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ANALYSIS OF A STEAM FACILITY IN A PULP AND PAPER INDUSTRY

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Abstract. In the current national scenario, the search for efficiency and reduction of cost and losses in the process are necessary and fundamental for the growth and maintenance of the companies. Pulp and papers companies are among the largest, most capital-intensive companies in the world with highly profitable investments. With this, the demand for a system without losses is indispensable for the development in this sector. Besides, this sector is a significant energy consumer, either from electrical or steam in the process. Therefore, this paper presents an analysis of the energy efficiency of a pulp and paper industry in Brazil. The principle of thermal balance applied to evaluate the production, detecting operational functioning deficiencies through the evaluation of energy parameters.

Keywords: pulp, paper, steam, boiler, thermal balance

1. INTRODUCTION

Over the years, Brazil developed as a producer of eucalyptus and currently stands out in the pulp and paper market. This segment has been growing with the world demand for market pulp. Brazil is the fourth largest producer of pulp, and the first producer of eucalyptus pulp, according to data from the Brazilian Association of pulp and paper (Bracelpa, 2011), with around 95% of the pulp production in Brazil (in 2011) comes from the Kraft chemical process. Pulp and paper industrial sector in Brazil has been growing substantially and reached a prominent position in the national economy. The facts responsible for this growing industry advance are the lower production costs and higher productivity of wood per hectare, derived from genetic improvement research (Potrich, 2014). Also, this sector has a great concern with the conversion of energy, and some practices for which this occurs is actively used, such as the use of co-generation power, mainly using gas and steam turbines; recovery boilers to recover the chemicals; recovery of humid air and among others (Barbeli, 2008). Bachmmann (2009) emphasizes that the industry always given importance to the energy consumption of the process due to their relevance as a cost component and recently come to be seen by environment aspect. With this, the current energy management has sought the lowest cost along with the use of inputs and technologies that cause the least social and environmental impacts.

Steam generation is the primary source for the whole process in this segment, and it can be practiced in various ways in manufacturing and process; in electrical energy generation; in obtaining mechanical energy (rotation and/or translation); heating of fuel oil lines and reservoirs; and the provision of services. For example, in the manufacturing and the processing, the steam is used in the cooking wood in the digesters, drying with rotating cylinders, drying of the clue, the fabrication of the corrugated paper, the generation of electrical energy through steam turbines.

The pulp and paper sector is a significant energy consumer, either from electrical ou steam in the process and used co-generation system in its industrial plants, mainly by the Kraft process (Filho *et al.*, 2009). Co-generation generally is composed of a biomass boiler (responsible for the chip burning, bark and wood waste) and a chemical recovery boiler, responsible for burning the black liquor (Gallego, 2005).

Pulp and papers companies are among the largest, most capital-intensive companies in the world with highly profitable investments. With this, the demand for a system without losses is indispensable for the development in this sector. Besides, because steam is critical to the entire process, used in various production steps and producers, its

generation must precisely be planned. Distribution form should also be studied and analyzed to obtain the most efficient way, because any pressure drop, temperature, flow, fundamentals factors for the process can interfere in the final product result.

The main objective of this paper is to analyze the energy efficiency of the boilers, through calculations of the boiler´s yield by using indirect methods. It allows to obtain the losses (quantitative values) as the basis of a conservation solution and energy management in the steam generation and distribution in a pulp and paper industry.

1.1 Literature review

The Kraft process, in Brazil, has as the primary raw material eucalyptus wood, but it can use other types. The wood undergoes several processes where the cellulose fibers contained therein are separated from one another and extracted as a paste at 90% dry content. On some types of paper, these folders undergo a bleaching process. In the various production stages (there is steam consumption as a source of thermal energy, and also steam systems, boilers, collectors, and steam turbines are used not only to generate steam but also to generate electricity and to recover chemicals (Mendes and D'angelo, 2007).

The recovery boiler has the function of incinerating the pollutant load of the black liquor to minimize environmental impact, generate thermal energy, co-generate electric energy, and recover the inorganic reagents (Almeida, 2006; Ribeiro *et al.*, 2007). Its use is widely adopted in heavy industries to reduce costs with fuel, such as steel mills, chemical plants, pulp mill, among others (Silva, 2014). This equipment is both a chemical reactor and a steam generator (Cunha, 2005). The concentrated black liquor composed of organic and inorganic materials is injected into the furnace through burner nozzles. Since the organic part burns and generates heat for the production of steam and the inorganic component is extracted as a melt. Besides, the primary purpose of the boiler is to complement the generation of steam for the production of cellulose and electricity from the plant. For this, it uses biomass as the main fuel, which is a mixture of wood waste that has been rejected for the production of pulp and sawmill waste suppliers (Cunha, 2005).

Because of the poor environmental and energy performance of most combustion processes, the use of new fuels to increase efficiency, reduce costs and reduce emission levels of pollutants has led to the development of new combustion technologies. In the industry, the most used arrangements are grids and fluidized bed systems. The grille system was the first to be used, and are the most suitable when it is intended to process fuels with high moisture content and ash. They can provide a more homogeneous fuel distribution and a correctly distributed primary air supply throughout the entire grate. These systems can be refrigerated in order to avoid slagging and increase equipment lifetime (Loo and Koppejan, 2008; Pinto, 2011).

2. METHODOLOGY

To identify the energy losses related to the current operation mode, this work seeks to propose a first solution for steam rationalization and to minimize energy waste. The development of this paper consisted of the following steps:
  A- Process identification: The steam generation and distribution system was identified raising the points to be studied. The focus for this paper was the recovery and force boiler.
  B- Data collection: In this stage, the temporal information was collected in the historical data storage system, searching for the most critical variables for the energy evaluation of the system.
  C- Energy Balance: The analysis of the efficiency of the boiler was carried out using the indirect method, and the losses of the systems were quantified.

2.1 Case study

The pulp and paper mill under study operates in four different steam levels: 6178.19, 4118.79, 1078.73 and 196.133 kPa. Each level of steam has its respective collector, which are pressure vessels with the function of storage and distribution. The steam is produced through two continuously operating boilers, one is the chemical recovery boiler, and the other is the generator boiler, to generate the required amount of steam for the plant.

The recovery boiler can burn 850 tons.day^{-1} of dry solids, generating 145 tons.h^{-1} of steam at 6178.19 kPa. It aims to: recover chemicals used in the paper making process, generating steam to feed Turbo Generators and other departments of the factory. Its fuel is black liquor with a percentage of 72% solids. The recovery boiler has three air intakes, and there are 28 air blowers to force the particles in the flue gases to withdraw at four opening points, in the superheater, in the convector chiller, and in the economizers. After the steam overheats, it is sent to a steam collector of 6178.19 kPa.

The generator boiler has a nominal steam generation capacity of 140 ton.h^{1}, and a pressure of 6178.19 kPa. It uses as biomass fuel, a solid material composed of wood bark and chips. This biomass is composed of wood tailings, such as chips and barks from the debarking and pruning process, and the purchase of third parties from this material. There are two air intakes, the primary air is responsible for fluidization of the bed and start of combustion, and secondary air, aims to complete the combustion. When leaving the superheaters, the steam goes to the collector of 6178.19 kPa.

The main uses of steam in the factory under study are:
• Steam of 6178.19 kPa: Turbo Generator (Production of Electric Power);
• Steam of 4118.79 kPa: Turbo Generator and Thermo-Compressors of the Paper Machine;
• Steam of 1078.73 kPa: Cooking of the cellulose, group of dryers of the Paper Machine and auxiliary operations;
• Steam of 196.133 kPa: Steam used in evaporation and concentration.

2.2 Data collection

The collect of the variables that encompass the production of steam in the industry under study was done through the 1 Distributed Control System, the DCS, which is composed of an integrated package of devices that are in fulfillment of this main functions, the control, and supervision of the productive process of the unit. An example screen of the use of SDCD is in Figure 1.
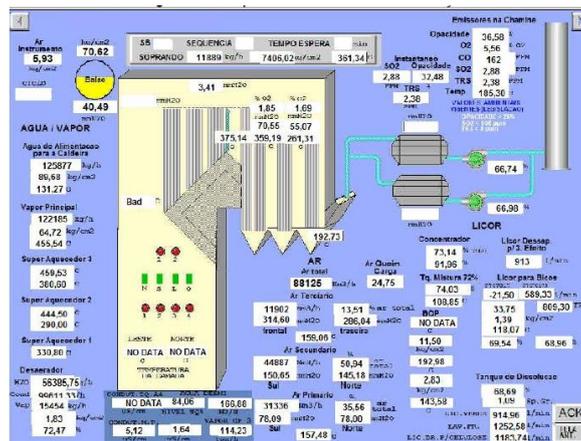

Figure 1. Example of a Generator boiler Screen

The entire process system consists of sensors and actuators of various types, remote units, and other components. They are connected to several graphical interfaces that is screened with figures, animations, icons, alarms indication that represent the entire line production of the stage, in other words, which equipment has control screens with all the information for proper operation. The Figure 2 shows the complete system screen of the black liquor.
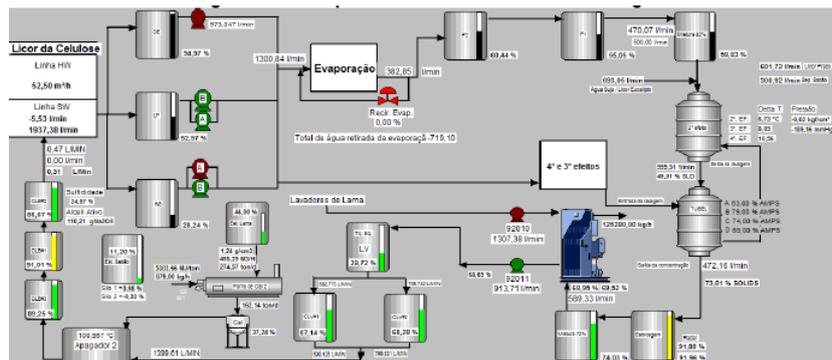

Figure 2. Example of a black liquor line screen

All equipments, sensors, actuators are calibrated by the department spceliazed in this subject, in a time determined by the company standard. All data is stored in a database for 5 years and is identified by a tag. The unit, description and the value of which data in the system are stored. With the help of the database, the general data collected from the recovery boiler are presented in the Table 1.

Table 1. Recovery boiler data.

Steam pressure (kPa)	6178.19
Steam temperature (ºC)	457.76
Steam flow (kg/s)	41.14
Flue flow (black liquor) (kg/s)	16.54
Fuel humidity (%)	31.7
Feed water flow (kg/s)	41.34
Feed water pressure (kPa)	9041.73
Feed water temperature (ºC)	132.84
Continuous Discharge Flow (Purge) (kg/s)	0.713
Total air flow (kg/s)	47.26
Exhaust gas temperature (ºC)	210.77
Smelt flow (kg/s)	7.3
Amount of ash generated per day (ton)	47.2

Black liquor has a high calorific value, with its PCI of 11966.24 kJ/kg, varying according to the percentage of chemical reagents, cellulose, hemicellulose, sodium and calcium salts and will be higher when the content of lignin and extractives are higher (Fortunatto, 2014). Black liquor combustion is described by the chemical composition of smelt in Table 2; as reference temperature, authors considered $T_\infty = 25$ºC and $T = 900$ºC at the smelt temperature.

Table 2. Chemical composition and percentage by mass of the compounds constituting the smelt (Zsargut, 2005)

Component	Mass flow (kg/s)	Molar mass (kg/mol)
Sodium carbonate (Na_2CO_3)	5.6222	105.989
Sodium Sulfide (Na_2S)	1.5742	78.044
Sodium sulfate (Na_2SO_4)	0.1049	142.041

Table 3. Chemical composition and percentage by mass of the compounds constituting smelt (Perry, 1999)

Component	Cp (kJ/kmolK)
Sodium carbonate (Na_2CO_3)	28.9
Sodium Sulfide (Na_2S)	72.4
Sodium sulfate (Na_2SO_4)	32.8

Ashes from recovery boiler have, on average, the composition indicated in Table 4.

Table 4. The composition of recovery boiler ash (average mass values) (Isenmann, 2016)

K_2SO_4	13%
Na_2CO_3	9%
Na_2Cl	17%
Na_2SO_4	9%

General data collected from the generator boiler, are presented in the Table 5. Company in study performed a biomass analysis and found a lower calorific (PCI) value of 8493.52 kJ/kg). Forest Biomass Waste ashes typycal composition are indicated in Table 6 (Vogel *et al*., 2003).

Table 5. Generator boiler data.

Steam pressure (kPa)	6178.19
Steam temperature (ºC)	455,28
Steam flow (kg/s)	20,18
Flue flow (Biomass) (kg/s)	9,17
Fuel humidity (%)	11
Feed water flow (kg/s)	41,84
Feed water pressure (kPa)	9129.99
Feed water temperature (ºC)	223,67
Continuous Discharge Flow (Purge) (kg/s)	0,585
Total air flow (kg/s)	48,65
Exhaust gas temperature (ºC)	138,63
Amount of ashes generated per day (ton)	61,63

Table 6. Generator boiler data (Vogel *et al*, 2003)

pH (H_2O)	12.3
Humidity lost at 75° C (%)	60.0
Organic carbon (g/kg)	135.1
Total nitrogen (g/kg)	3.93
Total phosphorus (g/kg)	3.50
Total potassium (g/kg)	17.48
Total calcium (g/kg)	64.08
Total magnesium (g/kg)	7.94
C/N ratio (organic C and total N)	34 / 1

2.3 Mathematical equations

To determine the gross output in kW of the boiler, this method uses the sum of the boiler losses. The total heat loss is by the amount of the heat transfer losses and the losses associated with the flows leaving the boiler, with the exception of the steam flow.

$$\Sigma \, (Losses) = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + Q_u \tag{1}$$

Where:
Q_1 – Losses through the chimney [kW];
Q_2 – Heat losses due to incomplete chemical combustion [kW];
Q_3 – Losses from unburned fuel [kW];
Q_4 – Losses by fuel humidity [kW];
Q_5 – Losses via the purge [kW];
Q_6 – Losses associated with ash temperature [kW];
Q_7 – Losses by radiation and convection [kW];
Q_u – Effective heat to generate steam [kW].

By considering mass conservation principle, everything that enters of air and fuel must leave, not mixing with the water of boiler feeding. Since specific heat of the combustion gases does not differ much from air specific heat, the equation for the losses through the chimney is (Strobel, 2015).

$$Q_1 = (m_{air} + m_c) \times cp_{air} (T_g - T_\infty) \tag{2}$$

Where:
m_{air}- mass flow of air [kg/s]
m_c- mass flow of fuel [kg/s]
cp_{air} – average specific air heat between T_g and T_∞ [kJ/kg ºC]
T_g- gas temperature [ºC]
T_∞ - reference temperature adopted [ºC]

For the calculation of the losses by unburned fuel, it is normal to adopt the analysis of the amount of carbon without burning in the ashes. Thus, the loss associated with the unconverted fuel present in the ashes can be estimate by:

$$Q_{2,1} = m_{carb} \; x \; PCI_{\;carb} \tag{3}$$

Where:
m_{carb} – mass flow rate of ash present in the ashes [kg / s]
PCI_{carb} - is the lower calorific value of carbon [33780 kJ/kg]
In the burning of black liquor, the smelt is generated, an inorganic melt, to calculate the loss of heat of it, it is used:

$$Q_{2,2} = m_{smelt} \; x \; cp_{smelt} \; (T_{smelt} - T_\infty) \tag{4}$$

Where,
m_{smelt} - mass flow of smelt [kg/s]
cp_{smelt} - specific smelt heat [kJ/kg°C]
T_{smelt} - smelt temperature [°C]
Theoretically, this loss should not happen because excess air must be provide to ensure complete combustion of the fuel, given by Eq. (5):

$$Q_3 = (m_{air} + m_c) \; x \; \rho_g \; x \; (126 \; CO + 108H_2 + 358CH_4) \tag{5}$$

Where:
CO, H_2 e CH_4 - volumetric percentage of dry gases in the chimney.
The values attached to each gas symbol represent the calorific value of each in kJ/m^3. All fuel has a percentage of humidity that vaporized and leaves the boiler in the form of superheated steam. Considering that its temperature is equal to that of the gases resulting from the combustion and its partial pressure as 10kPa (Lima, 2003), for the calculation of Losses due to the humidity of the fuel has,

$$Q_4 = m_u \; (h_v - ha') \tag{6}$$

Where,
m_u – mass flow of fuel humidity [kg/s]
h_v - enthalpy of superheated steam [kg/kJ]
ha' - enthalpy of the saturated liquid at the air inlet temperature [kJ/kg]
The losses via purge is related with the loss of energy caused by the flow of water withdrawn in the purge, carried out to maintain the concentration of salts in the water of the boiler at tolerable levels, given by the following equation:

$$Q_5 = m_p \; x \; cp_{water} \; x \; (T_p + T_\infty) \tag{7}$$

Where,
m_p - mean purge water flow [kg/s]
$cp_{water} = Water$ specific heat, at liquid state [kJ/kg°C];
T_p - water saturation temperature at boiler [°C].
When burning the fuel, the ash output entails losses that must be calculated for each specific case. We can calculate this value by Eq. (8), where, $\dot{m}_R$ - mass flow rate of ash [kg / s] and the h is 1170 – the approximate mean value of the sensitive enthalpy of the ashes [kJ / kg].

$$Q_6 = m_R \; x \; h \tag{8}$$

Determination of the losses by radiation and convection by the side of the boilers is very complicated due to the necessary measurements (Eletrobrás, 2005). Therefore, for these losses is adopted a variation between 1% and 4% of the energy supplied. The value of the energy supplied can be considered as being equal to the lower calorific value of the fuel. To calculate the useful heat to generate steam, the heat of exit considered, in other words, the difference of enthalpy between the water and the vapor, at the same temperature. The heat consumed by the water for conversion to steam is calculated by,

$$Q_u = m_v \; x \; (h_v - ha') \tag{9}$$

Where,
m_v – mass flow of steam [kg/s]
With the determination of the losses that can occur, the efficiency of a boiler by the indirect method is given by Eq. (10), while Eq. (11) provides the optimum fuel consumption:

$$\eta_{MI} = 1 - \Sigma\ (Losses) / q_d \tag{10}$$

$$Comb = Q_u / PCI \tag{11}$$

Combustion requires an amount of stoichiometric air, known as theoretical air. But for it to occur an excessive amount of air completely is needed to maintain a sufficient oxygen content until the end of the flame, Table 1 represents the typical values of the coefficient of excess air, concerning the type of fuel burned (Pinheiro and Valle, 1995). The coefficient of excess air (α) is the ratio between the total amount of air used in the combustion (V_{air}) and the amount of stoichiometric air (V^o_{air}).

$$\alpha = V_{air}/V^o_{air} \tag{12}$$

In another way of expressing the air / fuel ratio, the value of the excess air coefficient can be calculated from the analysis of the volumetric composition of the combustion products:

$$\alpha = 20,9 / [20,9 – (\%O_2 - \%CO/2)] \tag{13}$$

It is a determinant of combustion efficiency because it controls the volume, temperature, and enthalpy of the combustion products. Therefore, a large excess of air is undesirable because it lowers the flame temperature and increases heat loss due to the enthalpy of the effluent gases, thus reducing the thermal efficiency of the boiler and decreasing the flame length. But if the excess air is low, it can result in incomplete combustion and the formation of CO, soot and smoke, and also allow the accumulation of unburned fuel, which can cause a risk of explosion. In the Table 7, show the common values of excess air coefficient in the literature.

Table 7. Common values of excess air coefficient. (Considine, 1977)

Fuel	α - air coefficient
Natural Gas	1.05 – 1.10
Blast furnace gas	1.15 – 1.18
Wood Biomass	1.20 – 1.35
Bagasse	1.25 – 1.35
Black Liquor	1.05 – 1.07

3. RESULTS

From the knowledge presented in previous chapters, the results of the results were found. The tables 8 and 9 gives the result of the application of the equation using the collected parameters, evidencing the energy losses throughout the process.

Table 8. Losses in the chemical recovery boiler.

Losses	kW	Equation
Losses through the chimney	11765.56	2
Heat losses due to incomplete chemical combustion	3.101	4
Losses from unburned fuel	2634.3	5
Losses by fuel humidity	2301.77	6
Losses via the purge	180.27	7
Losses associated with ash temperature	643.5	8
Losses by radiation and	478.65	4%PCI
Effective heat to generate steam	80173.81	9

Applying the values in Tab. 1 in the Eq.10, the efficiency calculation through the indirect method for the chemical recovery boiler is: η_{MI}=0.5215 and η_{MI}=52.15%.

Optimum fuel consumption, which is, the necessity to have no loss concerning its consumption is 6.7 kg/s. Therefore, the company uses 10 kg/s of more fuel than it needs, showing a waste of power, and resource.

Table 9. Losses in the generator boiler.

Losses	kW	Equation
Losses through the chimney	6466.30	2
Heat losses due to incomplete chemical combustion	12.012	3
Losses from unburned fuel	3240.21	5
Losses by fuel humidity	1988.82	6
Losses via the purge	146.6	7
Losses associated with ash temperature	830	8
Losses by radiation and	3115.42	4%PCI
Effective heat to generate steam	39155.13	9

Applying the values in Tab. 2 in the Eq.10, the efficiency calculation through the indirect method for the generator boiler is: $\eta_{MI}=0,.6330$ and $\eta_{MI}=63,.30\%$. And the optimum fuel consumption is, 4.61 kg/s. Therefore, the company uses 5 kg/s of more fuel than it needs, showing a waste of power, and resource.

The most significant loss of boilers is concerns the temperature of the exhaust of the chimney; it is worth remembering that there are laws that monitor the temperature and the flow of these gases. This loss can be related to the excess of air that the company uses.

Tables 9 represent the values of excess air of 15 days in August/2016, which were found in the application of Eq. 13.

Table 9. Coefficient of excess air

Days	α – Recovery boiler	α – Generator boiler
August/01	1.28	2.05
August/02	1.36	2.11
August/03	1.24	2.08
August/04	1.51	2.13
August/05	1.21	2.11
August/06	1.23	3.06
August/07	1.24	2.03
August/08	1.25	2.08
August/09	1.25	2.06
August/10	1.26	2.10
August/11	1.26	2.11
August/12	1.26	2.05
August/13	1.45	2.07
August/14	1.25	2.04

By analyzing the theoretical value of surplus air with the calculated value, it is noticed that the excess air value in the two boilers is well above the usual value that the literature suggests, that is, evidencing a waste of energy in the air intake. In the case of fuel combustion, the combustion rate (air/fuel ratio) cannot be achieved by controlling the fuel flow because the energy generated by the boiler depends on the amount of fuel introduced. Thus, the only variable that can be regulated is the flow of combustion air. Besides, to optimize excess air, a more precise combustion control is required, which can be performed by analyzing O_2 and CO in the combustion products at the furnace outlet. Controlling the excess air based on CO measurement has an advantage because its formation is due to insufficient local air to complete combustion; if combustion is complete, CO level tends to zero (Pinheiro and Valle, 1995).

4. CONCLUSIONS

With rising energy prices, rational consumption is essential for the strategy for pulp and paper mills, as the availability of steam directly reflects the development of the company. With this, studies and energy assessments make it possible to optimize the entire steam generation and distribution system, and with that, the sustainability of the installation and the reduction of production costs are improved.

Some critical areas of improvement and possible actions to reduce energy waste in its generation: Control the temperature of the flue gases, balancing with environmental standards; Minimize excess air in the combustion, using what is necessary to aid the combustion; Improve water treatment to minimize boiler discharges, and to avoid fouling of pipes and damaging heat exchanges; Remove as much moisture as possible from the biomass used for combustion, improving the black liquor evaporation system and biomass storage.

Typically, the most significant losses associated with boiler operation are in the energy lost in the flue gas exhaust, and is directly related to the temperature of those flue gases and the amount of excess air supplied to the combustion process. Excess air influences both the thermal efficiency and the pollutant emission level of the furnaces. Its control allows optimizing the thermal efficiency of the boilers, ensuring at the same time a reduction of the emission level of pollutants and the fulfillment of the environmental norms.

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