

ENERGETIC EFFICIENCY MAXIMIZATION OF A STEAM SYSTEM FUELED BY SUGAR CANE BAGASSE

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Abstract. *The objective of this paper is to maximize the energetic efficiency of a cogeneration plant fueled by sugar cane bagasse, considering the fuel moisture reduction. The studied system consists of a boiler, a cross flow air heater and a dryer. The boiler exhaust gases are used to preheat the air and to dry the bagasse. Two types of air heater - dryer arrangement were studied: the first consists of a sequence arrangement and the second of a parallel arrangement. The energetic efficiencies in the first case were determined throughout the temperature variation of the air preheater exit gases and in the second, by the variation of the flow gases division between the air preheater and the dryer.*

Keywords. *biomass; sugar cane bagasse; sugar cane plant; cogeneration; air preheater; boiler; dryer.*

1. Introduction

The world-wide energetic matrix is based on the energy production by fossil fuels, mainly coal and oil. Looking forward when the reserves of these fuels will be depleted, new energy sources are being researched, as wind power, solar power and biomass energy; the last one is the target of this paper, specifically sugar cane bagasse.

São Paulo State has approximately 100 alcohol and sugar mills. These plants use boilers to burn the process residue (cane bagasse), generating electric energy for themselves. Beyond the obvious saving in electricity, the bagasse burning avoid store and removal costs, even avoiding an ecological scandal, if it was thrown away in land, for instance.

However, the plants power needs are, nowadays, completely supplied. Because of this, there are few works about fuel use optimization. Until few years ago, the exceeding energy sailing to the State Energy Companies (Eletropaulo, CPFL and CESP) wasn't economically viable. But this situation changed: the 2000 Brazilian energetic crisis and the previous research and development necessity of renewable energy sources created conditions to optimize these plants.

Based on those premisses, this paper is intended to aid in the project of a sugar cane bagasse dryer using the exhaust boiler gases as drying agent. For this aim, the energy balance in the dryer and in the preheater were systematized using the software EES[®], seeking the best way to use the combustion gases energy. The set and boiler efficiencies are bigger with the boiler inlet air temperature increase, as well as the bagasse moisture diminishing.

2. Analysed systems

Two arrangements were proposed: the first in sequence, which the combustion gases passing through the preheater and then the dryer, and the second in parallel, in which the gas flow is split into the dryer and the preheater. These processes are shown in Fig.1 and Fig. 2.

This paper was carried out with some data collected on "Cruz Alta" Plant, which belongs to "Açúcar Guarani" Company, Olímpia, São Paulo State. These data, collected from other members of the staff, were reported in Sánchez Prieto et al. (2001) and Sánchez Prieto and Nebra (2001).

3. Bagasse composition

Bagasse composition is a function of the following factors: cane characteristics, soil type, season, harvest type, extraction method. Baloh and Wittner (1995) compiled bagasse analysis of different authors. They assumed an average composition, which has 47% of carbon, 6,5 % of hydrogen, 44 % of oxygen and 2,5% of ashes (not considered in the formulation, because they do not react). The previous percentages are based on 1 kg of dry mass. The bagasse lower heat value (LHV) can be determined by the correlation below (Eq. 1), proposed by Hugot (1964):

$$\text{LHV} = 17,790 - 50,23 s - 203 w, \text{ kJ/kg} \quad (1)$$

Where:

s=dissolved solids [%]

w=moisture in wet basis [%]

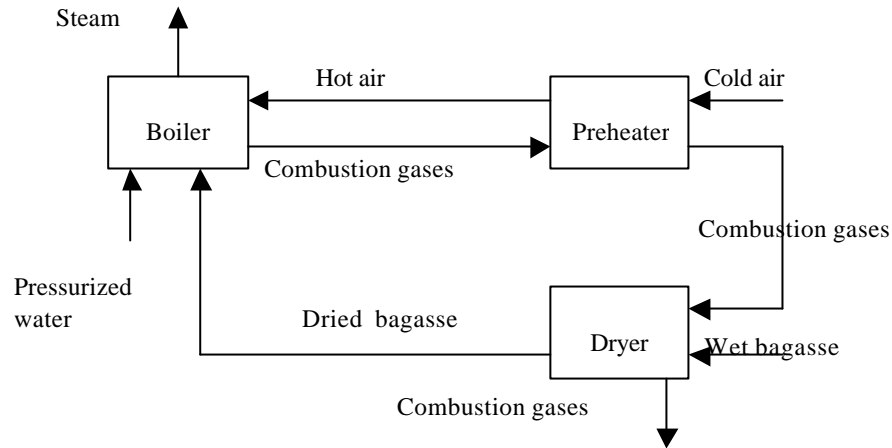


Figure 1: Sequence arrangement flowchart

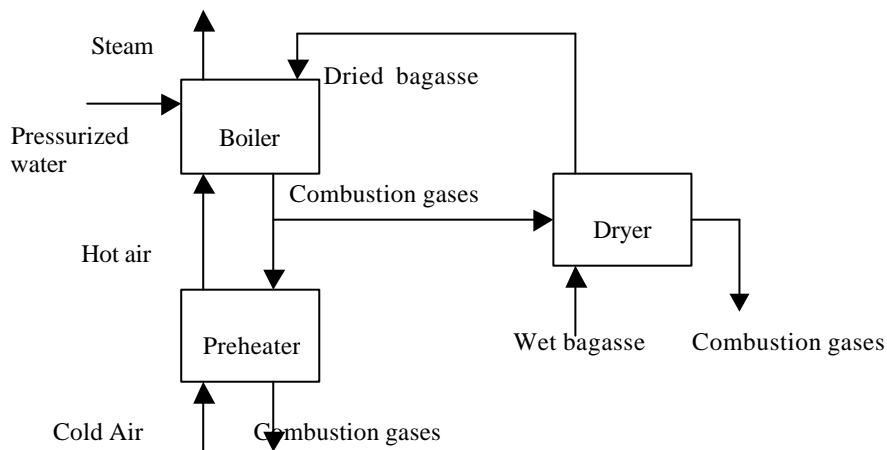
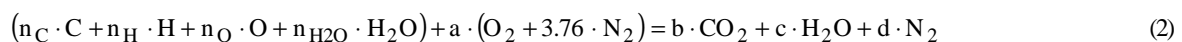


Figure 2: Paralell arrangement flowchart

4. Bagasse combustion

With the objective of performing the heat balance in the boiler, the combustion was assumed with air in excess, and without generation of CO and NO_x, as well as other products as result of incomplete combustion. The generated substances were determined by the combustion equation. Ideal gas conditions were considered. Air composition was 21 % of oxygen and 79 % of nitrogen. One kilogram of dry mass of fuel was taken as a base. The balance equation for an stoichiometric combustion is showed in Eq.2.



Where:

n_C, n_H, n_O= dry mass of fuel flow, kmol/s

n_{H2O}= flow of humidity contained in the fuel, kmol/s

a= theoretical air flow, kmol/s

b, c, d= theoretical combustion products flow, kmol/s

Equation (3) correspond to combustion equation with air in excess. It was necessary to measure the CO₂ dry gases concentration in the products to determine the excess air coefficient λ , which was 15% in volume, and some concepts as air-fuel ratio and excess air coefficient definition, that are shown below:

$$(n_C \cdot C + n_H \cdot H + n_O \cdot O + n_{H_2O} \cdot H_2O) + e \cdot (O_2 + 3.76 \cdot N_2) = f \cdot CO_2 + g \cdot H_2O + h \cdot O_2 + i \cdot N_2 \quad (3)$$

$$AF_{molar, theo} = \frac{a \cdot (4.76)}{n_{fuel}} \quad (4)$$

$$\lambda = \frac{AF_{molar, exc}}{AF_{molar, theo}} \quad (5)$$

$$AF_{molar, exc} = \frac{e \cdot (4.76)}{n_{fuel}} \quad (6)$$

Where:

e= air flow, kmol/s

f, g, h, i= combustion products flow, kmol/s

AF_{molar,theo}=theoretical air-fuel ratio, kmol_{air}/kmol_{fuel}

n_{fuel}=flow of humid mass of fuel, kmol/s

AF_{molar,exc}= air-fuel ratio, kmol_{air}/kmol_{fuel}

5. Adiabatic-saturation temperature calculation

In order of calculating the adiabatic saturation temperature of the combustion gases, an ideal process of saturation was assumed, as it is showed in the equations below. In Eq. (7), where the gases humidity is calculated, the coefficients are the same than in Eq. (3).

$$w1_{db} = \frac{g}{f + h + i}, \text{ dry basis} \quad (7)$$

Based on an ideal saturation process, the gases exit humidity is calculated by E. (8):

$$w2_{db} = \frac{M_{H_2O}}{M_{exit}} \left(\frac{p_{v_2}}{p_{atm} - p_{v_2}} \right), \text{ dry basis} \quad (8)$$

Where:

M_{H₂O}= water molarmass, kg/kmol

M_{saída}= dry gases molarmass, kg/kmol

p_{v₂}= saturated vapor pressure at the adiabatic-saturation temperature, kPa

p_{atm}= atmospheric pressure, kPa

The energy balance was calculated, using the relations above, Eq. (9)

$$(had1 - had3) + w1_{db} \cdot (had1_{H_2O} - had2_{H_2O}) = w2_{db} \cdot (had3_{H_2O} - had2_{H_2O}) \quad (9)$$

Where:

had1= dry gases specific entalphy at the saturation process inlet, kJ/kg_{bagasse}

had3= dry gases specific entalphy at the saturation process exit, kJ/kg_{bagasse}

had_{1H₂O}= water specific entalphy at the saturation process inlet, kJ/kg_{bagasse}

had_{2H₂O}= liquid water added to the gases, specific enthalpy, kJ/kg_{bagasse}

had_{1H₂O}= water specific entalphy at the saturation process exit, kJ/kg_{bagasse}

6. Sequence arrangement

The sequence arrangement modeling is discussed in this section. It was divided in the air preheater and the dryer, as follows.

6.1. Air preheater

The inlet cold air temperature was adopted as the average environment temperature, $T_{envr} = 25$ °C. The boiler exit gases temperature was measured in $T_{exit} = 259$ °C in Cruz Alta Plant. The preheater gases exit temperature was varied between $T_{exit,ph} = 120$ °C and $T_{exit,ph} = 200$ °C, and the boiler inlet air temperature T_{inlet} is the variable which was determined in the preheater energy balance bellow:

$$(m_g \cdot h_{g,phi}) + (m_{O2,air} \cdot h_{O2,env} + m_{N2,air} \cdot h_{N2,env}) = (m_g \cdot h_{g,phe}) + (m_{O2,air} \cdot h_{O2,hot} + m_{N2,air} \cdot h_{N2,hot}) \quad (10)$$

Where:

m_g = gases flow, kg/s

$m_{O2,air}$, $m_{N2,air}$ = inlet and exit preheater air flow, kg/s

$h_{g,phi}$ = preheater inlet gases specific entalphy, kJ/kg_{bagasse}

$h_{g,phe}$ = preheater exit gases specific entalphy, kJ/kg_{bagasse}

$h_{O2,env}$, $h_{N2,env}$ = preheater inlet air specific entalphy, kJ/kg_{bagasse}

$h_{O2,hot}$, $h_{N2,hot}$ = preheater exit air specific entalphy, kJ/kg_{bagasse}

6.2. Dryer

It was assumed the combustion gases withdraw moisture from the bagasse up to theoretical limit, therefore the exit gases will reach the adiabatic-saturation temperature. In this arrangement, the dryer receives the gases from the preheater at $T_{exit,ph}$ and the bagasse with 50% moisture (wet basis) at T_{env} . Also was assumed that the bagasse reaches the adiabatic-saturation temperature, and that the non-evaporated water in the bagasse reaches the liquid saturation temperature. The dryer energy balance is shown bellow:

$$m_g \cdot (h_{phe} - h_{ad}) = m_{dbg} \cdot (w_{inlet,db} - w_{exit,db}) \cdot (h_{H2O,vap} - h_{H2O,env}) + m_{dbg} \cdot cp_{dbg} \cdot (T_{sat} - T_{env}) + m_{dbg} \cdot w_{exit,db} \cdot (h_{H2O,liq} - h_{H2O,env}) \quad (11)$$

Where:

m_{dbg} = dry bagasse flow, kg/s

h_{ad} = gases specific entalphy at T_{sat} , kJ/kg_{bagasse}

$h_{H2O,vap}$ = water specific entalphy at vapor saturation, kJ/kg_{bagasse}

$h_{H2O,env}$ = water specific entalphy at T_{env} , kJ/kg_{bagasse}

$h_{H2O,liq}$ = water specific entalphy at liquid saturation, kJ/kg_{bagasse}

$w_{inlet,db}$ = inlet bagasse humidity, dry basis

$w_{exit,db}$ = exit bagasse humidity, dry basis

cp_{dbg} = dry bagasse specific heat, kJ/kg.K

7. Paralell arrangement – Preheater and dryer

All the assumptions referred to the preheater and the dryer in sequence arrangement are still valid to parallel arrangement, except that $T_{exit,ph}$ is fixed, and a new variable named x varies the flow splitting among the preheater and the dryer. The dryer receives now the exit gases at T_{exit} . The energy balances to the preheater and the dryer are defined bellow:

$$(1-x) \cdot (m_g \cdot h_{g,phi}) + (m_{O2,air} \cdot h_{O2,env} + m_{N2,air} \cdot h_{N2,env}) = (1-x) \cdot (m_g \cdot h_{g,phe}) + (m_{O2,air} \cdot h_{O2,hot} + m_{N2,air} \cdot h_{N2,hot}) \quad (12)$$

$$x \cdot m_g \cdot (h_{phe} - h_{ad}) = m_{dbg} \cdot (w_{inlet} - w_{exit}) \cdot (h_{H2O,vap} - h_{H2O,env}) + m_{dbg} \cdot cp_{dbg} \cdot (T_{sat} - T_{env}) + m_{dbg} \cdot w_{exit} \cdot (h_{H2O,liq} - h_{H2O,env}) \quad (13)$$

8. Boiler efficiency

The boiler efficiency was determined by an indirect method, following ASME Code (American Society of Mechanical Engineering, 1975), because the Cruz Alta Plant does not have an equipment to measure the fuel flow. In this paper the method proposed by Beatón and Lora (1991) was used to determine the efficiency. This methodology, based on the heat losses, was used also by Sánchez Pietro et al. (2001). The following equations (14 and 15) define the fuel physical heat and the fuel available heat:

$$q_{ph} = cp \cdot T_{sat}, \text{ kJ/kg} \quad (14)$$

$$q_a = LHV + q_{ph}, \text{ kJ/kg} \quad (15)$$

Where:

cp= wet bagasse specific heat, kJ/kg.K

The boiler efficiency was determined from the sum of all heat loss fractions (Eq. 16), which will be discussed in the next sub-items.

$$\eta_{boiler} = 100 - (q_2 + q_3 + q_4 + q_5 + q_6), \% \quad (16)$$

8.1. Exit gases losses (q_2)

The heat losses by the exit gases enthalpy occurs when combustion production temperature is bigger than T_{env} . Among all heat loss fractions, this is the most significant. The next equation (17) allows calculating it:

$$q_2 = \frac{(m_g \cdot h_g - m_{air} \cdot h_{air})}{q_a} \cdot (100 - q_4), \% \quad (17)$$

Where:

h_g = exit gases specific enthalpy, kJ/kg_{bagasse}

m_{air} = air flow at T_{env} , kg/s

h_{air} = air specific enthalpy at T_{env} , kJ/kg_{bagasse}

q_4 = incomplete mechanical combustion losses, %

8.2. Incomplete chemical combustion losses (q_3)

These losses are related to CO, H₂ and CH₄ formation, as well as other products resulting of an incomplete combustion. Those elements were previously neglected, thus this loss was done equal to zero.

8.3. Incomplete mechanical combustion losses (q_4)

q_4 is a fraction referred to unburned fuel particles, that go out mixed with the ashes, or are carried by the exit gases. It is calculated by the following equation:

$$q_4 = \left(a_g \cdot \frac{C_g}{100 - C_g} + a_{pa} \cdot \frac{C_{ph}}{100 - C_{ph}} + a_1 \cdot \frac{C_1}{100 - C_1} \right) \cdot \frac{327.9 \cdot m_{ashes}}{q_a}, \% \quad (18)$$

Where:

a_g = fuel ash fraction, in the grate, %

C_g = fixed carbon content in the grate ashes, %

a_{ph} = fuel ash fraction in the preheater residues, %

C_{ph} = fixed carbon content in the preheater residues, %

a_1 = fuel ashes fraction in the ashes carried by the exhaust gases, %

C_1 = fixed carbon content in the ashes carried by the exhaust gases, %

m_{ashes} = ashes flow, kg/s

8.4. Environment heat losses (q_5)

The correct way to calculate these losses would be equating all the heat exchanged by convection and radiation from boiler walls to the environment, but, in practice, this work is almost impossible, thus a solution for the q_5 calculation is to use the ASME PTC 4.1 (1975) graphic, which is based on an average boiler wall temperature, measured by the staff.

8.5. Heat losses by slags and ashes (q_6)

The last lost fraction refers to the sensible heat lost by slag and ashes. According to Beatón and Lora (1991), this fraction is responsible for less than 0,1 % of the available heat, therefore can be neglected.

9. Net efficiency

Evaluating the boiler efficiency by the indirect method, the fuel flow can be calculated using a direct method:

$$\eta_{\text{boiler}} = \frac{m_{\text{H}_2\text{O,boiler}} \cdot (h_{\text{vap}} - h_{\text{liq}})}{m_{\text{bag}} \cdot \text{LHV}} \cdot 100, \% \quad (19)$$

Where:

$m_{\text{H}_2\text{O,boiler}}$ = boiler water flow, kg/s

h_{vap} = vapor specific enthalpy, kJ/kg

h_{liq} = water inlet specific enthalpy, kJ/kg

m_{bag} = fuel flow, kg/s

With the fuel flow in hands, the net efficiency was evaluated as:

$$\eta_{\text{net}} = \frac{m_{\text{H}_2\text{O,boiler}} \cdot (h_{\text{vap}} - h_{\text{liq}})}{m_{\text{bag,net}} \cdot \text{LHV}_{\text{bag,net}}} \cdot 100, \% \quad (20)$$

Where:

$m_{\text{bag,net}}$ = fuel flow with 50 % of moisture (wet basis), kg/s

$\text{LHV}_{\text{bag,net}}$ = low heat value of the fuel with 50 % of moisture (wet basis), kJ/kg

10. Results

The results obtained are reported in the tables and graphics below, Tab. 1 and Fig. 3 for the sequence arrangement, Tab. 2 and Fig. 4 for the parallel arrangement.

Table 1: Data on the sequence arrangement

Simulation	$T_{\text{exit,ph}}$	η_{net}	η_{boiler}	$w_{\text{exit,db}}$	T_{inlet}
1	120	84.51	83.26	0.9065	149.4
2	125	84.83	83.16	0.8840	144.9
3	130	85.05	83.06	0.8616	140.4
4	135	85.27	82.97	0.8394	135.9
5	140	85.50	82.88	0.8173	131.4
6	145	85.73	82.80	0.7953	126.9
7	150	85.95	82.71	0.7736	122.4
8	155	86.18	82.64	0.7519	118.0
9	160	86.41	82.56	0.7304	113.5
10	165	86.65	82.49	0.7090	109.0
11	170	86.88	82.43	0.6877	104.6
12	175	87.12	82.37	0.6666	100.1
13	180	87.35	82.31	0.6457	95.69
14	185	87.59	82.25	0.6248	91.24
15	190	87.83	82.20	0.6041	86.79
16	195	88.07	82.16	0.5835	82.35
17	200	88.32	82.11	0.5630	77.9

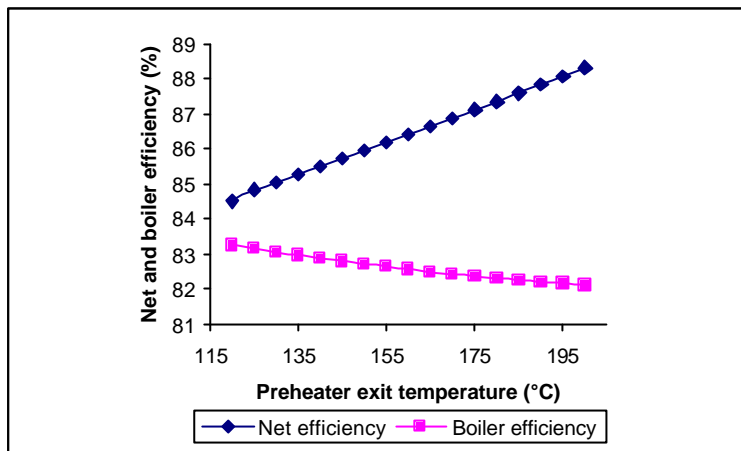


Figure 3: Net and boiler efficiencies as function of preheater exit temperature

Table 2: Data on the parallel arrangement

Simulation	x	η_{net}	η_{boiler}	$W_{exit,db}$	T_{inlet}
1	0.1	78.72	79.41	1.00	113.7
2	0.2	80.07	79.55	0.9626	103.5
3	0.3	81.42	79.73	0.8772	93.43
4	0.4	82.78	79.93	0.7938	83.5
5	0.5	84.16	80.17	0.7123	73.66
6	0.6	85.54	80.43	0.6326	63.9
7	0.7	86.94	80.72	0.5547	54.18
8	0.8	88.35	81.04	0.4784	44.47
9	0.9	89.78	81.38	0.4038	34.76

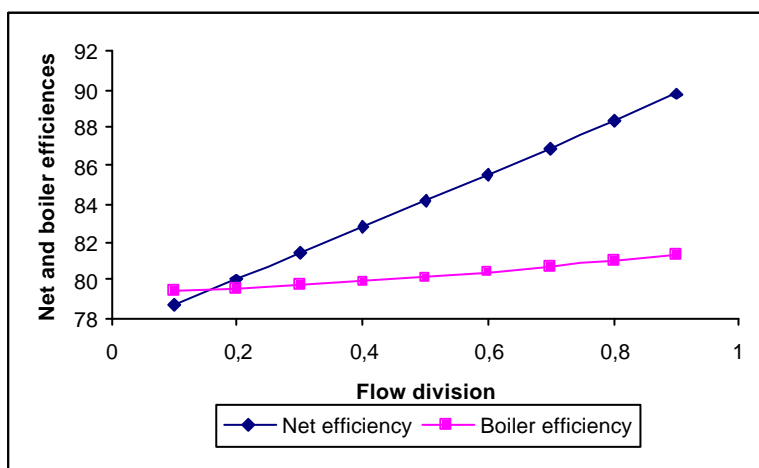


Figure 4: Net and boiler efficiencies as function of flow division

11. Data analysis and conclusions

Data of the modeling strongly indicate that the best option to improve the efficiency of the steam generation unit is the combination of the preheater and the dryer. The best efficiency (89.78%) was found in a parallel arrangement, with the gases flow mainly directioned to the dryer ($x=0.9$). This high value shows that it is possible to eliminate the preheater, substituted by the dryer. Although, it must be said that the lowest exit temperature admitted in the preheater, which was 120 °C, must be penalized the energy performance of this equipment.

Otherwise, a viable option of the sequence arrangement was also shown, with a high preheater exit temperature ($\eta_{net}=88.32\%$). From other point of view, it must be considered that the sequence arrangement, with a high preheater exit temperature must result in a preheater with less exchange area, consequently a cheaper equipment.

Relative to the dryer project, it must be said that the dryer was modeled in an ideal condition: the exit gases were saturated. Cruz Alta Plant, from which were taken all simulated boiler parameters, has pneumatic bagasse dryers installed in parallel with preheaters, and the gases exit temperatures measured in these dryers were in a low value, closer to saturation (Prieto et al., 2001), this fact permits us to affirm that it is possible to project and construct bagasse dryers which work closer to that condition. Considering the most important project conditions: first, the boiler exhaust gases are the only available energy source, and second, the own fuel boiler, is that must be dried; the lowest moisture that can be reached in the bagasse is 28% (wet basis), for the boiler working conditions presented here.

As suggestions for future papers, would be indicated a research on boiler exit gases temperature influence on net efficiency. In this particular case a high temperature may not be damaged, considering that the gases enthalpy is useful later on. Another suggestion would be a complementary study with a Second Law Thermodynamic analysis.

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