to increased energy losses and the difficulty of maintaining constant sludge feed into the feed hopper.*

Keywords: *Efficiency, combustion, floated sludge, woodchips.*

1. INTRODUCTION

The evaluation of the thermal efficiency of a steam generator is a necessary step for the reduction of fuel consumption. The improvement of thermal efficiency can be accomplished by reducing significant energy losses, improving operation, reducing the amount of unburned fuel in the ashes, among other improvements.

The ASME PTC 4 (2013) standard is applied to the efficiency calculation of steam generators. It establishes the indirect method, which consists in the identification of energy losses in the control volume of the steam generating unit. The advantage of applying this method is normally related to reduced uncertainties in comparison to the direct method and that main energy losses can be identified.

In the design phase of an industrial scale boiler it is crucial to consider the aspects related to energy savings in order to extract maximum heat from the combustion process, the environmental impacts and the type of fuel used (Erbas, 2021). Conventionally, the fuels used in steam generators are: fuel oils, coal, natural gas, woodchips, biomass, among others. As an alternative to these fuels, agroindustry plants are recovering their residues that are appropriate for energy use. Among them is the sugarcane bagasse, from the sugar and ethanol sector, and the black liquor from the paper and cellulose industries (MORAES *et al*., 2017).

A residue from meat processing sector that presents an important energy potential is the floated sludge. This is a by-product of the effluent treatment systems and has in its composition organic materials from the slaughtering process, which associated with the combustion process, can contribute to the reduction of fuel consumption in steam generators.

Some works in the literature have investigated the physicochemical characteristics, the energy potential and the gaseous emissions resulting from the combustion of the floated sludge from meat processing effluent treatment plants (SENA *et al.*, 2008; FLORIANI *et al.*, 2010; VIRMOND *et al.*, 2011; PADILHA *et al.*, 2019; FAGNANI *et al.*, 2019). However, they have not investigated the application of this material in industrial scale boilers.

In this regard, the present work aims to evaluate the efficiency of an industrial scale steam generator different co-firing ratios of floated sludge with eucalyptus woodchips, with the purpose of promoting an appropriate destination for the residue, reducing the consumption of the main fuel and promoting an increase in efficiency in the steam generating unit.

2. STEAM GENERATING UNIT

This work was conducted using real operational data from a boiler for process steam generation in a poultry and fish processing plant located in the state of Paraná, Brazil.

Implemented in 2017, the steam generating unit has a nominal capacity of 40 $t.h^{-1}$ of saturated steam at 15 bar (absolute pressure). It is a mixed firetube steam boiler equipped with a reciprocating moving grate, with a furnace involved with water walls of finned tubes interconnected to a flamotubular drum, through which the hot combustion gases pass in two stages. After the heat exchange in the drum, the combustion gases are directed to the heat recovery section, where they first pass through the air preheater, transferring heat to the primary air that enters the furnace at a higher temperature than the secondary air, kept at room temperature. Next, the flue gases pass through the economizer, used to heat the boiler feedwater. Then the flue gases flow through the multicyclone, where part of the particulate material is retained, and follow the gas path until they reach the stack, where they are released into the atmosphere. Figure 1 shows a representation of the steam generator structure.

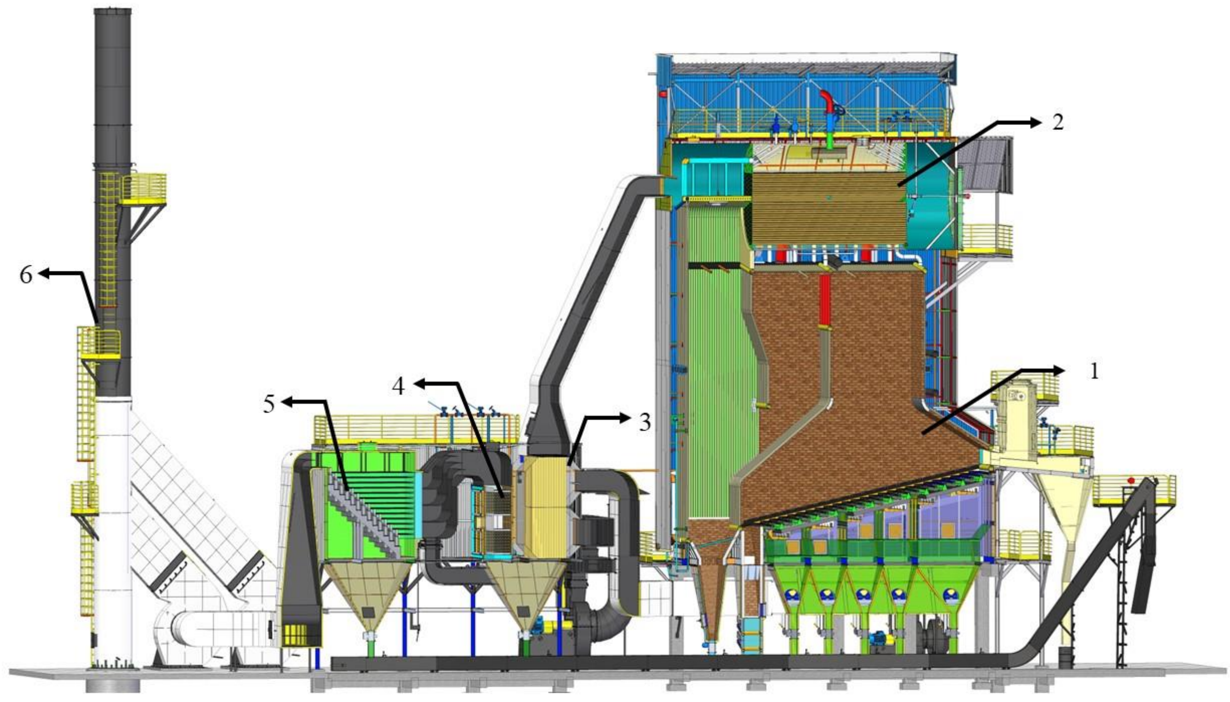

Figure 1. Schematic representation of the steam generator: 1) Furnace; 2) Drum with firetubes; 3) Air Preheater; 4) Economizer; 5) Multicyclone; 6) Chimney.

The main fuel used in the steam generating unit is eucalyptus woodchips. Considering the generation of floated sludge in the effluent treatment plant of the slaughterhouse, tests regarding the co-firing of this waste with the main fuel were performed and the thermal efficiency of equipment evaluated. In order to feed the floated sludge into the combustion chamber, the residue was dosed over the conveyor belt used for eucalyptus woodchips transportation.

Results here presented regarding the co-firing of sludge and woodchips were obtained considering the operation of equipment without the economizer, which was deactivated due to corrosion problems. The design conditions of the steam generator at rated load can be presented by Mantovan *el al*. (2021).

3. FUELS CHARACTERIZATION

The physicochemical characteristics of the eucalyptus woodchips and the floated sludge were determined according to the immediate (ASTM E870, 2019), elemental (ASTM D3176, 2015) and the higher heating value (HHV) (ASTM D5865, 2019) analyses. Chlorine and fluorine contents were quantified by ion chromatography, following BS EN 14582 (2016) and ASTM D4327 (2017) standards. The floated sludge used in this work is the residue from the effluent treatment system of poultry and fish slaughterhouses, which uses ferric chloride as a coagulant to remove suspended solids. Results are presented in Table 1.

Table 1. Properties of eucalyptus chips and floated sludge.

	Units	Eucalyptus chip	Floated sludge
Proximate analysis			
Ash	(wt %, db[a])	0,6	7,0
Moisture	(wt %, raw[b])	30 - 53	60 - 70
Volatile matter	(wt %, daf[c])	84,5	92,7
Fixed carbon	(wt %, daf[c])	15,6	6,8
Ultimate analysis			
C	(wt %, daf[c])	47,01	58,6
H	(wt %, daf[c])	7,27	9,3
N	(wt %, daf[c])	<0,02	7,3
S	(wt %, daf[c])	<0,02	0,7
O	(wt %, daf[c])	45,40	24,2
Cl	(wt %, daf[c])	0,052	0,02
F	(wt %, daf[c])	<0,0025	<0,0025
Calorific Value			
HHV	($MJ\ kg^{-1}$, daf[c])	18,8	27,9
LHV	($MJ\ kg^{-1}$, daf[c])	17,2	25,2

[a]Dry base.
[b] The fuel moisture varied in the range shown.
[c]Dry and ash free.

The lower heating value (LHV), considered for the steam generator efficiency calculation, was determined according to Eq. (1).

$$LHV = HHV - 2440.(9H) \tag{1}$$

where HHV is the higher heating value ($kJ.kg^{-1}$) and H is the hydrogen content of the fuel ($kg.kg^{-1}$). For each test, the LHV of fuels was corrected for raw basis according to the moisture and ash contents.

4. EVALUATION OF THE STEAM GENERATOR THERMAL EFFICIENCY

The efficiency of the steam generator was determined according to ASME PTC 4 (2013) standard. The standard presents two methods for calculating efficiency: the direct and the indirect methods. The first method requires the direct measuring of the net energy generated in the boiler and the total energy available from the fuel. However, this method tends to present a higher uncertainties, due to the difficulty in measuring some of the variables involved. On the other hand, the indirect method allows the identification of the energy inputs/outputs in the steam generator control volume, and results are normally associated with lower uncertainties.

The method adopted to determine the efficiency of the steam generator in this work is the indirect method. The adopted control volume involved the generating unit and the thermal efficiency was calculated according to Eq. (1),

$$\eta_b = \left(1 - \frac{Losses}{Input}\right) 100 \tag{1}$$

where η_b is the boiler thermal efficiency, *Input* is the energy input [kW] and *Losses* is the sum of all identified energy losses [kW] calculated according to Eq. (2),

$$Losses = L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 \tag{2}$$

where L_1 is the energy loss associated with the flue gases leaving the unit [kW], L_2 is the heat loss associated with the fly ash leaving the unit through the multicyclone [kW], L_3 is the heat loss associated with the bottom ash leaving the unit through the furnace [kW], L_4 is the loss due to carbon monoxide (CO) content in the flue gas [kW], L_5 is the energy loss related to purges [kW], L_6 is the heat loss by radiation and convection on the boiler surfaces [kW] and L_7 is the energy loss due to the presence of unburned carbon in ash [kW].

The energy loss associated with the flue gases leaving the unit (L_1) takes into account the energy associated with dry gases from combustion (L_{gases}) and the loss associated with moisture present in the gases (L_{water}), Eq. (3).

$$L_1 = L_{gases} + L_{water} \tag{3}$$

The dry gas energy loss was calculated according to Eq. (4) and the associated moisture loss was calculated according to Eq. (5),

$$L_{gases} = (\frac{44}{12} C \, \Delta H_{CO2} + \frac{64}{32} S \, \Delta H_{SO2} + (0{,}7685 \, m_{air}(1+e) + N) \, \Delta HN_2 + e \, m_{air} \, \Delta H_{air}) \, m_{fuel} \tag{4}$$

$$L_{water} = (9\,H + H_2O_{water} + (e+1)\, m_{air} \, \omega) \Delta H_{water} \, m_{fuel} \tag{5}$$

where C is the fuel carbon content [kg/kg$_{fuel}$], ΔHco_2 the CO_2 enthalpy [kJ/kg], S the fuel sulfur content [kg/kg$_{fuel}$], ΔHso_2 the SO_2 enthalpy [kJ/kg], m_{air} is the dry stoichiometric air mass flow per kg of fuel [kg$_{air}$/kg$_{fuel}$], N the fuel nitrogen content [kg/kg$_{fuel}$], ΔHN_2 the N_2 enthalpy [kJ/kg], e is the air excess, ΔH_{air} the enthalpy of dry air [kJ/kg$_{air}$], m_{fuel} the fuel mass flow [kg$_{fuel}$/s], H the fuel hydrogen content [kg/kg$_{fuel}$], $H2O_{fuel}$ the fuel moisture [kg/kg$_{fuel}$], ϖ the air absolute humidity [kg$_{water}$/kg$_{air}$] and ΔH_{water} the water enthalpy[kJ/kg]. The enthalpies were calculated according to the stack temperature and based on the same reference condition [T = 25°C e P = 1 bar]. In case of moisture enthalpy, the latent heat was not considered, once LHV was used in calculations.

The excess air was calculated according to Eq. (6) Bazzo (1995):

$$e = \frac{\%O_2}{21 - \%O_2} \tag{6}$$

where $\%O_2$ is the measured oxygen content in the flue gases (%).

The heat loss associated with the fly ash (L_2) was calculated according to Eq. (7),

$$L_2 = \Delta H_{ash} \, Fr \, A \, m_{fuel} \tag{7}$$

where ΔH_{ash} is the enthalpy of ash calculated according to the correlations available in the standard ASME PTC 4 (2013) [kJ/kg$_{ash}$]; Fr is the proportion of fuel ash leaving the multicyclone [Fr = 0,3] and A is the ash content of the fuel [kg$_{ash}$/kg$_{fuel}$].

The heat loss associated with the bottom ash (L_3) was also calculated according to Eq. (7), using Fr = 0,7, and assuming the bottom ash temperature of 1100°C, as recommended by the standard for cases where the flow temperature is not measured.

The loss L_4 related to the carbon monoxide (CO) content in the flue gas was calculated according to Eq. (8),

$$L_4 = \frac{CO \, \rho \, V_{gases} \, HV_{CO} \, m_{fuel}}{10^6} \tag{8}$$

where CO is the concentration of carbon monoxide in the flue gas [ppm], ρ is the CO density [ρ = 1,25 kg/Nm^3], V_{gases} is the volume of dry flue gas per unit mass of fuel burned [Nm^3/ kg$_{fuel}$] and $HVco$ is the CO heating value [$HVco$ = 10111 kJ/kg].

To calculate the heat losses related to purges (L_5) it is necessary to know the purge flow rate, as well as the frequency and duration of the purging operations (Bazzo, 1995). However, in this work, it was considered that the purge flow corresponds to 3% of the steam flow, as reported by Cortes-Rodriguez *et al.* (2016).

Similar analysis was performed for the calculation of radiation and convection losses (L_6). In this work this loss was considered to be equal to 1% of the total energy available in the furnace in the design condition, within the range suggested by Bazzo (1995).

Finally, in order to estimate the energy loss due to the presence of unburned carbon in the ash (L_7), ash samples were collected along each run and the unburned carbon content was determined according to the standard ASTM D1102 (2013). In Eq. (9) is presented the calculation to determine the loss by unburned carbon,

$$L_4 = \frac{C_{unb} \, A}{1 - C_{unb}} HV_c \, m_{fuel} \tag{9}$$

where C_{unb} is the unburned carbon content in the ash sample [kg_{carbon}/kg_{ash}] and HV_c the carbon heating value [HV_c = 33727 kJ/kg_{carbon}].

Oxygen (O_2) and CO contents in the flue gas were determined using a TESTO 340 flue gas analyzer. The steam generator operational data was collected from the supervisory system and calculations were performed using Engineering Equation Solver (EES) software.

5. FIELD TESTS

5.1 Experimental Planning

The field tests were performed for the floated sludge co-firing ratios of 0, 5, 10, 15 and 20% (mass basis) with woodchips. Each experiment consisted of two test runs of 4h each performed in the afternoon period, totaling in the end 10 days of tests.

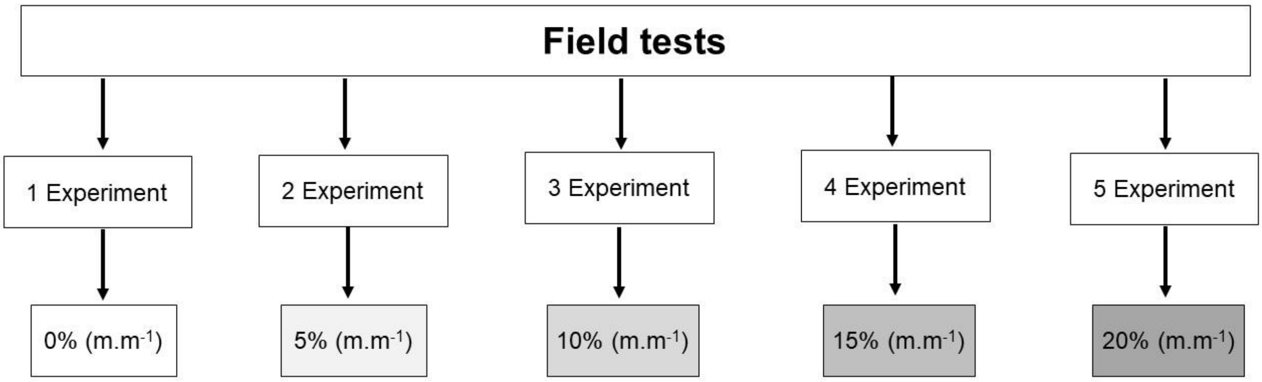

Figure 2: Field tests for different proportions of sludge mixed with eucalyptus chips

The limit of 20 % ($m.m^{-1}$) is established by SEMA N°42 (SEMA, 2008) resolution, which defines the criteria for burning waste in boilers. In addition, the tests were performed progressively with increasing sludge content mixed to the woodchips.

Aiming to standardize the field tests and ensure greater stability of parameters during testing, as suggested by ASME PTC 4 (2013), the set point of oxygen in the stack was maintained at 7% on a volumetric and dry basis, and the distribution of primary to secondary air mass flows was kept around 80% and 20% in relation to total air flow, respectively.

During the tests, samples of eucalyptus woodchips and floated sludge were collected to determine fuel moisture content, and boiler ash samples were collected to determine the unburned carbon content. The flue gas was also sampled to determine O_2 and CO contents. In addition, data was collected from the steam generator's supervisory system for subsequent calculations.

5.2 Determination of the moisture content of fuels

The moisture content of the eucalyptus woodchips and the floated sludge samples collected during the field tests was determined according to ABNT 14929 (ABNT, 2017) and ASTM E871 (ASTM, 2019) standards, respectively.

The moisture content of each fuel was calculated by considering the average of the moisture values of the samples of each material collected every one hour of testing, totaling four woodchips and four floated sludge samples for each run.

5.3 Unburned carbon content

The content of unburned carbon present in ash was determined according to ASTM D1102 (ASTM, 2013). The samples were conditioned in a muffle furnace for a period of 9 hours at 600°C.

The content of unburned carbon was calculated by considering the average of the unburned carbon values of the samples collected from the boiler ash deposit every one hour of testing, totaling four ash samples for each run.

6. RESULTS AND DISCUSSION

After performing the field tests on the steam generator, the averages of the data collected from the supervisory system, of the moisture of the fuels, of the unburned carbon content in the ashes and of the concentration of O_2 and CO in the flue gases were obtained. Results are presented in Table 3.

The flue gas temperature in the chimney remained stable and close to 162 °C during tests. The unburned carbon content in the ash varied between 10 and 30 %. The oxygen content in the flue gas varied between 6.1 and 8.3 %, corresponding to an excess of air of 41 and 65 %, respectively. According to Bazzo (1995), the recommended range of excess air based on firewood is 30 to 60%, close to the values found in this study for eucalyptus woodchips. The boiler feedwater temperature in the tests varied between 68 and 79 °C, being reduced as more make-up water was added to the condensate tank.

Table 3. Steam generator operating parameters for the field tests

Parameters/proportion	**0%**		**5%**		**10%**		**15%**		**20%**	
Races	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Steam flow ($t.h^{-1}$)	29.1	29.1	29.1	28.4	24.0	29.7	25.9	28.7	23.1	23.7
Fuel flow[a] ($t.h^{-1}$)	10.7	11.3	11.9	12.2	7.9	8.5	8.2	9.1	8.4	8.1
Vapor pressure (bar)	9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	9.0	9.0
Unburned carbon (%)	30.2	12.7	15.2	10.6	14.2	25.6	13.0	15.6	11.5	26.6
Relative humidity (%)	74.3	98.8	43.9	43.9	40.1	36.3	37.5	67.7	29.5	26.7
Ambient temp.[b] (°C)	24	20	21	21	32	29.2	33	28	39	36
Primary air temp. (°C)	135	133	133	133	132	124	126	126	134	135
Flue gas temp. (°C)	162.2	162.5	162.6	162.5	162.1	162.2	162.5	162.9	162.5	162.5
Feed water temp. (°C)	68.4	74.7	69.2	69.4	78.5	71.6	74.5	72.2	71.0	70.8
Eucalyptus chips moisture (%)	47.7	49.7	51.5	52.9	43.7	36.5	40.7	41.5	47.2	42.4
Moisture of the float sludge (%)			64.1	67.4	62.6	65.4	63.8	62.3	62.4	65.7
Moisture of the mixture[a] (%)	47.7	49.7	52.1	53.6	45.6	39.4	44.2	44.6	50.3	47.1
LHV[a] ($kJ.kg^{-1}$)	7787	7408	7053	6747	8456	9650	10835	8789	7806	8370
CO[c] (ppm)	69	175.4	13.7	14.3	10.2	19.4	9.5	11.2	10.2	9.2
O_2[c] (ppm)	7.5	7.8	7.1	7.6	7.6	6.9	6.3	6.1	8.3	7.8
Excess air (%)	56.2	58.8	50.0	55.9	54.0	49.0	43.3	40.9	65.4	59.6

[a] Calculated as a function of moisture and fuels mass fractions.
[b] Temperature.
[c] Volumetric and dry basis.

One important result consisted on the identification of the main energy losses of the steam generating unit. In Figure 3 are presented the energy losses obtained for the field tests performed for the different floted sludge co-firing ratios.

As it can be seen, L_1, which corresponds to the energy loss associated with the flue gases, represented the highest energy loss for all the field tests, ranging between 10 and 13%. These values were close to those reported by Cortes-Rodriguez, Nebra, and Sosa-Arnao. (2016), who analyzed the thermal efficiency of six sugarcane bagasse boilers and found energy loss values associated with flue gases ranging between 8.8 and 11.5%. The authors Lahijani, Supeni, and Kalantari (2018) evaluated the efficiency of a boiler by the indirect method using diesel as fuel and found 11.7% flue gas loss. According to Barroso *et al*. (2003), exhaust gas heat losses can reach up to 30 % of the total fuel available energy.

The high flue gas loss is associated with the temperature that the gases exit the chimney and the excess air flow. The flue gases should exit the boiler at the lowest possible temperature to minimize flue gas losses, however, problems with cold end corrosion limit the flue gas temperature to 150 - 200°C (Lahijani, Supeni and Kalantari, 2018).

Next, L_6, which corresponds to the fraction of energy lost to the environment by radiation and convection, represented the second highest energy loss, with values between 1 and 2 % of the energy made available by burning the fuel. Authors Cortes-Rodriguez, Nebra, and Sosa-Arnao. (2016) found values in the range of 0.5 to 0.6 %, this being the second most important energy loss for most of the tests performed in this work. The authors Lahijani, Supeni, and Kalantari (2018) considered a 1 % energy loss for radiation and convection. These differences found may be related to the physical structure of the steam generating unit and its thermal insulation.

The purge loss (L_5) represented the third largest energy loss ranging between 0.4 and 0.5 % of the available energy. The authors Cortes-Rodriguez, Nebra and Sosa-Arnao (2016) found values in the range of 0.58 to 0.70 %. The other losses showed values always below 1 % for all the tests performed. The energy loss L2 that is related to the fly ash that leaves the generating unit through the multicyclone showed a loss close to 0 % in all cases analyzed, indicating low influence of this parameter on the boiler efficiency.

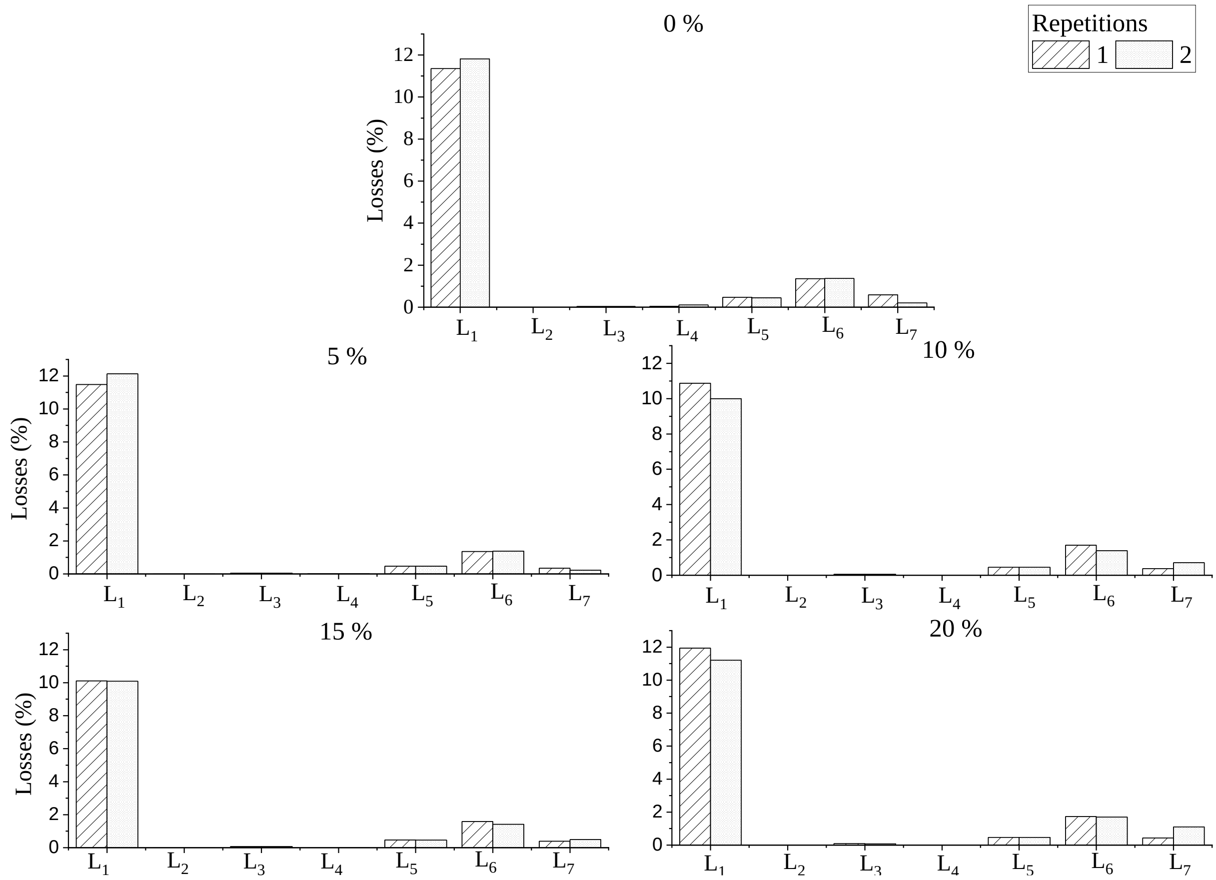

Figure 3. Energy losses at the steam generator

In Figure 3 it is possible to observe the value of the thermal efficiencies of the tests performed in the field for the different co-firing ratios of floated sludge mixed with woodchips. The efficiency values suggested by the manufacturer as a function of the operating load are also presented, as well as the experimental data obtained by Almeida (2018). The curve provided by the boiler manufacturer and the data from the work of Almeida (2018) are efficiency data for the same steam generator equipped with air preheater and economizer. At the time the sludge and woodchips co-firing tests were performed, the unit was equipped only with the air preheater in the heat recovery section.

The dispersion of data for each repetition occurred due to the variation of process steam demand. It is possible to see that there is a tendency in the increase of efficiency with the increment of sludge in the mixture until the percentage of 15%, with average values of 85.7 and 87.9 % for the conditions of 0 and 15%, respectively. However, for the 20% test the average efficiency had a slight reduction to 86.6%.

By analyzing Table 3 and Figure 2, we can see that at 15% there was less O2 concentration in the flue gases (lower air excess) and, as a consequence, less energy loss associated with the gases. With the exception of the first run of 5% test, the second run of 10% test and the 15% test runs, the other runs maintained an excess of air higher than 50%, which is the value considered in the manufacturer's design condition, which contributed to the increase of the flue gas flow in the chimney and related losses.

Another important parameter to be considered is the concentration of CO in the combustion gases. Table 3 shows high concentrations of CO for the combustion of pure woodchips, while the opposite situation occurs with the mixtures of sludge and woodchips. The emission of this pollutant is related to the efficiency of combustion in the furnace, since the release of hydrocarbons through the stack reflects the incomplete combustion of volatiles released during combustion. Thus, the tests performed with the mixtures of sludge and woodchips showed to be promising because of the low rates of energy loss related to CO emissions.

An important factor for the reduction of efficiency in the 20% test was the difficulty in maintaining stable the feeding of the floated sludge in the boiler feed screw, which did not ensure a continuous sludge feeding when compared to the other tests. In this regard, the dynamics of the combustion process did not follow the same pattern of the previous tests, leading to increased O2 content in the flue gas and, as a consequence, a higher excess air. In addition, the boiler load for the 20% test was lower due to the reduction of steam demand in the industrial process caused by the production of hot water for sanitization from the heat recovery of the refrigeration system. Despite this, the efficiency found was higher when compared to results found for the 10, 5 and 0% tests, showing the positive contribution of the presence of floated sludge to the eucalyptus woodchips.

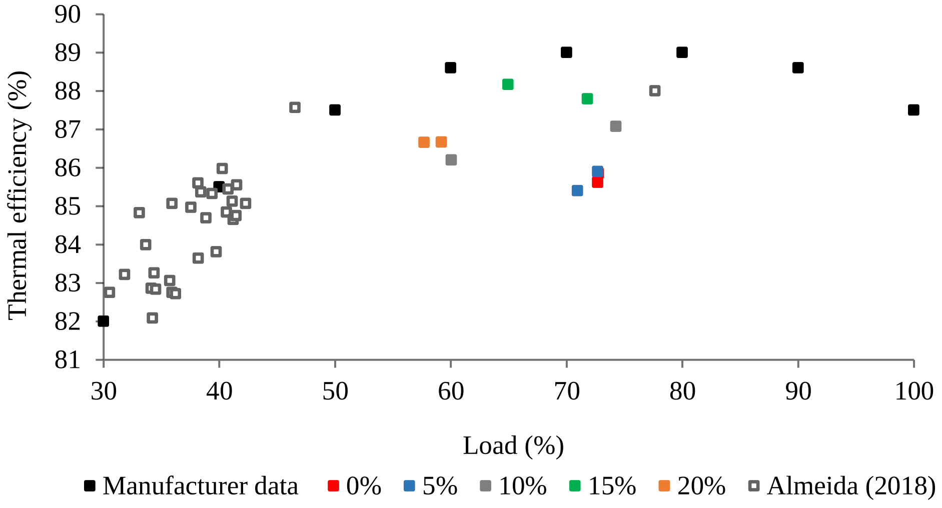

Figure 3. Steam generator thermal efficiency

For comparison level, Almeida (2018) employed the indirect method to evaluate the performance of the same equipment when new, still equipped with the economizer and air pre-heater, and operated exclusively with eucalyptus woodchips. In relation to the author's tests, it is observed that there was agreement with the efficiency curve suggested by the manufacturer for operation at partial loads.

7. CONCLUSIONS

Considering the obtained results, it is possible to infer that increasing the co-firing ratio of floated sludge mixed with eucalyptus woodchips contributes positively to increasing the efficiency of the steam generator unit, due to the low concentration of O_2 and CO in the combustion gases. Despite the slight reduction in efficiency in the percentage of 20%, given the reduced load and the difficulty of maintaining constant the sludge feeding, the efficiency of the steam generator was higher when compared to the tests of 10, 5 and 0%.

Thus, co-firing floated sludge with eucalyptus woodchips is an attractive option, since it reduces fuel consumption, increases the efficiency of the generating unit and promotes an appropriate destination of the waste within the industrial complex itself.

8. ACKNOWLEDGEMENTS

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10. RESPONSIBILITY NOTICE

The authors Fabiana de Marqui Mantovan, Joel Gustavo Teleken, Adriana Ferla de Oliveira, Eduardo Lucas, Korand Burin e Edson Bazzo are the only responsible for the printed material included in this paper.