An Integral Exergoeconomic Evaluation of an Ethanol Distillery Process and Cogeneration Plant

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Abstract. *The objective of this paper is to carry-out an integrated thermodynamic analysis for an ethanol distillery and the mill cogeneration plant.*

In previous works reported in the literature the cogeneration system has been analyzed separately using thermoeconomic tools to calculate the product`s cost and to define the best scheme and also to conduct parametric alternative analysis. Similar researches were carried-out aiming to reduce the energy consumption in the distillation process. This paper proposes a simultaneous evaluation of both systems using an exergoeconomic approach to optimize the energy integration process.

The study includes different schemes of ethanol distillation processes (considered as black boxes) coupled with a cogeneration plant that uses condensing-extraction turbines, and considers steam parameters (pressure) ranging from 4,1 MPa up to 12,0 MPa. Cane trash as a surplus fuel was considered.

The exergetic efficiency, the average exergy costs, as well as, productivity indexes (kWh of surplus electricity/ton of cane and liters of ethanol/ton of cane) for involved energy flow (electricity and ethanol) are used as indicators for the integrated evaluation of both systems.

These results of alternatives cost and efficiency indicators are compared with a base case, which consists of an "usual or conventional" distillery (4,1 MPa).

Conclusions are made about the best schematic and parametric solutions for integrated distillery and cogeneration plants.

The results obtained allow improving the whole plant efficiency.

Keywords: *cogeneration, thermoeconomics, ethanol production*

1. INTRODUCTION

The Brazilian sugar-cane industry is in a new expansion cycle, with great expectations of production growth as much for sugar as for ethanol. To the big and consolidated internal market, the new expansion of production forces is added, which is represented by the bi-fuels engines and by the international market, characterized today by the continual rising of the petroleum prices and by the reduction commitments of CO2 emissions, assumed by developed countries with Kyoto Protocol (Rodrigues e Ortiz, 2006).

It is very important that the growth of ethanol production from sugar-cane comes accompanied by a rational utilization of the resources used in its attainment, as it will allow to increase and to guarantee the sustainability of this country important industrial sector.

In this sense, the Brazilian Ministry of Agriculture, Livestock and Provisioning establishes in its agriculture-energy national plan (2006-2011), among priorities in ethanol productive chain, the following aspects (MAP, 2005): to develop alternatives for the energy integral use of sugar-cane, with improvement of current processes or new processes development, related with water use rationalization and other inputs and processes improvement of energy co-generation.

This case study evaluates the opportunities for the progress in the sustainability aspects in the ethanol production from sugar-cane in a Brazilian distillery. In the context of a rational and sustainable use of the resources in the whole production process (co-generation plant – ethanol production), these systems are analyzed using the thermoeconomy as a tool. Some maximization possibilities of electric energy exportation to the electrical grid are also analyzed, considering steam initial parameters variation (temperature and pressure) and selecting the appropriate distillation configuration that should be coupled to the co-generation system, aiming the minimization of plant energy impacts.

Previous works have accomplished energetic analyzes for different cogeneration schemes and for the steam consumption reduction in the process (Ensinas *et al*., 2006). Others evaluated exergetically and thermoeconomically some stages of the process, but not the influence of the steam parameters variation and the selection of the appropriate distillation technology on the plant global efficiency and on the final cost of the obtained products (electricity and ethanol) (Modesto *et al*., 2006; Pellegrini e Oliveira, 2007; Ensinas *et al*., 2007; Pistore e Lora, 2006).

2. GENERAL ASPECTS

Co-generation systems used in the Brazilian sugar-cane industry are based in use of backpressure steam turbines. However, the current tendency is the use of condensation turbines.

The systems with extraction/condensing turbines (CEST) are recommended for maximizing the electric power produced, or where the demand of heat is reduced, up to the point of impeding that the demand of electricity is assisted in the condition of maximum thermal load, for a system with backpressure turbine.

The maximization of excess electricity produced in sugar-cane industry depends on the following factors: cogeneration system configuration, efficiency in electricity used and steam consumed in the different processes and the steam operation conditions. Therefore, energetic optimization of different processes that compose the plant is very important to the improvement of thermal and economic revenue in plants of sugar and alcohol production.

Among the processes that demand considerable use of energy is the distillation process, which is necessary to remove the excess of water of the fermented wine obtained in the fermentation process.

The main disadvantage of the distillation process is its high energy consumption in relation to requested usefulness, such as steam and cooling water, for the respective heating and cooling processes.

Different distillation technologies are used at the Brazilian plants for ethanol production. A typical case is presented in the "Fig. 1". The thermal energy consumed by the system is supplied directly from steam of co-generation system or from a thermal cascade in the plant. For example, the distillation system can be fed with exhaustion steam of drive turbines or with vegetable steam retired from evaporation system.

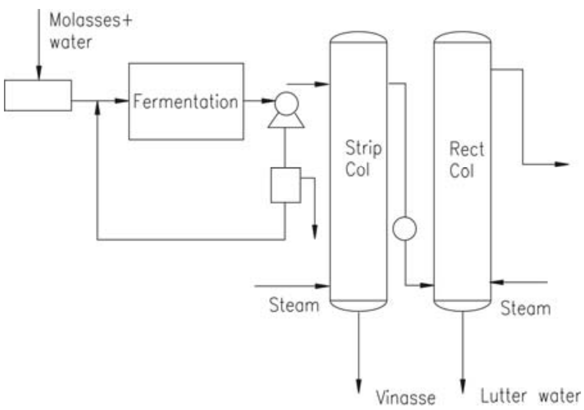

Figure 1. Conventional distillation process

In the case of a plant that exports electricity, each steam ton that is not used to satisfy demand in distillery, due to a improvement in its process, can be used to increase the electricity in the condensation turbines. This way, the implementation of columns operating in thermal cascade, working under pressures lower than the atmospheric, can be very attractive. The vacuum application can be interesting in arrangements as the "split feed ".

The distillation with "split feed" is characterized by the energy integration of the pressurized distillation columns and the ones operating under vacuum, in hydrated ethanol fuel production - AEHC "Fig. 2".

The main characteristic of this process (split fid) are (Dedini, 2007):

- ✓ 60% in pressurized process (steam consumption)
- ✓ 40% in vacuum process (without steam consumption)
- ✓ Use of exit steam
- ✓ Do not use thermocompressor
- ✓ Steam Consumption: 1,6 kg / liter AEHC

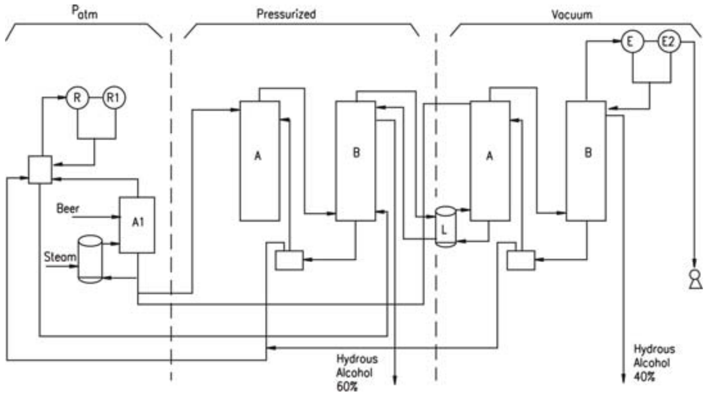

Figure 2. Distillation process “Split-feed”

There are three basic levels of steam pressure usually used in the Brazilian plants and distilleries:

- 2.1 MPa ;
- 4.2 MPa ;
- 6.5 MPa .

It is worth to point out that the exact pressure parameters are about of the basic values presented above, but it can be found plants with pressure levels from 8 to 12 MPa. The steam temperature presents small variations for each pressure levels. The values commonly found are 300ºC, 400ºC and 500ºC, respectively to each pressure level mentioned above (Zampieri, 2005).

The Brazilian plants, in the same way that ones in other places in the world, are characterized by steam consumption in the process around 500 steam kg / ton of processed cane (Lora et al., 2006). In this condition, almost all produced bagasse is consumed for steam generation to 2.2 MPa /300 °C. The amount of steam produced in conditions previously described is enough to produce all the thermal energy, electricity and mechanical power, demanded for plant operation (Hassuani et al., 2005).

Indicators

The indicators that characterized the energy use in autonomous distillery are:

- Ig.bruto. Specific index of gross electricity generation, expressed in kWh of gross electricity per ton of ground cane (kWh/tc), including the plant own consumption;

- Ig.exc. Specific index of surplus electricity generation, expressed in kWh of surplus electricity per ton of ground cane (kWh/tc). In this case, the plant own consumption is not considered;

The exergetic efficiency of a co-generation system can be defined as the relationship among the exergy products (heat and electricity) and the exergy in the entrance of the systems (bagasse exergy) “Eq. (1)”:

$$\eta_{\text{exerg, cog}} = \frac{(E_W + E_Q)}{E_F} \tag{1}$$

Where:
$\eta_{\text{exerg, cog}}$= Exergetic efficiency of the co-generation system
E_w = Exergy of mechanic and electrical power

E_Q= Exergy of the heat input to the system
E_F= Bagasse exergy

With the purpose of analyzing the system exergetic global efficiency (co-generation coupled to the distillation plant), it is considered the two main products of the plant (surplus electricity and ethanol). The system global exergetic efficiency is calculated using "Eq. (2)".

$$\eta_{exerg,global} = \frac{E_{e\tan ol} + E_{e.exced}}{E_{cana}} \tag{2}$$

Where:

E_{etanol} - Ethanol Exergy produced[kW]
$E_{e.exced.}$ – Surplus electricity [kW]
$E_{cana.}$ – Energy in ground sugar-cane [kW]

Thermo-economic evaluation concepts and methodology

The basic concepts for thermo-economics application (Lozano and Valero, 1993) are the exergetic cost (B*), that expresses the quantity of primary exergy required to obtain a functional product and the unitary unit cost (k); defined in "Eq. (3)", and that indicates the primary exergy consumption required by an system to generate a unit of exergy flow:

$$k = \frac{B^*}{B} \tag{3}$$

As real processes are not reversible (it happens with exergy losses and destruction), the exergy costs will always be greater than the product exergy (B* > B).

For the thermo-economics analysis in a cogeneration plant, the first step to be followed is the determinations of the plant physical structure, which is a simplified scheme of the system. It is especially important to define the necessary desegregation level, since it has a great impact on the quality of the results. It is important also to know the exergy value of each flow, the main equipments (or units) and their associated costs, and the matter and energy exchange patterns between units.

Case study of conventional and advanced distillation systems of autonomous distilleries, operating with high steam parameters.

Considering the highest steam parameters that are being implemented in sugar and alcohol plants in Brazil, this study assesses three cogeneration systems operating with the parameters shown in "Tab. 1". A base case is established with comparison purposes. The base consists of a cogeneration plant operating with steam parameters of 4.1 MPa e 420 °C coupled with a conventional distillation system (distillation columns operating with atmospheric pressure).

Table 1. The base (reference case) and the two proposed repowering scenarios with CEST and different distillation technologies.

Equipment and parameters	**Base case**	**D1**	**D2**
Boiler: 4.1 MPa (abs) @ 420°C	X		
Boiler: 6.6 MPa (abs) @ 520°C		X	
Boiler: 12 MPa (abs) @ 560°C			X
Process Steam Consumption (Conventional distillation) 361 kg_v/tc	X	X	X
Process Steam Consumption (Advanced distillation) Split-feed 325 kg_v/tc	X	X	X

Aiming the establishment of common reference scenery for the study cases of "Tab. 1", their evaluation were s accomplished considering constant the parameters described in "Tab. 2".

Table 2. Assumed general parameters during the calculations

Production and energy data	
Ethanol production [m^3/h]	22.58
Cane milling capacity [tc/h]	380
Cane harvest duration [%]	210 / 85
Steam production [t/h]	200
Process steam consumption[kg_v/tc]	526
LHV of bagasse[kJ/kg]	7562
Bagasse moisture [%]	50
Electric energy consumption [kWh]	6000
Steam extraction from CEST 2 [Mill and Process] [ton/h]	74
Steam extraction from CEST 1 [Process] [ton/h]	69-56
Condensation pressure CEST 1 [kPa]	5.94
Condensation pressure CEST 2 [kPa]	7.35
Boiler feed water temperature [°C]	98.31
Cane milling system	
Mill 1 – 4 – multiple stages turbine	
Inlet steam pressure [KPa abs]	2200
Inlet steam temperature[ºC]	320-375
Exhaust steam pressure [KPa abs]	170
Isentropic efficiency [%]	90

The vapor consumption in the process which this related to the applied distillation technology was considered equal to 361kgv/tc for the f conventional distillation technology operating at atmospheric pressure, what demands 2.4 steam kg / liter AEH. The steam consumption reduction in the process was obtained by considering the utilization of Split-feed distillation, which allows obtaining a decrease in plant steam consumption up to 1.8 steam kg / liter AEH. In this case the steam consumption adopted was of 325 kgv/tc. . A black box model will be considered in the simulation of the distillation systems, and considering only the hydrated alcohol production. The cane exergy was calculated considering Nebra and Fernández (2005) methodology, while for fermented wine and hydrated alcohol was considered the methodology of Modest et al. (2005). The mass and energy balances in heating systems, evaporation and distillation distillery were accomplished using the software EES, with following considerations:

- Only water and sucrose are present in the solution (Pz=100%)
- Efficiency considered in evaporation system equal to 1.866 kg evaporated water/kg steam.
- Cogeneration system steam is used to heat up juice cane from of 85°C to 105 °C in the heating system.
- Amount of vapor consumed in distillation, considering distillation conventional technology, equal to 2.4 kg steam/liter hydrated alcohol (Dedini 2007).
- Amount of vapor consumed in distillation process, considering Split-feed technology, equal to 1.8 kg steam/liter hydrated alcohol (Dedini 2007).
- The exergy calculation of hydrated alcohol exergy, it is only considered the ethanol-water mixture.

The physical structure for sceneries analyzed is presented in “Fig. 3”, and the productive structure is presented in “Fig. 4”.

With data from “Tab. 1” and “Tab. 2” the different schematic were modeled in Gate-Cycle. From these models it was possible to obtain the performance indicators, such as first law indicator FUE, as second law indicators η_{exerg}, $\eta_{exerg,\ global}$. The main characteristics of the co-generation system are presented in “Tab. 3”. The “Table 4” shows the values of these performance indicators considering the coupling of the cogeneration plant to a conventional distillation technology. In “Tab. 5” it is considered the integration of the cogenerations system with an advanced distillation technology that allows for reduction in steam consumption in distillation process.

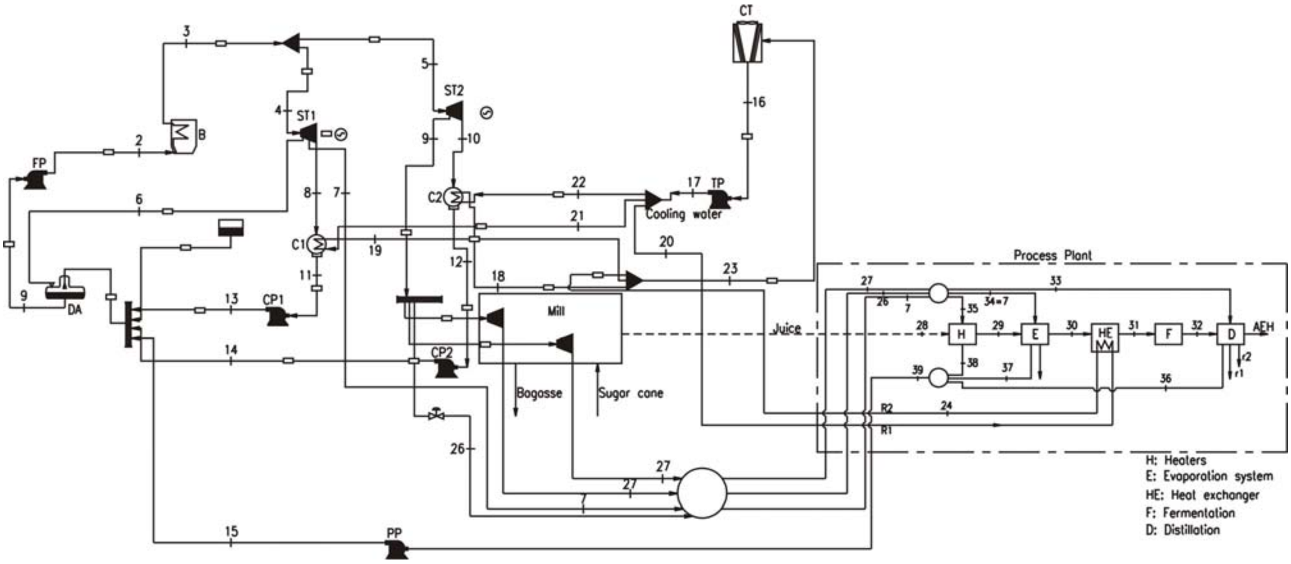

Figure 3. Physical structure for sceneries Base, D1 and D2

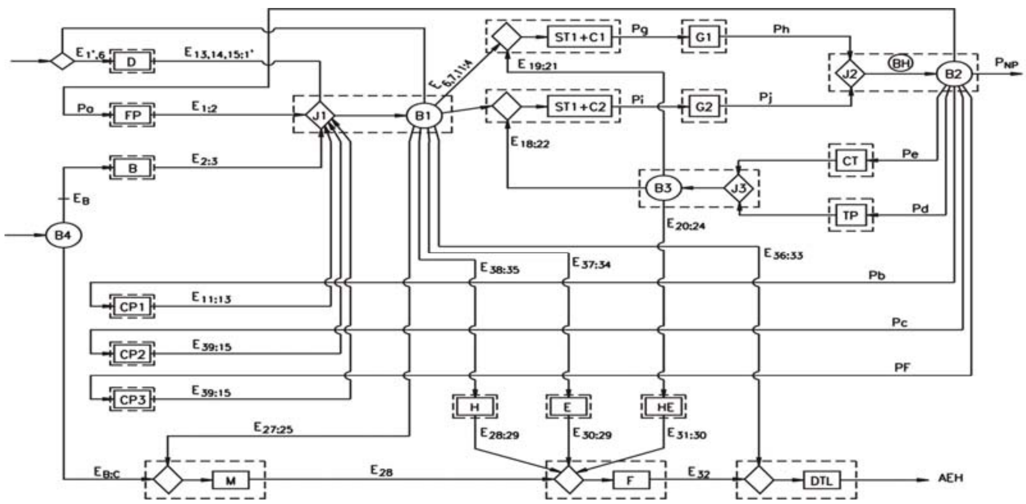

Figure 4. Productive structure for sceneries Base, D1 and D2.

Table 3. Energy consumption and generation in different analyzed cases

Scenario	Process Steam Consumption [kg_v/tc]	Specific Consumption of Mechanical E [kWh/tc]	Installed Power [MW]	Surplus Electric Power [MW]
Base	361	20.66	26.63	18.44
	325	20.66	26.63	19.84
D1	361	20.66	34.07	25.68
	325	20.66	34.07	27.12
D2	361	20.66	39.92	31.52
	325	20.66	39.92	32.64

Table 4. Criteria for cogeneration plant performance assessment without steam reduction in the distillation process

Scenario	FUE %	$\eta_{exerg,\ cog}$ %	$\eta_{exerg,\ global}$ %	$I_{g.exced.m}$ kWh/tc	$I_{g.exced.b}$ kWh/tc
Base	77	23.73	29.02	48.53	243.51
D1	77.4	26.19	29.53	67.58	316.92
D2	78.1	27.15	30.38	82.95	382.85

Table 5. Criteria for cogeneration plant performance assessment with steam reduction in the distillation process

Scenario	FUE %	$\eta_{exerg,\ cog}$ %	$\eta_{exerg,\ global}$ %	$I_{g.exced,}$ kWh/tc	$I_{g.exced.b}$ kWh/tc
Base	72.2	23.48	29.28	52.21	261.96
D1	73	25.90	29.79	71.37	334.67
D2	74	26.82	30.58	85.91	396.52

The “Figure 5” presents the different values of exergetic unitary cost of generated electricity and hydrated alcohol produced, for the different scenarios in the cogeneration-distillation plant system. In this figure the exergetic cost variation is shown in function of applied distillation technology (conventional or with reduction in steam consumption, indicated with the tag "red”) and steam parameters used in cogeneration system.

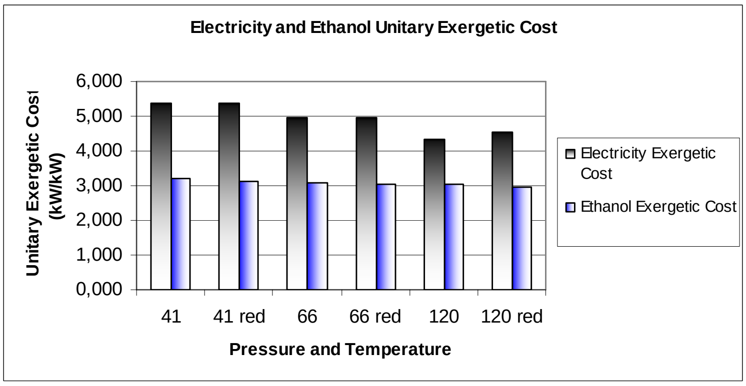

Figure 5. Unitary exergetic costs for evaluated scenarios.

The main results are as following:

In electricity generation, the exergetic cost for the different analyzed scenarios, without steam consumption reduction were 5.36, 4.94 and 4.34 kW/kW. When it was considered the steam consumption reduction, the results for unitary exergetic cost was 5.37, 4.95, 4.56, respectively to the steam pressure levels utilized (4.1, 6.6 and 12 MPa). It is observed a small increase in electricity unitary exergetic cost when considered the steam consumption reduction, this increase is originated by the increase in water condensation pressure in cogeneration plant system.

In relation to hydrated alcohol produced, the exergetic costs, when the conventional distillation technology is applied were of 3.19, 3.10 and 3.05 kW/kW. For advanced distillation technology, the results were 3.14, 3.05 and 2.97 kW/kW. It is observed a reduction in 2% for ethanol unitary exergetic cost, for each scenario. This is a consequence of increase in distillation system efficiency.

Conclusions

The energy use factor for the considered scenarios has an increase of 1.43%, when steam parameters are increased and conventional distillation technology is used. However, this indicator considers the equivalence within heat and work, so it is not possible the correct evaluation of cogeneration system operation, considering only this index. The increase of steam pressure and temperature lead to an improvement of l 13% in exegetics indicators of the cogeneration system and 5.38% in global exergetic indicator of the integrated cogeneration-distillation plant. The reduction to 11% in steam consumption of distillation process leads to an increase of approximately 6% in surplus energy from distillation.

The obtained indicators show that a better energy use of cogeneration-distillation plant can be achieved when operating with high steam parameters and process steam consumption reduction. Therefore, during the development of new cogeneration projects it is very important the application of technologies that allow the reduction of steam specific consumption. The scenario that presents better results is D2, due the best input energy c use and lower exergetic costs from ethanol production, due to the utilization of advanced distillation technology.

The results obtained in present work allowed quantifying, through determination of performance parameters (based on first and second law of thermodynamics) the improvement in the process of an integrated cogeneration-distillation plant. Analyzing the increase in the parameters of used steam and its consumption reduction, it is clear that the implementation of these the advanced distillation technologies and high steam parameters is advantageous , but it is still necessary to conduct an economic analysis to justify its implementation. Future works will have these objectives.

3. ACKNOWLEDGEMENTS

The authors would like to acknowledge Dedini engineers for available process data and CAPES for the financial support to do this study.

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