MASS BALANCE FOR STEAM GENERATION SYSTEM WITH BIOMASS DRYER

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Abstract. *This article presents an energetic, exergetic and economic assessment of a small capacity-steam based cogeneration plant, whose typical steam generation unit has the alternative of consuming partially dried biomass. This small capacity plant, at the present time submitted to study due to its ecological and soocial benefits, constitute the productive nucleus of the proposal for the energy generation integrated to the alcohol production at small scale. The biomass considered in this work is sugar cane bagasse at the exit of the juice extraction section. The dryer is a suspended bed type, where biomass is in intimate contact with the ascending products of combustion of the steam boiler. The assessment is acomplished in a samall scale (120000 Liters of alcohol per day plant), with the productivity of 75 Liters/ton of cane in accordance with two alternatives: A; a backpressure steam turbine cogeneration plant consuming 50% moisture bagasse, B; a similar steam-based cogeneration plant with an extraction condensing steam turbine and partially dried consuming bagasse steam generation unit. Basic equations of bagasse combustion, as well as those from mass and energy balance are carried out in order to evaluate the availability of fuel and the capacity of the plant. The concept of exergy and the methods arised from the Second Law of Thermodynamic suggest interesting results sustained by economical analysis.*

Keywords*: dryers, biomass, combustion, sugar cane, alcohol*

1. INTRODUCTION

The traditional steam-based cogeneration plant Sugar Mills, usually consume 50% moisture bagasse, which is the solid sub-product of the sugar cane extraction juice. In Brazil, accepting the information of Sánchez (2003), each ton of sugar cane produces between 240 – 300 kg of bagasse, half of those amounts are quantities of bagasse fiber, which is definitely the responsible for the available heating value of the fuel, considering that a non despicable part of the energy from combustion is used during the evaporation of water formed in the process.

The decision of drying bagasse has been considered in previous researches (Correa and Nebra 2002), as a way of increasing the availability of energy from the fuel in sugar mills. However, its introduction put together a contentious theme, given the exigency of restraining the combustion mechanisms of the boiler to accomplish efficient combustion, which is closely concerned with the increasing emission of small size particles of fuel. This effect denotes fuel wastes unless suitable technologies to retain and usefully using those wastes of fuel are performed. The result is the decreasing in the water vapor formed during combustion and hence, in the energy employed on that process.

The outcome of this criterion can be the starting point to re-analyze the efficient use of the solid waste in Sugar Mill cogeneration plants, and according to this, one of the most important purposes urgently needs to be, the fact of realizing that each ton of cane processed into sugar and/or alcohol, contains a potential of surplus energy, which has been traditionally non considered in sugar mill power plant projects. This argument raises the question of the viability of promoting cogeneration from renewable sources, close to the consumption locations aiming the reduction of the transmission costs.

In recent bagasse boiler experience, the process of combustion starts with the drying of fuel in the furnace by means of almost 260 ^{o}C pre-heated air temperature prior to combustion itself, which involves frequently over 50% moisture bagasse with direct consequences on the air excess coefficient and the primary air temperature required (Lora, 2004), presuming that implementing previous bagasse drying means to enable more suitable conditions for combustion, while increasing the performance of the unit.

The issue has been retaken in this work by means of the proposal of a small-scale steam-based cogeneration plant for the energy generation integrated to alcohol production, in which regenerative and recyclable transformations in all productive sectors have been explored (Ramos *et al.*, 2002). The idea of admitting bagasse drying in the boiler projects offer the opportunity of re-evaluates the electric energy real capacities which can provide substantial amounts of electricity to export. Therefore the objective of this study is to develop a low cost drying system to eliminate the boiler Air Pre heater, to improve the GERIPA cogeneration of electricity and reduce the MWh cost.

This work is based on a 120000 Liters/day production alcohol plant associated to a steam-based power generation plant, in which, according to its own productivity, the steam boiler performance, and the percent of cane fiber, the proper steam demands is settle to warrant its production. The calculation and comparison follows an energetic and exergetic pattern, understood as a first step on achieving the necessary feasibility for economical investments. Economical analysis is supposed to argue the investment.

2. DESCRIPTION OF THE PLANT

The 50% moisture bagasse from the juice extraction section is admitted in the dryer where it is dragged vertically in a suspended bed way, transported by the combustion products from the boiler. The heat transfer between the bagasse and the gas flow is facilitated by their intimate contact. Bagasse expected at 35% moisture leaves the dryer at its top section through the entrance tube of the cyclone, where it is separated from the combustion products and decanted in the storage at the bottom of the cyclone and then injected into the boiler. The inclusion of bagasse partial drying system very much attends simplicity design criteria as illustrated in Fig. 1.

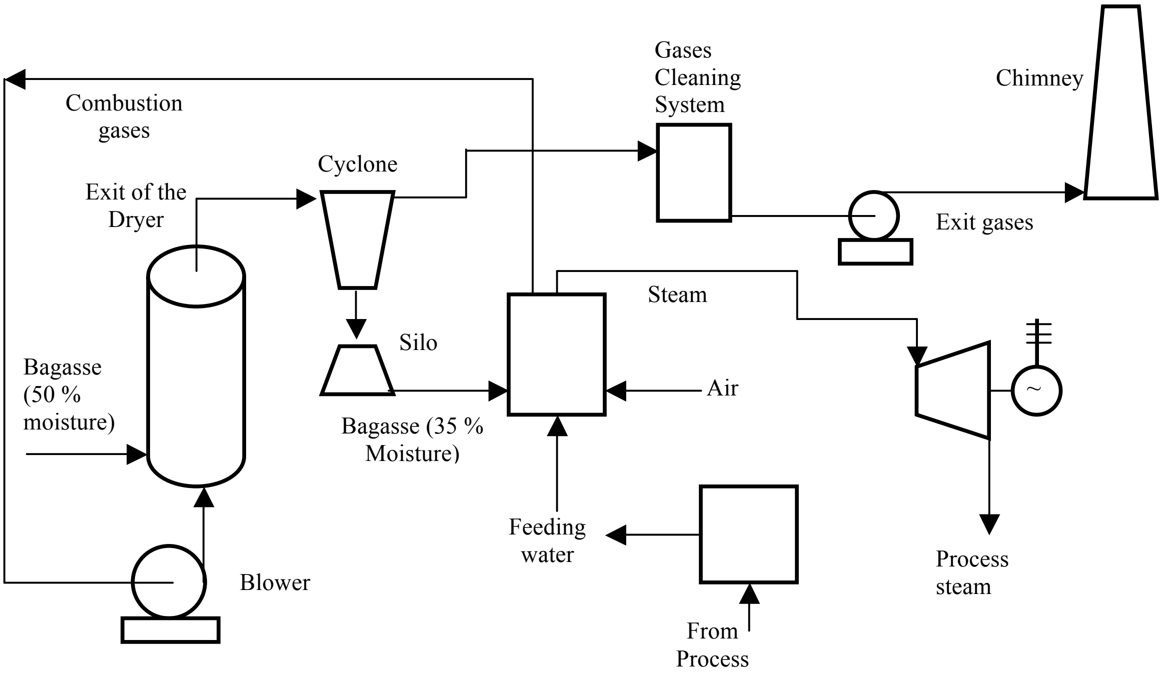

Figure 1. Cogeneration plant with a bagasse dryer steam boiler unit

The dryer itself does not have surfaces of thermal exchange, unless only those of the biomass during the drying process, as the biomass maintains a close contact with its drying agent while dragged up into the entrance of the cyclone. Its main pieces are one tube of large diameter with a cover on top, a perforated plate conveniently positioned at the bottom imposing superficial uniform distribution of exhaust gas, thermal insulation against the environment in order to concentrate the heat exchange in the biomass, a blower and a cyclone with a storage at the bottom where the biomass is deposited and injected into a boiler. Before leaving the boiler, the exhaust gases passes through a cleaning system in order to eliminate small particles that eventually can remain in the gas current.

3. DESCRIPTION OF THE METHODOLOGY

The cogeneration plant referenced in Ramos *et al.* (2008), has been taken as a basis for calculation. Caldema Equips. Inds. Ltda.(a Brazilian steam boiler manufacturer), had previously conceived the single drum boiler as the steam generation unit, considering to-day tendency of increasing the steam generation parameters and the operational suitability of the single drum unit with this criteria (Sánchez, 2008). Considering the drying of bagasse, two alternatives can be analyzed, being briefly described as:

A-Back pressure cogeneration plant with 50% moisture bagasse steam boiler

B-Extraction-condensing steam turbine cogeneration plant with 35% moisture bagasse steam boiler

Both of the alternatives had the same common features such as:

- Daily production (P_d): 120000 L/d
- Alcohol productivity in cane (PA_C): 75 L/ton of sugar cane
- Bagasse fiber in cane (F): 13%

- High heating value of bagasse fiber (HV_F): 18890,9 kJ/kg
- Steam Pressure (P_s): 100 bar (G)
- Steam temperature (T_s): 520 °C
- Process steam pressure (P_p): 1,5 bar (G)
- Process steam temperature (T_p): 132 °C
- First law steam boiler efficiency (η_{gv}): 0,88

Other common features as bagasse ultimate analysis; the air mass composition and the higher heating value of bagasse fiber can be found in the appendix of this work.

Since the effects of drying of bagasse can comprehend diverse situations, the steam boiler efficiency has purposely remained constant, on visualizing how significant can be the surplus of electricity obtained as a result of expanding the increasing steam capacity –conceived as the effect of activating the heating capacity of the fuel by its drying- in an extraction –condensing steam turbine. A more detailed observation denotes that the surplus steam associated to the restrains of this work expands producing extra useful work from initial pressure to the condensate pressure assumed 0,06 bar.

On the other hand, for both cases, the steam temperature for process has been kept in 132 °C (a slightly superheated steam at the process pressure), which response to a common practice leaded to avoid condensation in the line.

Direct mass balance equations permit to calculate the steam capacity in each alternative and basic equations for bagasse combustion concerning air requirements are widely exposed in Baloh and Wittner (1995):

Total processed cane, (T_C) (ton/d):

$$\mathbf{T_C = \frac{P_d}{PA_C}} \tag{1}$$

Available bagasse fiber, (F_B) (kg/h):

$$\mathbf{F_B = 10T_CF} \tag{2}$$

Bagasse available at 50% moisture ($M_{B50\%}$) (kg/h):

$$\mathbf{M_{B50\%} = \frac{F_B}{(1-\frac{w_A}{100})}} \tag{3}$$

Bagasse available at the exit of the dryer (M_{BX}) (kg/h):

$$\mathbf{M_{BX} = \frac{F_B}{(1-\frac{w_B}{100})}} \tag{4}$$

Where w_A and w_B corresponds with the moisture of bagasse at the exit of the extraction juice (50% in alternative A), and that at the exit of the dryer (alternative B). Table 1 offers preliminary results:

Table 1. Mass results from mass balance

Total Processed cane (ton/d)	66,67
Available bagasse fiber (kg/h)	8666,67
Available bagasse at 50% moisture	17333,3
Available bagasse at 35% moisture	13333,3

The calculation proceeding is assisted by the ASME code (PTC 4.1, 1991), to determine the high heating value – humid basis (HV_{HB})- in both alternatives by means of the following relation:

$$\mathbf{HV_{HB} = HV_F(1-\frac{w_i}{100})} \tag{5}$$

According to the same code, the recommended equation for the Low Heating Value (LV_{HB}) is:

$$\mathbf{LV_{HB}} = \mathbf{HV_{HB}} - \frac{\mathbf{2441{,}68(8{,}936H + w_1)}}{\mathbf{100}} \qquad (6)$$

Where:
2441,68 (kJ/kg): water vapor latent heat at 25 °C
8,936 (kg): kg of water formed per each kg of hydrogen in the combustion process
H: Composition of hydrogen from ultimate analysis
w: fuel moisture in humid basis (%)

Through the concept of first law efficiency, the steam capacity of both of the units is to be determined. The value obtained in alternative A express the process steam demand (M_S), which is valid for both of the alternatives. The well-known direct method for the first law efficiency indicates:

$$\eta_I = \frac{\mathbf{M_S(h_S - h_{fw})}}{\mathbf{M_B LV_{HB}}} \qquad (7)$$

Where:
h_S: Enthalpy of superheater steam (kJ/kg)
h_{fw}: Enthalpy of feeding water (kJ/kg)

Energy balance equations and manufacturers recommendations (TGM, 2007), determine the electric power produced, while restrains regarding the media value of isentropic efficiency are given basically from setting the steam temperature at the exit of the turbine. In alternative A, that value corresponds with the back pressure turbine exit, in alternative B, the value corresponds with the temperature at the extraction of steam to process. The steam moisture also restrains results in alternative B at the turbine last stages, allowing a maximum of 13% according to Lora and Nascimento (2004). Table 2 shows the results.

Table 2. Results from energy balance in the plant

Index	Alternative A	Alternative B
Low Heating Value (kJ/kg)	7520	10500
Steam Capacity (ton/h)	39,4	42,3
Electric Power (MW)	7,4	8,4
Annual Additional Income (1,000 $R)*		1,110

The difference between the two alternatives reaches approximately 1 MW, which considering the sale of energy from biomass according the selling prices of energy from biomass according to the São Paulo Energy Cogeneration Association (COGEN-SP, 2008), rated at R$ 130/MWh* during a whole year period, lead to substantial economical benefit in alternative B.

4. APPLICATION OF EXERGETIC METHOD

The exergetic method, widely applied in thermal plants as a tool to truthfully evaluate the usefulness of an energetic resource, has been performed through the concept of exergy and its efficiency, closely associated to terms like product and resource that fulfills the theory developed by Lozano and Valero (1993). This methodology previously requires the subdivision of the plant into subsystems as a way of settling the "objective" (product), of each subsystem and of the plant itself. The frequently treated concept of exergy is depicted in Szargut (1988) who describes the terms as a maximum useful capability of producing work of a system from its physical and chemical state.

The own principle appoints its expedience since it is feasible to appreciate how close is any real process from its maximum thermodynamic performance, which means that irreversibility express the decrease in the capability of producing work. As described, the physical and chemical state of the matter defines the concept of exergy, whose physical (b_{PH}) portion is exhibited in Eq. (8). The chemical portion is showed in Szargut (1988).

$$\mathbf{b_{PH} = (h_x - h_0) - T_0(s_x - s_0)} \qquad (8)$$

Where:
h_x and h_0 (kJ/kg): Enthalpies of the matter at its physical condition and at the state of reference, respectively. The state of reference (featured by pressure and temperature conditions, P_0 = 101,325 kPa and T_0 = 298,15 °K), constitute the natural source of equilibrium with the ambient
s_x and s_0 (kJ/kg°K): Entropies of the matter at its physical condition and at the state of reference, respectively.

The steam boiler unit, the steam turbine and the cogeneration plant as a whole were the key elements submitted to analysis, and for each of them, a product and a resource function were based. Alternatives A an B can be resumed graphically as in Fig. (2) and Fig. (3):

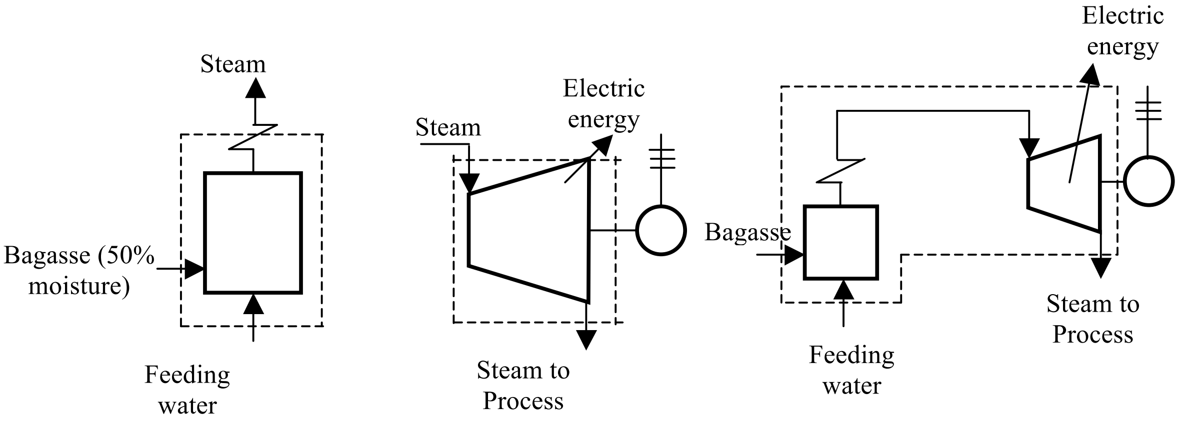

Figure 2. Arrangement of Alternative A for the three elements included in the exergetic analysis

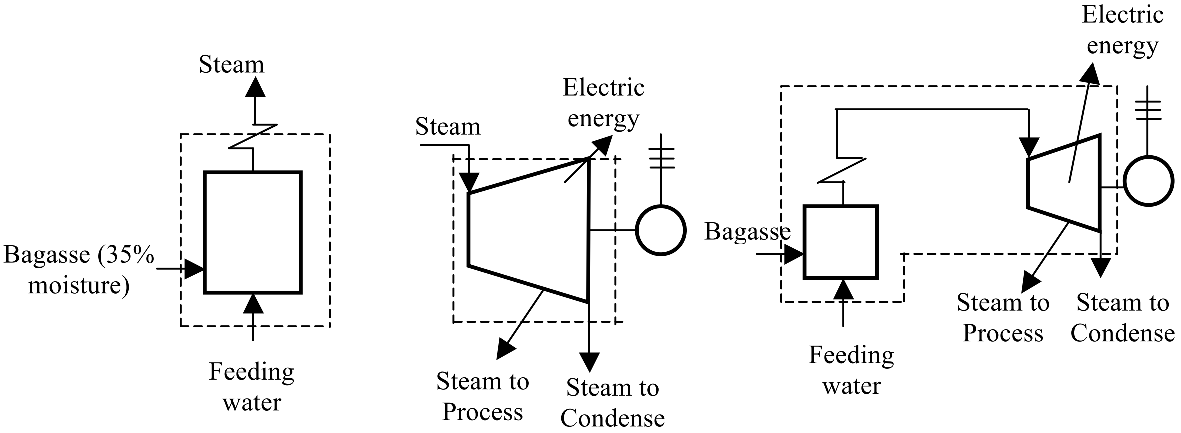

Figure 3. Arrangement of Alternative B for the three elements included in the exergetic analysis

The magnitude of the thermodynamic lost –the irreversibility- is expressed as the conception of the decreasing exergy during real processes, despite the fact that the total energy intervenient remains unalterable. So the destruction of exergy and the calculations of the efficiencies involved is the way of quantitatively showing the degradation occurred in the available energy. The exam of exergetic efficiency applied to each subsystem lead to a suitable understanding of the concepts of product and resource, which interact with each control volume with the purpose of defining the degree of perfection, i.e. the relation between the recovery exergy and the one employed. For instance, this criterion (η_{SB}), for the steam boiler in both of the alternatives can be expressed by Equation (9)

$$\eta_{SB} = \frac{M_S(b_S - b_{fw})}{M_B b_B} \qquad (9)$$

The exergy of bagasse (b_B) was calculated according Eq. (10) proposed by Szargut (1988):

$$b_B = \beta(LV_{HB} + 2441{,}681 w_x) + b_{CH_W} w_x \qquad (10)$$

Equation (10) employs the chemical exergy of the water (b_{CHw} = 50 kJ/kg), according to Szargut (1988). This very researcher proposed the following relation to determine coefficient β:

$$\square = \frac{1{,}0412 + 0{,}216\frac{Z_{H2}}{Z_C} - 0{,}2499\frac{Z_{O_2}}{Z_C}[1 + 0{,}7884\frac{Z_{H2}}{Z_C}] + 0{,}045\frac{Z_{N2}}{Z_C}}{1 - 0{,}3035\frac{Z_{O2}}{Z_C}} \quad (11)$$

Where all the Z_i terms obey to bagasse ultimate analysis offered in the appendix of this work.

The exergetic efficiency of the turbine for alternatives A and B can be determined according Eq. (12) and (13) respectively:

$$\square_T = \frac{W3600}{M_S(b_{Si} - b_{So})} \quad (12)$$

$$\square_T = \frac{W3600}{M_S(b_{Si} - b_{Se}) + (M_S - M_{Se})(b_{Se} - b_{S_c})} \quad (13)$$

Equations (12) and (13) relates products and resources, distinguishing the terms b_{So} and b_{Se} that represents the steam exit exergy of the turbine (alternative A), and the steam extraction exergy in alternative B. The other terms express the steam exergy at the inlet (b_{Si}), and (b_{Sc}) the steam exit exergy in alternative B.

The relation between the sum of the electric power and the steam to process exergy with the exergy of bagasse, Eq. (14) depicts the exergetic efficiency of the plant, expressed as follows:

$$\square_P = \frac{W + M_P b_{SP}}{M_B b_B} \quad (14)$$

Results from the exergetic efficiency analysis are given in Table 3.

Table 3. Results of the exergetic efficiency in alternatives A and B

Index	A	B
Boiler exergetic efficiency (%)	31,5	31,02
Turbine exergetic efficiency (%)	82,82	83,54
Plant exergetic efficiency (%)	30,9	30,2

Analyzing the results as a whole from Tabs. 2 and 3, though seeming somewhat contradictory, performance indexes from alternative B express more efficient results than those from alternative A. The boiler exergetic efficiency reflects the comparison patterns of this paper concerning the fact that thermodynamic steam parameters remains constant and direct effect of drying bagasse is the exceeding steam capacity that is going to produce surplus electricity for sale. Equation (9) and the concept of exergy of bagasse itself show that resources have more influence in the results.

Turbine exergetic efficiency did not consider the steam to process exergy as a product of the turbine subsystem. The exceeding steam capacity expresses the expected consequence in its exergetic index. Attention should be paid to the fact that the steam exergy at the exit of the turbine –appeared as a subtraction term in the denominator in Alternative B- is part of the resource of that subsystem. However, the plant as a whole brings a different approach since the steam flow at the exit of the extraction-condensing turbine is no longer a resource, and that issue is revealed as a benefit for alternative A.

A more detailed economic evaluation about the economical investments in the energy generation plant integrated to alcohol production at small scale can be found in Lombardi *et al.* (2008). By means of economical methods those researchers reached the results showed in table 4.

Table 4. Analysis of investments for three analyzed options

Index	Unit	First	Second	Third
Cogeneration Investment	(US $)	5.68 x 10^6	5.924x10^6*	5.36x10^6
Bagasse Low Heating Value	(kJ/kg)	7,660	10,700	10,700
Steam Production	(kg/d)	779,000	836,000**	836,000
Electricity Cogenerated	(MW)	8.66	+0.66	9.32
Investment Index/Steam	(US $/kg s)	7.29	7.09	6.40
Investment per MW	(US $/MW)	611,000	386,000	575107
Dryer Pay Back Time	(year)	-	0.317	0.317
GERIPA´s Pay Back Time	(year)	5.77	5.66	5.66

*Dryer investment +0.244x10^6 US$, ** Additional steam production

The three options:

First: Boiler without dryer burning the 50% bagasse humidity

Second: Boiler with dryer and air pre heater not working burning the 35% bagasse humidity (during the period of the dryer development avoiding GERIPA work interruption).

Third: Final configuration of the steam generation system with biomass dryer and boiler without the air pre heater burning the 35% bagasse humidity.

Table 4 elucidates the economical benefits of the investments in alternative B, putting in relief the investment return rate of the cogeneration plant in that alternative. Even at small-scale degree the four months investment return rate difference between both alternatives tells about an outstanding acknowledge for the investment.

5. CONCLUSIONS

The results from this work should be judged as a necessary step to optimize the performance of the steam-based unit with the purpose of obtaining maximum performance in terms of efficient use of the energetic resources whilst maximizing its benefits from selling surplus electricity. The drying of bagasse proposed for this small-capacity steam-based plant reveals itself as an interesting topic to be more explored.

At this first stage, the analysis attempted to set the qualitative and quantitative differences between the plant performances, without examining what should be accomplished in future analysis, in which units with reducing air preheating and economizers surfaces are included, with bagasse drying as well. In that way it is possible to approach this study aiming maximizing the profits.

Basic combustion equation for bagasse together with energy and exergetic balance equation, including thermoeconomic methods are useful tools for this purpose.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Associação Paulista de Cogeração de Energia, “COGEN-SP” 2008, www.cogensp.com.br, (In Portuguese).

Baloh T., Wittwer E., 1995, “Energy Manual for Sugar Factories”, Verlag Dr. Albert Bartens Editors, Printed in Germany by Druckhaus am Treptower Park 230 p., Berlin

Correa J.L.G., Nebra S.A., 2002, “Estudo do conjunto Caldeira Secador de Bagaço de Cana e Pré-Aquecedor de ar de uma Usina de Açúcar”, Congresso de Iniciação Científica, Universidade Estadual de Campinas, UNICAMP, In Portuguese

Lombardi G. Ramos R.P.A., Moreira A.S., 2008, “Potencial da Secagem de Biomassa para Sistemas de Geração de Vapor”, In Portuguese

Lozano M.A., and Valero A., 1993, “Theory of Exergetic Cost”, Energy, Vol. 18, No. 9, pp 939-960

Lora E.E.S., Nascimento M.A.R., 2004, “Geração Termelétrica. Planejamento, Projeto e Operação”, Editora Interciência, Rio de Janeiro, Volume I, 631 p.

Ramos R.P.A., Corsini R., Lombardi G., 2002, “Evaluación Económica de uma mini-destileria de alcohol diversificada”, VII Congreso Internacional sobre azúcar y derivados de la Caña, Ciudad de la Habana, Cuba, In Spanish

Ramos, R.P.A., Lombardi G., 2008, “Estudo Econômico de Produção de Alcool Integrada à Geração de Energia”, In Portuguese

Sánchez P. M.G., 2003, “Alternativas de Cogeração na Industria Sucroalcooleira Brasileira. Estudo de Caso”, Faculdade de Engenharia Mecânica, Universidade Estadual de Campinas, UNICAMP, tese de doutorado, 280 p., In Portuguese

Sánchez P.M.G., 2008, “Caldeiras a bagaço. Inovações e Tecnologias”, Capítulo do Livro aceito para publicação, II Simpósio do Setor Sucroalcooleiro, Sucrojab2008, Faculdade de Ciências Agrarias e Veterinárias, UNESP Jaboticabal, SP, Brasil, In Portuguese

Steam Generating Units, ASME PTC 4.1, 1991, “The Power Test Code 4.1”, The American Society of Mechanical Engineers, United Engineering Center, New York 10017, USA

Szargut J., Morris D., Steward F., 1988, “Exergy analysis of thermal chemical and metallurgical process”, Hemisphere Publishing Corporation, 332 p.

TGM, 2007, “Comunicação Pessoal”, informação do fabricante, Sertãozinho, SP

8. APPENDIX

Ar Properties. Composition of dry air

element	%Volume	%Weight
Oxygen	21	23,21
Nitrogen	78,05	75,48
Argon	0,92	1,27
Carbon doixide	0,03	0,04

Fiber Bagasse Heating Value (HV_F) = 18891 kJ/kg

Bagasse ultimate analysis (%)

Element	w = 0	w = 35	w = 50	Molecular Mass (Kg/kmol)[1]
Carbon	47	30,55	23,5	12,0112
Hydrogen	6,5	4,23	3,25	2,01594
Oxygen	44	28,6	22	31,9988
Nitrogen	0	0	0	28,0134
Sulfur	0	0	0	32,064
Ash	2,5	1,74	1,25	-

1: Cameron A.E., Wichers E., Report on the International Comission on Atomics Weights, J. Am. Chem. Soc 84 (22:4192) November 20, 1962.

9. RESPONSIBILITY NOTICE

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