STUDY OF OPERATION PARAMETERS OF POWER GENERATION SYSTEMS ON SUGAR CANE MILLS

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Abstract. *The aim of this paper is to analyze the operation parameters of the power generation systems on the sugar cane mills. Therefore, two scenarios have been considered: The use of back-pressure turbines and the use of extraction and condensation turbines. The following parameters were studied: the moisture of the sugar cane bagasse and the pressure and temperature of the steam generation system. The steam generation subsystem (housed in the cogeneration plant) is made up of the boiler, the air preheater and the sugar cane bagasse dryer (in this order). For this arrangement, the gases from the boiler pass through the pre-air first and then through the dryer.*

Keywords*: sugar cane bagasse, cogeneration, dryer, boiler, exergy.*

1. Introduction

Industrialization and population growth have led to a sharp increase in power demand. Thus jeopardizing the economic and social growth of many countries. In fact in sugar cane producing countries, the cogeneration of energy in sugar cane mills is becoming an excellent alternative solution to this problem (Therdyothin et al. 1992; Sharma 1999; Ibarra and Medellín 2004).

Nowadays, most sugar cane mills use sugar cane bagasse as the only fuel. Since these mills produce more power than they need, they are not only producing sugar and alcohol but also selling electrical energy. Hence, it is important to study the parameters that affect the efficiency of the power generation system.

Different kinds of dryers have been installed with the intention of improving the efficiency of the steam generation system (Arrascaeta and Friedman, 1987; Sosa-Arnao et al. 2004). Many studies have highlighted the effects of bagasse moisture content reduction on boilers (Paiva Souza, et al. 1998; Marquezi and Nebra 2003). However, nothing has been reported on the effects of bagasse moisture on the power cogeneration system as a whole.

On the other hand, there has been a lot of research into the effects of the boiler temperature and pressure on the power cogeneration system (Upadhiaya, 1992; Sharma, 1999; Sánchez Prieto, 2003). Currently, there are boilers operating at maximum parameters of 62 bar and 470 ºC (in Brazil). In this paper, besides the market parameters, higher parameters were considered.

The aim of this paper is to analyze the effects of sugar cane bagasse moisture and the effect of the boiler temperature and pressure on sugar cane mill power cogeneration systems

As a result, two set-ups have been considered: the first one uses a back-pressure turbine and the second one uses an extraction and condensation turbine.

2. Analyzed Systems

Two scenarios were considered: the first one uses a Back-pressure Turbine [Fig. 1] and the second one uses an Extraction and Condensation Turbine [Fig. 2].

The cogeneration system is made up of the following subsystems: steam generation, electrical energy generation and mechanical energy generation (which includes the mechanical movers involved in the process of extraction, preparation, exhausting gas and water pumping.

For both set-ups the steam generation system presented a sequential arrangement. The Table 1 presents the thermodynamic state of the steam as well as its consumption in different stages of the process.

This paper was accomplished using data that was reported by Sánchez Prieto et al. 2001; and that belongs to Cruz Alta industry. This company is located in Olimpia, São Paulo state. Its processing capacity in 2003 was 10000 ton of sugar cane per day.

Table 1: Cogeneration System Data.

Description	Flux (kg/s)	Inlet Pressure (MPa)	Inlet Temperature (^oC)	Outlet Pressure (MPa)	Outlet Temperature (^oC)
Steam – blower turbine – B2	1.361	1.994	287	0.228	182
Steam – blower turbine – B3	1.639	2.023	289	0.228	181
Steam – pump turbine	1.583	2.014	295	0.2386	180
Steam - preparing system	13.89	2.112	302	0.219	168
Steam milling	7.5	2.112	300	0.221	169
Steam valve I	4.167	2.063	300	1.337	200
Steam valve II	6.527	2.063	299	0.219	195
Steam electric generation	25.83	2.033	300	0.2141	130
Steam - preparing system	13.89	0.219	168	0,219	168
Steam - milling1	3.75	2.014	293	0.2288	173
Steam - milling 2	3.75	2.023	294	0.2288	177

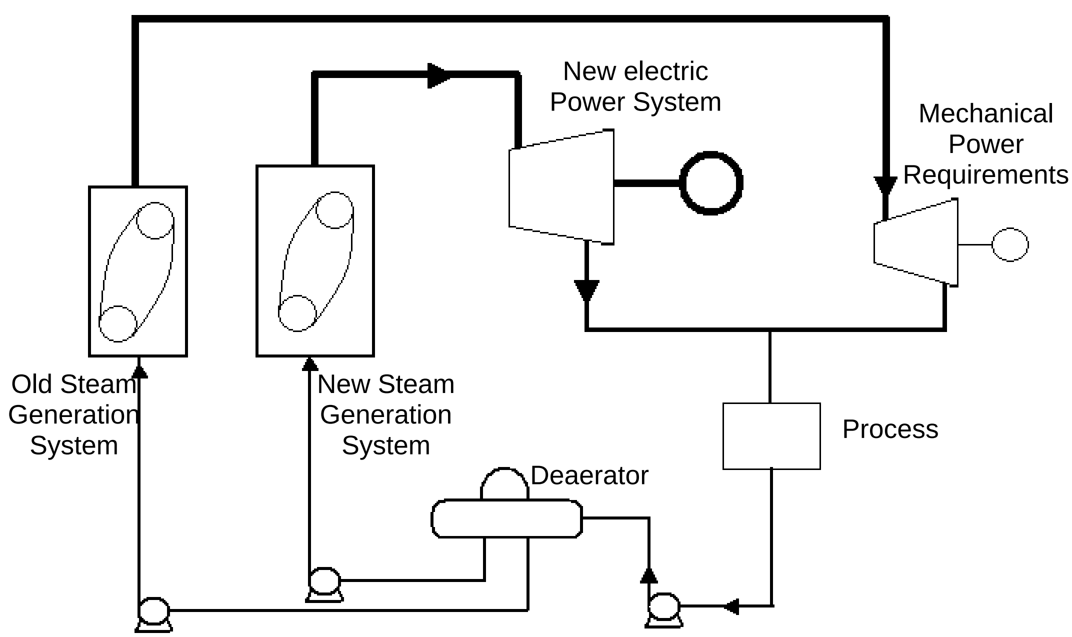

Figure 1: Scenario I – Back-pressure Turbine

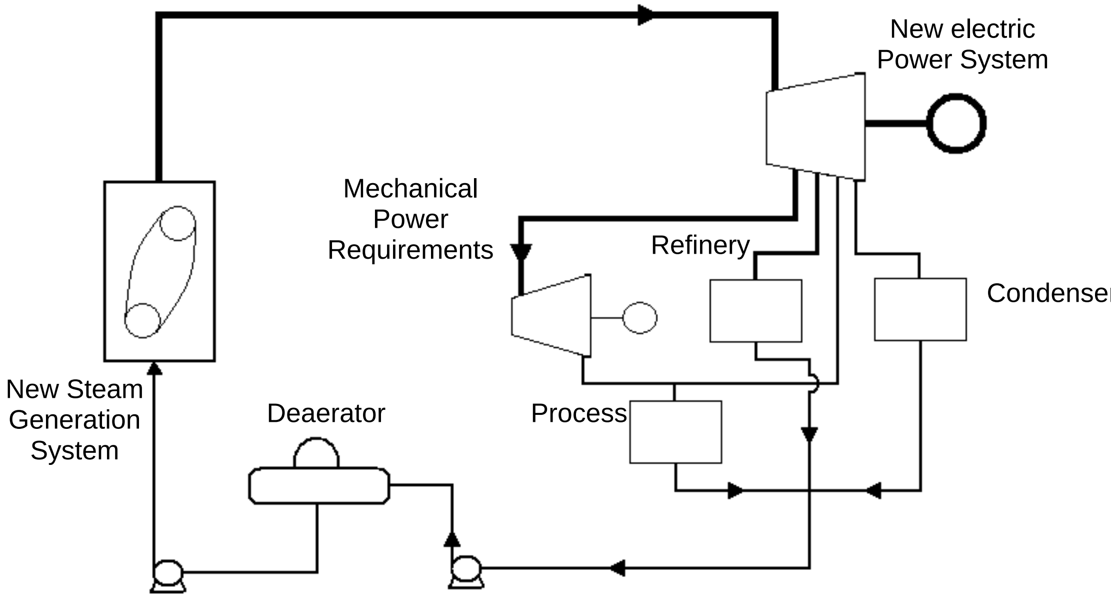

Figure 2: Scenario II – Extraction and Condensation Turbine

3. Calculation methodology

First was established a composition of cane bagasse according to Baloh and Wittwer (1995), who is compiled bagasse analysis of different authors. These authors assumed an average composition, which has: 47% of carbon, 6,5% of hydrogen, 44% of oxygen and 2,5% of ash.

3.1 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 base. The balance equation for stoichiometric combustion is shown in Eq.1.

$$(n_C C + n_H H + n_O O + n_{H2O} H_2O) + a(O_2 + 3.76N_2) = bCO_2 + cH_2O + dN_2 \qquad (1)$$

Where:
n_C, n_H, and n_O: dry mass of fuel flow (kmol/s),
n_{H2O}: flow of moisture contained in the fuel,
a, b, c, d: theoretical air flow and theoretical combustion products flow respectively (kmol/s).

The equation (2) corresponds to combustion equation with air in excess. In this equation was inserted the effect of bagasse moisture content, because the air excess depends of bagasse moisture content.

$$(n_C C + n_H H + n_O O + n_{H2O} H_2O) + e(O_2 + 3.76N_2) = fCO_2 + gH_2O + hO_2 + iN_2 \qquad (2)$$

The equation (3) presents the relationship between bagasse moisture content "u" (w.b.) and the air excess "φ" for dumping grate boiler (Beatón and Lora, 1991).

$$\varphi = 2.5 + 75u \qquad (3)$$

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

$$1 + \frac{\varphi}{100} = \frac{AF_{molar,exc}}{AF_{molar,theo}} \tag{5}$$

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

Where
e, f, g, h, i: air flow and combustion products flow,
n_{fuel}: flow of wet fuel (kmol/s),
$AF_{molar,\ theo}$; $AF_{molar,\ exc}$: theoretical air-fuel ratio and air-fuel ratio ($kmol_{air}/kmol_{fuel}$).

3.2. Adiabatic-saturation temperature calculation

In order to calculate the adiabatic saturation temperature of the combustion gases, an ideal process of saturation was assumed, also it was calculated the energy balance in the dryer.

3.3. 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

3.4. Dryer

It was assumed that 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, it 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 methodology used for calculation of adiabatic-saturation temperature and several parameters of the air preheater and the dryer was the same used by Marquezi and Nebra (2003) and Sosa-Arnao et al. (2004). In these works, it can be found more information
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3.5. Boiler efficiency (η_{boiler})

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 instruments to measure the fuel flow. 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 others authors (Sánchez Prieto et al. 2001; Marquezi and Nebra, 2003; Sosa-Arnao, et al. 2004).

$$\eta_{boiler} = 100 \quad (q_2 + q_3 + q_4 + q_5 + q_6) \tag{7}$$

3.6 Net Efficiency (η_{net})

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

$$\eta_{boiler} = \frac{\dot{m}_{steam}(h_{steam} - h_{liquid})}{\dot{m}_{bag}\, LHV} 100 \tag{8}$$

Where:
m_{steam}: new boiler steam flow, kg/s,
h_{steam}: steam specific enthalpy, kJ/kg,
h_{liquid}: water liquid specific enthalpy, kJ/kg,
$m_{steam,need}$: steam flow required for mechanical power and sugar refinery, kg/s,
m_{bag} : fuel flow, kg/s.

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

$$\eta_{net} = \frac{\dot{m}_{steam}\left(h_{steam} - h_{liquid}\right)}{\dot{m}_{bag,net}\, LHV_{net}} 100 \qquad (9)$$

Where:
$\dot{m}_{bag,net}$=fuel flow with 50% of moisture (w.b.), kg/s
LHV_{net}= lower heating value of the fuel with 50% of moisture (w.b.), kJ/kg.

3.7 Exergy of cane bagasse

As bagasse is very similar to wood, both are mainly cellulose, the proposal of Szargut et al. (1988) to calculate the bagasse exergy was adopted (Eq. 10). Wittwer (1993) proposed also a methodology for determining the bagasse exergy but the Szargut proposal is used by many authors.

$$\beta = \frac{b_f}{LHV} = \frac{1.0412 + 0.2160 \frac{Z_{H2}}{Z_C} \quad 0.2499 \frac{Z_{O2}}{Z_C} \quad 1 + 0.78849 \frac{Z_{H2}}{Z_C} \quad + 0.0450 \frac{Z_{N2}}{Z_C}}{1 \quad 0.3035 \frac{Z_{O2}}{Z_C}} \qquad (10)$$

Where:
β = Relationship between the chemical exergy and the lower heating value (LHV),
Z_{H2}, Z_C, Z_{O2}, Z_{N2} = Gravimetric content of hydrogen, carbon, oxygen and nitrogen respectively.

$$b_f = \beta\left(LHV_{net} + uh_{fg}\right) + ub_w \qquad (11)$$

Where:

b_f: Specific exergy of cane bagasse (kJ/kg),

3.8 Energy Utilization Factor EUF:

This parameter is a logical criterion in the analysis of cogeneration systems (Porter and Mastanaiah, 1982; Sanchez Prieto, et al. 2003).

$$EUF = \frac{\Sigma W + \Sigma Q_p}{\dot{m}_{bag,net}\, LHV_{net}} \qquad (12)$$

Where:
W: Electrical and mechanical power (kW),
Q_p : Heat for process and refinery (kW).

3.9 Second Law Efficiency ξ_{II}:

It was used the relationship suggested by Huang (1996).

$$\xi_{II} = \frac{\Sigma W + B_q}{B_f} \tag{13}$$

Where:
B_f : Exergy of fuel,
B_q : Exergy of heat flow.

4. Results

The results obtained are presented in the Figures below. In Figures 3, 4, 5 and 6, it was used several boiler steam pressures and temperatures with bagasse moisture content fixed at 35.7 % (w.b). In Figures 7, 8, 9 and 10, it was used several bagasse moisture content with boiler steam pressure and temperature fixed at 470ºC and 62 bar. The boiler steam pressures and temperatures used in this work were: (320 ºC, 21 bar; 360 ºC, 30 bar; 420ºC; 42 bar; 450ºC, 62 bar; 470ºC, 80 bar; 520ºC, 100 bar and 560ºC, 120 bar. The five first ones are produced by Equipalcool industry (Dalmazo 2004); the sixth one was analyzed by Coelho et al. (1997). Other boiler steam temperatures and pressures were considered to study the increasing of these parameters.

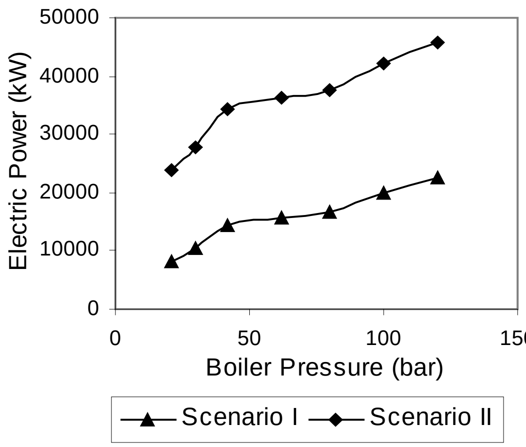

Fig. 3 Electric Power as function of increasing boiler steam temperature and pressure.

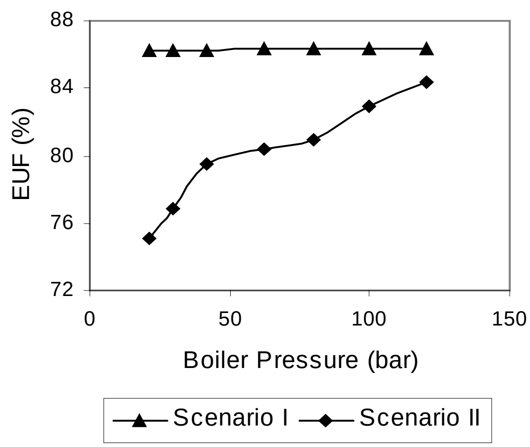

Fig. 4 Energy Utilization Factor as function of increasing boiler steam temperature and pressure.

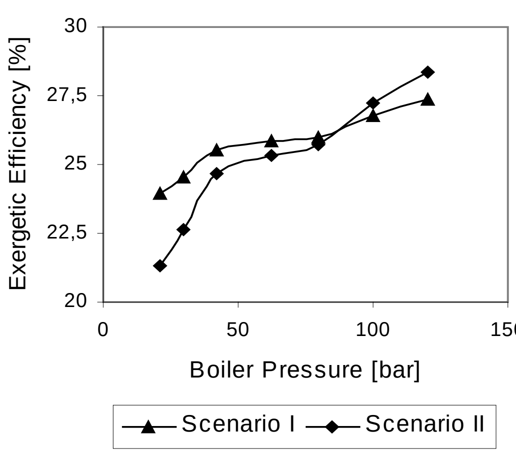

Fig. 5 Exergetic Efficiency as function of increasing boiler steam temperature and pressure.

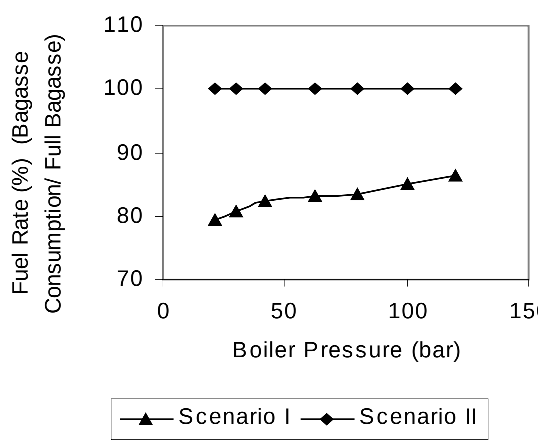

Fig. 6 Fuel Rate as function of increasing boiler steam temperature and pressure.

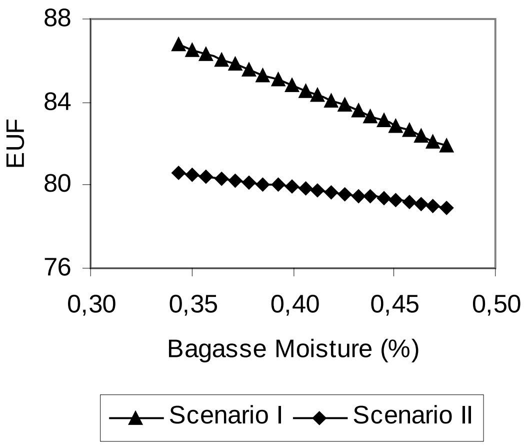

Fig. 7 Energy Utilization Factor (EUF) as function of cane bagasse moisture.

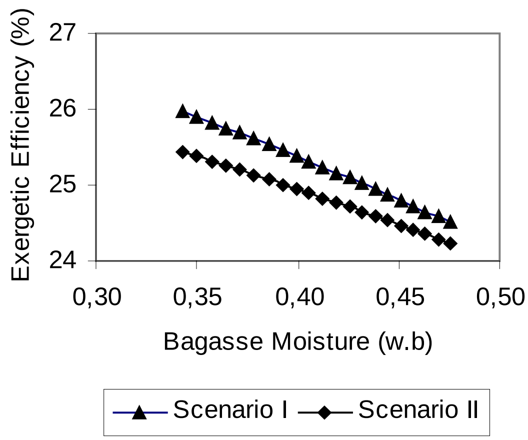

Fig. 8 Exergetic Efficiency as function of cane bagasse moisture.

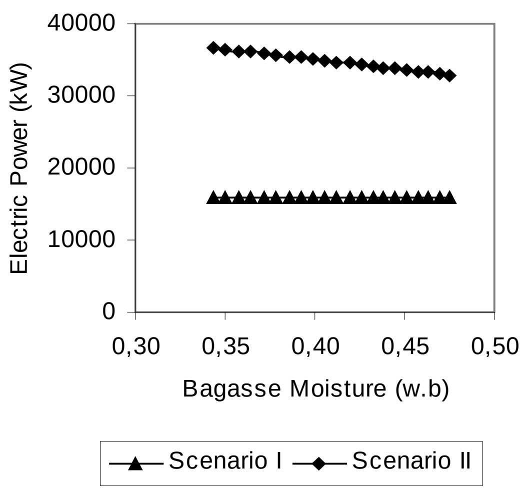

Fig. 9 Electric Power as function of cane bagasse moisture.

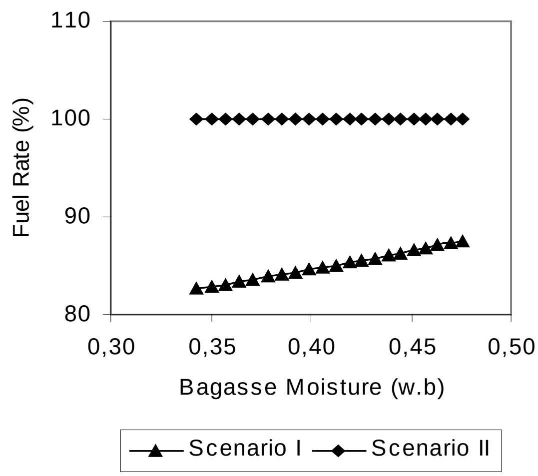

Fig. 10 Fuel Rate as function of cane bagasse moisture.

5. Data analysis and conclusions

Data of the modeling strongly indicate that the best option to improve the efficiency and electric power of the cogeneration system is to increase the boiler steam temperature and pressure. The best EUF and second law efficiency was found in the higher boiler steam temperature and pressure. In Figure 5, it can be observed the increase of exergetic efficiency of scenario II, which became higher than that the exergetic efficiency of scenario I when the boiler steam pressure is higher or equal than 100 bar. It happened because in the scenario II, it was used all cane bagasse (Fig. 6) while in the scenario I, it was used just between 79 and 86% of produced cane bagasse full.

It was observed also that between the pressures (42, 62 and 82 bar) the efficiency and electric power of the scenarios I and II slowly increase because the little increase of boiler steam enthalpy in these levels of pressure and temperature. The increase of steam temperature and pressure also produce the increase of cane bagasse consumption.

Otherwise, the reduction of bagasse moisture content increases the net efficiency of the steam generation system, the EUF and the exergetic efficiency of system and also reduces the consumption of cane bagasse in the scenario I (Fig. 10). The sequential arrangement used in this work, let to reduce the heat transfer area of preheater, which many times, is larger than that the heat transfer area of boiler. This can reduce the cost of the steam boiler.

The cane bagasse dryer is an interesting alternative to improve the performance of power cogeneration systems in sugar cane mills. In Brazil, they haven't had success but in other countries as Argentina and Cuba, where it was used other pattern, bagasse dryers are operating satisfactorily.

6. Acknowledgements

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