THERMAL ANALYSIS OF STEAM GENERATOR SYSTEM

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Abstract. *Although steam generators require large equipment investments in the sugar manufacturing industry, it is usual in Brazil that existing systems present low thermal efficiency. Due to the necessary cost reduction and better utilization in cogeneration plants, the performance improvement has become essential and consequently new systems showed up technical and economically feasibility. Some measures related to the use of gas exit flow have been adopted to heat the inlet water and the combustion air, as to reduce the fuel moisture in order to increase the steam generator efficiency using economizers, pre-heaters and bagasse dryers. The main purpose of this work is to evaluate the advantages of those accessories using thermal analysis in steam generator of sugar cane industry. Simulations were performed to compare those equipments and other possible influence variables as air excess are also included. The results allowed to quantify and to compare them in relation to the bagasse consumption, energetic and exergetic efficiency, and thermoeconomic cost, thus showing that it is possible to employ the fuel in more rational ways when these equipments are applied. Therefore, it is concluded that industries intending to recover the heat of gas exit flow must study and evaluate more accurately the possible options, before choosing the economizer or air pre-heating as it is usually done. Although bagasse dryer is commonly the last application option, it can present better performance and lower fuel consumption.*

Keywords: *steam generator, optimization; thermal efficiency, exergy, thermoeconomics*

1. INTRODUCTION

One of the main limiting factors for the best use of fibrous residue of sugar cane (bagasse) as fuel and also for the supply of electrical energy from the sugar/alcohol Brazilian sector to grid is the high inefficiency of the components in the power generation systems, in which the steam generators and the turbines are included.

In the case of the steam generator, one of the most significant thermal losses is the sensible heat of the exhaust combustion gases that leave the boiler chimney with a considerable energy and exergy potential when discarded to the surroundings due to their high temperature (Camargo *et al*, 1990).

In order to promote the thermal recovery from those gases, to improve the combustion process itself and to maximize the thermal efficiency of a steam generator, supplementary equipments are applied, such as the air pre-heater, the economizer and the bagasse dryer, where the dryers are only used for the specific case of generators that use the cane bagasse or another solid vegetable fuel.

Moreover, other great advantage obtained with the implantation of those three steam generator auxiliary equipments is the better control and stability of the furnace temperature during the combustion.

Based on those considerations, a study was elaborated trying to quantify and to compare the performance of a steam generation system, in order to evaluate the thermal efficiency, bagasse consumption and thermoeconomic costs. In the configuration of the evaluated thermal system (Fig. 1), the combustion gases circulate first through the main module of the steam generator, following to the economizer, air pre-heater and finally to the bagasse dryer.

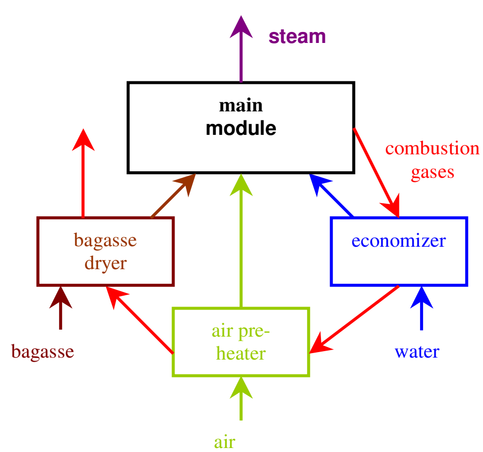

Figure 1. Configuration of steam generator system

2. HEAT RECOVERY EQUIPMENTS

2.1. Economizer

Economizers are heat exchangers directed to increase the feedwater temperature before it enters in the main module. For this purpose, the equipment makes use of the residual energy still available in the flow of combustion gases. Economizers are usually installed in the high part of the steam generator system. They use to be the first external obstacle through which gases should pass towards the external side of the tubes carrying the feedwater. The great purpose of the economizer is that fluid enters the boiler at higher temperature decreasing the necessary energy to vaporization. Consequently, less fuel is burned in order to transform the water into steam, thereby tending to increase the thermal efficiency of the steam generator. However, due to technical or economic reasons, the application can be restricted to the units of larger load. In economical terms, it is necessary to evaluate the capital gains, taking into account the investment and the maintenance costs versus the energy really saved with the process (Bazzo, 1995).

2.2. Air Pre-Heater

The air pre-heater is used to take advantage of the energy contained in the combustion gases to heat up the air that enters in the furnace previously for combustion. It is a heat exchanger, usually in the sequence of the economizer, where the gases flow inside of the tubes and the air flows outside. The great advantage of the air pre-heater is the possibility of controlling the temperature in the furnace. Using previously pre-heated air, the thermal shock in the furnace will be lower, because it will not be necessary to heat up, and consequently to spend so much energy in order to increase the air temperature.

The installation of the air pre-heater decreases the residual gas temperature to minimum values and that can present economy in energy. Besides reducing the fuel consumption, pre-heating air takes considerable advantages to increase the combustion speed and to contribute for the combustion reaction occurrence in a uniform and stable way (Bazzo, 1995, Sosa-Arnao *et al*, 2004).

2.3. Bagasse Dryer

The bagasse dryer can usually be accomplished as the last device through which combustion gases should circulate before leaving the chimney. Combustion gases previously treated for elimination of particulate and still in high temperature, are supplied to the cane bagasse with the purpose of removing the water content found in the bagasse. The moisture is inversely proportional to the high heat value of fuel. A bagasse stream grows up in the dryer where the hot gas, coming from the treatment combustion gases, is injected. The contact is direct between bagasse and gases. Sosa-Arnao *et al* (2004) showed an improvement of the steam system efficiency due to sugar cane bagasse drying. They also presented a review of the main published drying systems in the literature, including problems associated with cleaning the dryer exhausts, which can be significant.

2.4. Air Excess

Although the steam fraction in the exhaust is relevant, according to Baloh (1995), the losses related to the sensible heat of combustion gases depend mainly on two parameters: their temperature and the air excess coefficient.

In a combustion process, it is common that the actual amount of supplied air exceeds the stechiometric. This measure is adopted on purpose to guarantee a complete combustion, mainly in the case of solid fuel. As a consequence, however, the temperature of the combustion products may be several hundred degrees below the maximum adiabatic flame temperature, what becomes significant because of decrease in the exergy of gas combustion.

3. METHODOLOGY AND FORMULATIONS

In order to evaluate a steam generator system, it was necessary to combine mass, energy and exergy balances of steam generator systems. Moreover, to turn a project executable, it is necessary to justify it economically. Thus, the economic costs must be added with the balances mentioned previously to obtain the necessary information to make decisions.

The design and operation analysis and optimization of complex thermal plants, in terms of both, thermal and economic variables, is the subject of Thermoeconomics, consequently various methodologies have been suggested in the literature as a means to pursue such objective based on different approaches (Prieto *et al.*, 2001; Cerqueira *et al.*; 1999; Toffolo and Lazzaretto, 2002). Thermoeconomics studies have been applied in the steam generator systems presenting excellent results, but most of them are related to heat recovery steam generator (HRSG) in combined cycle plants (Valero *et al.*, 1994, Lazzaretto and Toffolo, 2004).

The models used in this study were idealized. Assumptions, such as, negligible heat transfer to the surroundings, unappreciable kinetic and potential energy effects are considered reasonable for using the conservation of mass and energy principles.

To compare the performance in each of the equipments mentioned, the outlet steam conditions were considered as constant, in accordance with typical values used in Brazilian mills (Tab. 1).

Table 1. Outlet steam conditions.

Temperature [^{o}C]	300
Pressure [bar]	22
Mass flow [ton/h]	64

In supplementary equipments, the air inlet conditions and its maximum outlet conditions, as well as water temperatures, bagasse moisture and air excess, are established (Tab. 2). By using those values, it was possible to the steam generator determine the thermal load of the steam generator (Q_{STEAM}), that is the sum of the energy supplied to the economizer ($Q_{ECONOMIZER}$) and to the main module (Q_{MAIN}) as given in Eq. (1) and (2).

Table 2. Inlet and outlet conditions in system equipments.

Equipment	Inlet	Max Outlet
Pre-Heater -T_{air}- (^{o}C)	25	250
Economizer -T_{water}- (^{o}C)	94	217
Bagasse Dryer -w- (%)	50	0
Combustor -Air Excess- (%)	50	150

$$Q_{STEAM} = Q_{ECONOMIZER} + Q_{MAIN} \tag{1}$$

$$Qi = m_{STEAM}\,(h_{T\text{-}OUT} - h_{T\text{-}IN}) \tag{2}$$

Where, m: Mass flow rate [kg/s];
h_T: Specific enthalpy in *"T"* condition [kJ/kg].

By using bagasse chemical composition (Tab. 3), a complete combustion was assumed in the combustor, in order to calculate the gas-fuel ratio ($R_{GAS/FUEL}$) and the adiabatic flame temperature (T_{AD}). Once the main module outlet temperature was adopted as a constant value (T_{OUT} = 450^{o} C), it was possible to calculate the gas (m_{GAS}) and bagasse (m_{FUEL}) mass rate by Eq. (3) and (4), the thermal load (Q_{FUEL}) supplied by fuel in Eq. (5), and, finally, the energy efficiency of the steam generator (η), that includes all equipment such as, the dryer, the economizer and the air pre-heater using Eq. (6). Since the steam conditions and thermal load (Q_{STEAM}) are always the same in this work (Tab. 1) and the heat value of fuel (*HHV*) changes according to the moisture, it is important to maintain the reference in order to compare the results. Therefore, the fuel consumption refers to the mass flow going into the dryer, not into the main module.

Table 3. Chemical composition of bagasse (mass basis).

	C	H	O	S	Z
(%)	47.6	5.8	46.5	0	0.1

$$m_{GAS} = Q_{MAIN}\,(h_{T\text{-}AD} - h_{T\text{-}OUT}) \tag{3}$$

$$m_{FUEL} = m_{GAS} / R_{GAS/FUEL} \tag{4}$$

$$Q_{FUEL} = m_{GAS}\;\; HHV_{MOIST} \tag{5}$$

$$\eta = Q_{FUEL} / Q_{FUEL} \tag{6}$$

The heat value of the moisture bagasse used (HHV_{MOIST} = 9.450 kJ/kg) is the result of both, the moisture level (50%) and heat value in bagasse dry basis (HHV_{DRY} = 18.900 kJ/kg).

Afterwards, the exergy transfers (*Ex*) received by the steam (Eq. 7) and supplied from the bagasse (Eq. 8 and 9) were calculated, thus allowing the determination of exergetic efficiency (ε) by Eq. (10). Due to the difficulty in determining the entropy of the reaction, with reasonable accuracy, the expression applied to the calculation of bagasse chemical exergy uses a ratio (φ) based on heat value, as seen by Szargut and Styrylska (Kotas, 1985). Those authors assumed that the ratio of chemical exergy to the net heat value for solid fuels is the same as the one for pure chemical substances having the same ratios of chemical constituents.

$$Ex_{STEAM} = m_{STEAM}\ [(h_{T\text{-}OUT} - h_{T\text{-}IN}) - T_0\,(s_{T\text{-}OUT} - s_{T\text{-}IN})] \quad (7)$$

$$\varphi = [1.0438+0.1882\ H/C - 0.2509\ (1+0.7256\ H/C) + 0.0383\ N/C] \,/\, [1-0.3035\ O/C] \quad (8)$$

$$Ex_{FUEL} = \varphi\ (LHV_{MOIST}+h_{fg}\ w)+9.417\ S \quad (9)$$

$$\varepsilon = Ex_{STEAM}\ /\ Ex_{FUEL} \quad (10)$$

where,
T_0: Abs. temperature at dead state [K];
s_T: Specific entropy in *"T"* condition [kJ/kg];
C,H,O,N,S,Z: Mass fraction of carbon, hydrogen, oxygen, nitrogen, sulfur and ash;
LHV: Lower Heating Value [kJ/kg];
h_{fg}: Enthalpy during vaporization [kJ/kg];
w: mass fraction of fuel moisture

Finally, exergo-economic value was attributed to the steam (k_{STEAM}), generated by the generator, as well as to the exergetic destruction, in equipments associated to the steam generation, by a thermoeconomic balance as given in Eq. (11).

$$k_{STEAM} = [k_{FUEL}\ Ex_{FUEL} + Z_{EQUIPMT}] / Ex_{STEAM} \quad (11)$$

where, $Z_{EQUIPMT}$: Cost rate associate with capital investment and the maintenance costs [$/s].

4. SIMULATIONS AND RESULTS

To accomplish the simulations it was developed a computational program making use of the formulations and methodologies previously mentioned, which allowed obtaining results in accordance to the parameter variation.

As initial condition of simulation, the adopted values are the commonly used in factories located in Paraná State-Brazil (Tab. 4). That performance (Tab. 5) was set up to compare results, when the parameters of air and water temperatures, fuel moisture and combustion air excess are changed.

Table 4. Initial condition in steam generator system.

Moist. Bg (%)	Air Excess (%)	T_{air} (°C)	T_{water} (°C)
50	50	80	180

Table 5. Steam generation performance using initial condition.

η (%)	ε (%)	Bg (ton/h)	k_{ST}
64.4	23.1	27.6	86.4

The first simulation refers to the economizer use (Fig. 2), in which all of the initial conditions are preserved, except the water temperature inlet in the main module.

It is observed that the increase in water temperature, at economizer outlet, is beneficial in all aspects. This happens due to the reduction of the thermal load in the main module (Q_{MAIN}), and consequently, bagasse consumption (Eq. 3-6), due to a better use of the available energy and exergy in the gas combustion.

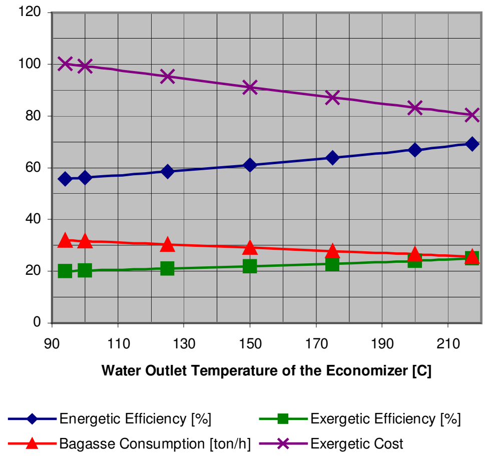

Figure 2. Steam generator performance in relation to economizer water temperature outlet.

The second simulation refers to the use of the pre-heater (Fig. 3), in which the initial conditions are also preserved, except for the inlet temperature of air combustion in the main module.

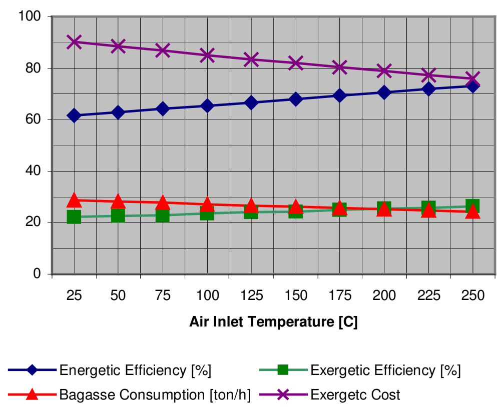

Figure 3. Steam generator performance in relation to the air inlet temperature.

Similarly to the water temperature increase in the economizer utilization, the increase in the air temperature, by using pre-heater is also beneficial in all aspects. Comparing the equipments, the best results, by using a pre-heater, were above the obtained with the economizer.

In that case, the best performance is due to the increase of the adiabatic flame temperature ($T_{adiabatic}$) and of the related gas/fuel ($R_{gas/fuel}$), which allows to reduce the amount of gas and fuel (Eq. 3-4).

The third simulation refers to the bagasse dryer use (Fig. 4). In this case, in relation to the initial conditions, besides bagasse moisture that is a variable, the water temperature of the economizer outlet is changed from 180^o C to 132^o C. This happens because the available heat in the gases is not enough to accomplish the bagasse drying at a desired level. As the air pre-heater presented better performance, when compared to the economizer, the priority was to reduce the water temperature.

When the economizer and the pre-heater are used, it is observed (Fig. 2 and 3) that the performance variation was almost linear, what does not happen in the bagasse dryer operation. Although the performance gets continually better until the water content is completely removed, the abrupt increase in the performance happens when the value is reduced up to 30%. It can be an important factor depending on the investment level desired for application in a new project or in the improvement of an already existing system.

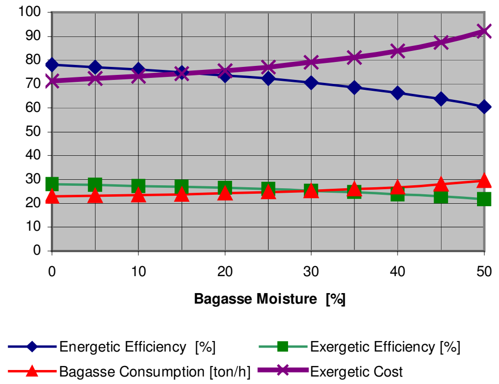

Figure 4. Steam generator performance in relation to the bagasse moisture.

The fourth simulation refers to the control of air excess used in the combustion (Fig. 5), in which, all of the initial conditions are the same.

Although controlling air excess during combustion is not exactly a measure to improve the efficiency, the simulation shows that special attention should be given to that operation parameter, because in extreme cases of air excess, the performance can present very low values.

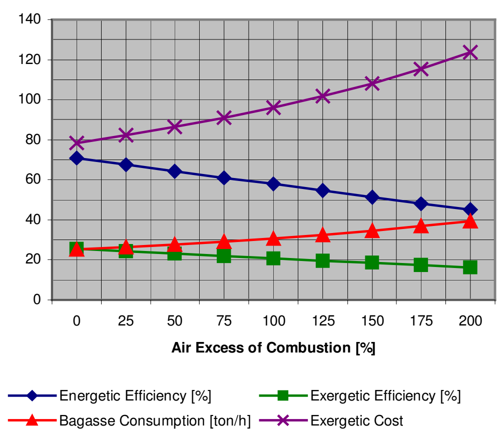

Figure 5. Steam generator performance in relation to air excess in combustion.

Table 6. Worst and best result in simulations.

η (%)	ε (%)	Bg (ton/h)	k_{ST}
Economizer			
55.6	20	32	100
69.2	24.9	25.7	80.5
Air pre-heater			
61.7	22.2	28.8	90.3
73.2	26.3	24.3	76
Bagasse dryer			
60.5	21.7	29.4	92.1
78	28	22.8	71.4
Air Excess			
45	16.1	39.5	123.9
70.9	25.5	25.1	78.5

The best and worst performances in all the previous simulations (Tab. 6) demonstrate that, in terms of investments, the use of bagasse dryers should always be an option to be considered, due to the economic potential, when making use of this equipment.

The results indicate that special attention should be given to the control of air excess, in order to have a good operation in the steam generator. In simulations using 150% of air excess (Tab. 7 and 8) and when having the equipment in better operation conditions to recover the heat of the gases, it is verified that the savings from large investments can be useless if the operation parameter is not appropriate. It is possible to get a performance worse than the one obtained without the use of the equipments.

Table 7. Inlet conditions in steam generator system.

Simulation	Moist.Bg (%)	AirExcess (%)	T_{air} (°C)	T_{water} (°C)
I	50	50	80	180
II	50	150	80	217.2
III	50	150	250	180
IV	0	150	80	180

Table 8. Steam generation performance using 150% of excess of air combustion.

Simulation	η (%)	ε (%)	Bg (ton/h)	k_{ST}
I	64.4	23.1	27.6	86.4
II	56.4	20.3	31.5	98.7
III	67.2	24.1	26.5	82.9
IV	71.9	25.8	24.7	77.5

5. CONCLUSION

Some evaluations were applied to a typical steam generation system used in Brazilian sugar and alcohol factories, by using energetic, exergetic and thermoeconomic concepts. System performances were compared in relation to the use of heat recovery equipments available from gases flow combustion, economizer, air pre-heater and bagasse dryer, besides a verification of the steam generator, in accordance with the air excess used in the combustion. The parameters analyzed were the energetic and exergetic efficiency, the fuel consumption and the thermoeconomic costs of the steam produced. According to the previous hypothesis, the overall system performance of the steam generator gets continually better when the mentioned equipments are used. The best results were obtained when the removal of water content in the fuel is prioritized, that is, with the use of the bagasse dryer. The importance of such result should be distinguished, since in Brazil, it is common to have systems with air pre-heaters and economizers, whereas, systems including bagasse dryers are hardly ever found. A possible reason for that can be the fact such an industry is still far from fully making use opportunities offered by bagasse to improve its own profitability, and the fuel is almost treated as a residue after juice extraction, without costs to the factory.

Another parameter verified was the excess of air used in the bagasse combustion. Due to the difficulty in burning a solid fuel in an efficient way, the amount of air supplied is usually greater than theoretical amount of air. However, when that value is too above the stoichiometric coefficient, it is observed that the efficiency can have a great reduction, thus increasing the thermoeconomic costs. Then, although the burning, by using an appropriate amount of air is not exactly a measure to increase the system efficiency, a lot of attention should be given, in order to control such a parameter, since the use of unacceptable values can bring such great losses that can also exceed the earnings obtained with the use of the equipments of heat recovery.

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