

Exergy Analysis of Different Configurations of Multiple-effect Evaporators in Sugarcane Mills

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Abstract. Multiple-effect evaporators are the main consumers of backpressure steam in sugarcane mills. The purpose of these equipment is to concentrate juice extracted in the milling process into syrup. During this process, many types of steam can be produced and used as heat sources in other processes. In this sense, one could say that multiple-effect evaporators are responsible for the integration of the utilities plant and the process plant in sugarcane mills. Thus, any optimization procedure aiming to enhance power generation in sugarcane mills must take into account possible modifications in this process. This paper intends to analyze and compare, based on exergy concept, different configurations of these systems. These configurations have been proposed by different authors, but the analysis focused mainly in energy concepts. The methodology used has been successfully applied to a real multiple-effect evaporator of a Brazilian sugarcane mill.

Keywords: exergy analysis, multiple-effect evaporators, sugarcane mills

1. Introduction

According to UNICA (“*União da Agroindústria Canavieira de São Paulo*”), the 2006/07 sugarcane harvest will achieve 375 million tons, 11% higher than the last harvest. Also, 89 new projects are being developed in Brazil to increase the production of sugar and alcohol in the next 5 years. These numbers indicate that the sugar and alcohol industry is gaining more and more importance over the last years. This increase is a result of the new incentives for the alcohol market and high prices of sugar from cane in international markets.

Accompanying this growth, an effort is being made to improve the use of energy in the industrial production and in cogeneration facilities (FAPESP, 2002; Prieto, 2003; Pellegrini and Oliveira Jr., 2005; Zanetti et al., 2005; Modesto and Nebra, 2005).

As multiple-effect evaporators are the main consumers of backpressure steam in Brazilian sugarcane mills, any optimization procedure aiming to improve energy use in sugarcane mills must take into account possible modifications in this process (Christodoulo, 1996).

Previous works have developed exergy analysis for this process (Baloh, 1968; Goutte, 1987; Guallar and Valero, 1989; González, 1990; Paz and Cárdenas, 1997; Tekin e Bayramoğlu, 1997 and 2001; Fernández-Parra and Nebra, 2001; Fundora, 2002; Bayrak et al., 2003), but the exergy calculations were based on different correlations and reference systems. Hence, no general methodology could be developed for the analysis of processes in the sugar industry.

Recently, Nebra and Fernández-Parra (2005) reviewed more than 20 papers on the calculation of sucrose-water solutions, and proposed a method for the calculation of the exergy of these solutions. The method has been successfully applied to a real system by Pellegrini and Oliveira Jr (2006).

This paper intends to analyze and compare, based on exergy concept, different configurations of multiple-effect systems, as proposed in the works cited above. For this purpose a general model has been developed, which allows the analysis of a triple, quadruple and quintuple effects with the same input data.

2. Multiple-effect Evaporators in Sugarcane Mills

Robert type multiple-effect evaporators are the most common used in Brazilian mills, even though plate evaporators are used in some mills.

The purpose of this equipment is to concentrate juice extracted in the milling process into syrup. Still, this process is responsible for the “production” of the so-called vegetable steam, used for different heating purposes in the mill (for instance, juice treatment, cooking and distillation).

Figure 1 shows the schematic representation of a quintuple effect evaporator with a thermo-compression device for the first effect and flash tanks.

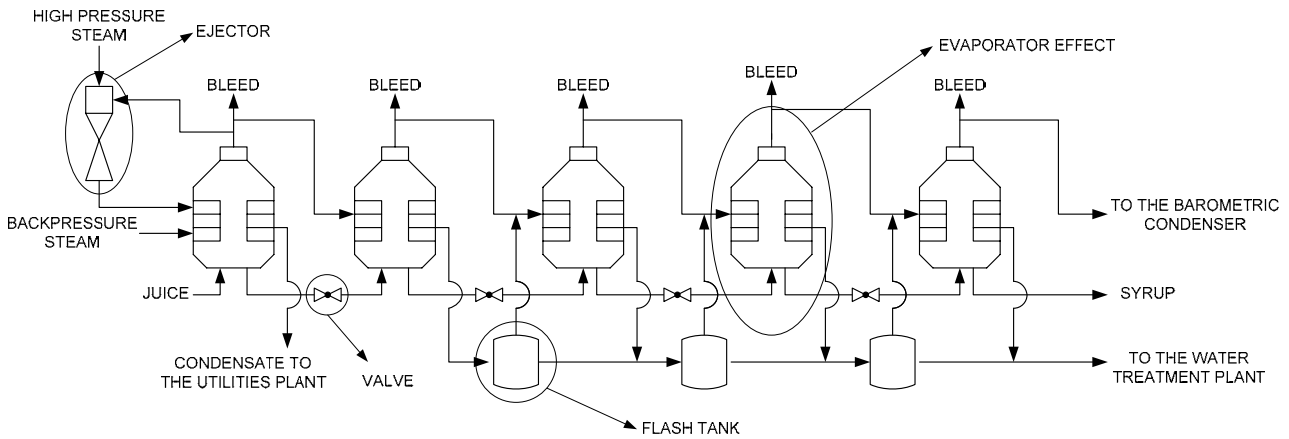


Figure 1. Schematic Representation of a Quintuple-effect.

Quintuple effects are commonly used in sugarcane mills, even though the use of flash tanks and ejectors might vary from one mill to the other.

Backpressure steam (in Brazil, 140°C@2.5 bar) from the turbines is fed to the first effect, which also receives juice at 115°C and mass fraction of solids of 12-15%.

Condensate from the first effect returns to the utilities plant (some mills return also condensate from the second effect), and the concentrated juice goes to next effect. Part of the steam “produced” in this effect goes to next effect, and part goes to process as a heat source.

In the following effects, the steam produced during the concentration of the juice is used only as heat source for the next effect, until the fifth effect. The steam from this effect is sent to a barometric condenser, and then joins the condensates from the other effects. Condensates from the second, third and fourth effects pass through a flashing process, from one effect to the other, in order to re-use part of its energetic content. Then, they are sent to the wastewater treatment plant and/or used as imbibition water in the milling process.

Although, it is not a common practice in Brazil, it is possible to use steam from all five effects for heating purposes, what would reduce the consumption of backpressure steam.

Studies for a better integration of these bleeds into the sugar and alcohol production processes can be found in Higa (2003).

3. Properties Calculations

Based on the work of Nebra and Fernández-Parra (2005), the following correlations were used to calculate specific enthalpy, specific entropy and specific exergy of the different flows of sucrose-water solutions in the process.

3.1. Solubility

According to Peacock (1995), solubility (x_{sol}) is given by:

$$x_{sol} = 63.753 + 0.13542 \cdot t + 8.869 \cdot 10^{-4} \cdot t^2 - 2.222 \cdot 10^{-6} \cdot t^3 \quad (1)$$

When the concentration of the solution is above the solubility point, two phases will coexist: water-sucrose solution and sugar crystals.

With the solubility value, it is possible to find the saturation molar fraction of sucrose through:

$$y_{suc,sat} = \frac{\frac{x_{sol}}{MM_{suc}}}{\frac{x_{sol}}{MM_{suc}} + \frac{(1-x_{sol})}{MM_w}} \quad (2)$$

3.2. Specific Heat Capacity

The best available correlation for the specific heat (kJ/kg.K) is given by (Nebra and Fernández-Parra, 2005):

$$c_p = 4.1868 - 0.0297 \cdot x + 4.6 \cdot 10^{-5} \cdot x \cdot Pz + 7.5 \cdot 10^{-5} \cdot x \cdot t \quad (3)$$

The main advantage of this correlations is that it takes into account both temperature and purity effects.

3.3. Specific Enthalpy and Specific Entropy

Enthalpy (kJ/kg) and entropy (kJ/kg.K) can be obtained through the integration of the following equations (Smith et al., 2000):

$$dh = c_p \cdot dT + \left[v - T \cdot \left(\frac{\partial v}{\partial T} \right)_p \right] \cdot dp \quad (4)$$

$$ds = c_p \cdot \frac{dT}{T} + \left(\frac{\partial v}{\partial T} \right)_p \cdot dp \quad (5)$$

For the integration, the reference state considered was null enthalpy and entropy at 0°C and 0,006 bar (in accordance with the function STEAM_IAPWS of EES software (Klein and Alvarado, 2005), used for the calculations). Thus, using Eq. (3) in Eqs. (4) and (5), neglecting the integral referred to the effect of pressure, gives:

$$h = (4.1868 - 0.05018265 \cdot x + 4.6 \cdot 10^{-5} \cdot x \cdot Pz) \cdot t + 3.75 \cdot 10^{-5} \cdot x \cdot t^2 \quad (6)$$

$$s = (4.1868 - 0.05018265 \cdot x + 4.6 \cdot 10^{-5} \cdot x \cdot Pz) \cdot \ln \left(\frac{T}{T_0} \right) + 7.5 \cdot 10^{-5} \cdot x \cdot (T - T_0) \quad (7)$$

A word of caution must be left here regarding the second integration. It is necessary to change the temperature scale before the integration (Nebra and Fernández-Parra, 2005).

3.4. Coefficient of Activity

The coefficient of activity of water in sucrose-water solution is given by Starzak and Peacock (1997) cited in Nebra and Fernández-Parra (2005):

$$\ln \gamma_w = \frac{-2121.4052}{T} \cdot y_{suc}^2 \cdot (1 + a \cdot y_{suc} + b \cdot y_{suc}^2) \quad (8)$$

where the coefficients are:
 $a = -1.0038$
 $b = -0.24653$

The reference values for Eq. (8) are: $\gamma_w = 1$ for $y_{suc} = 0$, accordingly $y_w = 1$.

Using the Gibbs-Duhem relation it is possible to calculate the sucrose activity in the solution through (Smith et al., 2000):

$$\sum_i y_i \cdot d \ln \gamma_i = 0 \Rightarrow \int d \ln \gamma_{suc} = - \int \frac{y_w}{y_{suc}} \cdot d \ln \gamma_w \quad (9)$$

The integration limits were defined between a generic state and the saturated state corresponding to the maximum solubility (x_{sol}).

The state of maximum solubility corresponds to a state where the solution is in equilibrium with the solid pure sucrose; so, the reference value for the sucrose activity corresponds to pure sucrose:

$$\gamma_{suc,sat} = \frac{1}{Y_{suc,sat}} \quad (10)$$

Inserting Eq. (8) in Eq. (10), and integrating between a generic state and the saturated state gives:

$$\ln\left(\frac{\gamma_{\text{suc,sat}}}{\gamma_{\text{suc}}}\right) = \frac{2121.4052}{T} \left[2 \cdot y_{\text{suc}} + \frac{(3 \cdot a - 2)}{2} \cdot y_{\text{suc}}^2 + \frac{(4 \cdot b - 3 \cdot a)}{3} \cdot y_{\text{suc}}^3 - b \cdot y_{\text{suc}}^4 \right] \begin{matrix} \text{saturated} \\ \text{state} \\ \text{generic} \\ \text{state} \end{matrix} \quad (11)$$

3.5. Specific Exergy

Given the environment proposed by Szargut (Szargut et al., 1988), the exergy of sucrose-water solutions can be calculated according to (Kotas, 1985):

✓ Specific Physical Exergy (kJ/kg):

$$b_{\text{ph}} = h(T, p) - h(T_0, p_0) - T_0 \cdot (s(T, p) - s(T_0, p_0)) \quad (12)$$

✓ Specific Chemical Exergy (kJ/kg):

$$b_{\text{ch}} = \frac{1}{MM_{\text{sol}}} \left[(y_{\text{suc}} \cdot b_{\text{ch,suc}}^0 + y_{\text{w}} \cdot b_{\text{ch,w}}^0) + R \cdot T_0 \cdot (y_{\text{suc}} \cdot \ln(y_{\text{suc}} \cdot \gamma_{\text{suc}}) + y_{\text{w}} \cdot \ln(y_{\text{w}} \cdot \gamma_{\text{w}})) \right] \quad (13)$$

where $b_{\text{ch,suc}}^0 = 6007800 \text{ kJ/kmol}$

$b_{\text{ch,w}}^0 = 900 \text{ kJ/kmol}$

3.6. Water and Steam Properties

Fluid property library STEAM_IAPWS of the EES software (Klein and Alvorado, 2005) was used for the calculation of water and steam properties.

4. Energy and Exergy Balances

In what follows, the first and second laws are applied to the control volumes considered (Fig. 2 through 5).

4.1. For a single effect

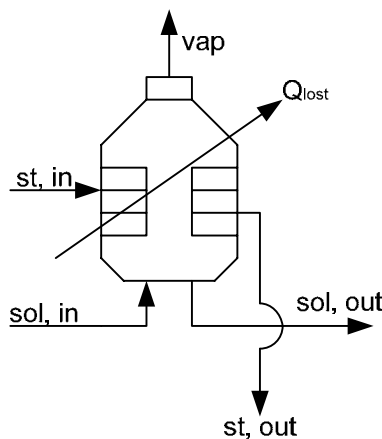


Figure 2. Control volume considered for a single effect.

Mass Balance:

$$\text{Heating Steam: } \dot{m}_{\text{st,in}} = \dot{m}_{\text{st,out}} \quad (14)$$

$$\text{Solution: } \dot{m}_{\text{sol,in}} = \dot{m}_{\text{sol,out}} + \dot{m}_{\text{vap}} \quad (15)$$

$$\text{Solids: } \dot{m}_{\text{sol,in}} \cdot x_{\text{in}} = \dot{m}_{\text{sol,out}} \cdot x_{\text{out}} \quad (16)$$

Energy Balance (First Law):

$$\dot{m}_{sol,in} \cdot h_{sol,in} + \dot{m}_{st,in} \cdot h_{st,in} = \dot{m}_{sol,out} \cdot h_{sol,out} + \dot{m}_{vap} \cdot h_{vap} + \dot{m}_{st,out} \cdot h_{st,out} + \dot{Q}_{Lost} \quad (17)$$

$$\eta_e = 1 - \frac{\dot{Q}_{Lost}}{(\dot{m}_{st,in} \cdot h_{st,in} - \dot{m}_{st,out} \cdot h_{st,out})} \quad (18)$$

$$(\dot{m}_{st,in} \cdot h_{st,in} - \dot{m}_{st,out} \cdot h_{st,out}) \cdot \eta_e = U \cdot A \cdot (T_{st,in} - T_{sat,effect}) \quad (19)$$

Second Law:

$$(\dot{m}_{sol,out} \cdot s_{sol,out} + \dot{m}_{vap} \cdot s_{vap} + \dot{m}_{st,out} \cdot s_{st,out}) - (\dot{m}_{sol,in} \cdot s_{sol,in} + \dot{m}_{st,in} \cdot s_{st,in}) = -\frac{\dot{Q}_{Lost}}{T_0} + \dot{S}_g \quad (20)$$

Exergy Balance:

$$(\dot{m}_{sol,in} \cdot b_{sol,in} + \dot{m}_{st,in} \cdot b_{st,in}) = (\dot{m}_{sol,out} \cdot b_{sol,out} + \dot{m}_{vap} \cdot b_{vap} + \dot{m}_{st,out} \cdot b_{st,out}) + \dot{I} \quad (21)$$

4.2. Valve

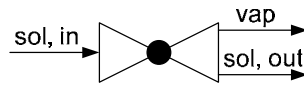


Figure 3. Control volume considered for a valve.

Mass Balance:

$$\text{Solution:} \quad \dot{m}_{sol,in} = \dot{m}_{sol,out} + \dot{m}_{vap} \quad (22)$$

$$\text{Solids:} \quad \dot{m}_{sol,in} \cdot x_{in} = \dot{m}_{sol,out} \cdot x_{out} \quad (23)$$

Energy Balance (First Law):

$$\dot{m}_{sol,in} \cdot h_{sol,in} = \dot{m}_{sol,out} \cdot h_{sol,out} + \dot{m}_{vap} \cdot h_{vap} \quad (24)$$

Second Law:

$$(\dot{m}_{sol,out} \cdot s_{sol,out} + \dot{m}_{vap} \cdot s_{vap}) - (\dot{m}_{sol,in} \cdot s_{sol,in}) = \dot{S}_g \quad (25)$$

Exergy Balance:

$$(\dot{m}_{sol,in} \cdot b_{sol,in}) = (\dot{m}_{sol,out} \cdot b_{sol,out} + \dot{m}_{vap} \cdot b_{vap}) + \dot{I} \quad (26)$$

4.3. Flash Tank

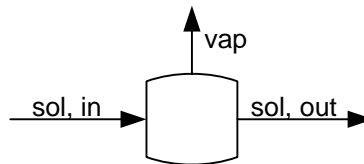


Figure 4. Control volume considered for a flash tank.

Mass Balance:

$$\dot{m}_{liq,in} = \dot{m}_{liq,out} + \dot{m}_{vap,out} \quad (27)$$

Energy Balance (First Law):

$$\dot{m}_{liq,in} \cdot h_{liq,in} = \dot{m}_{liq,out} \cdot h_{liq,out} + \dot{m}_{vap,out} \cdot h_{vap,out} \quad (28)$$

Second Law:

$$\left(\dot{m}_{liq,out} \cdot s_{liq,out} + \dot{m}_{vap,out} \cdot s_{vap,out} \right) - \left(\dot{m}_{liq,in} \cdot s_{liq,in} \right) = \dot{S}_g \quad (29)$$

Exergy Balance:

$$\left(\dot{m}_{liq,in} \cdot b_{liq,in} \right) = \left(\dot{m}_{liq,out} \cdot b_{liq,out} + \dot{m}_{vap,out} \cdot b_{vap,out} \right) + \dot{I} \quad (30)$$

4.4. Ejector

In some mills, the total amount of backpressure steam generated by the turbines is not sufficient to run the system. In such cases, it is necessary to use reduction valves that take high pressure steam from the boilers to the process pressure. Whenever this situation occurs, it is possible to use thermo-compression devices (ejectors).

The operation of such devices is based on using high-pressure steam flowing through an ejector, aiming at recompress part of the vapor separated from the juice in the effect, to be used in the same effect or in previous ones (Fernández-Parra and Nebra, 2001).

Figure 5 shows a schematic representation of an ejector:

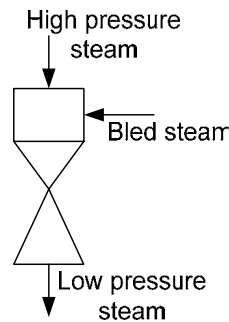


Figure 5. Control volume considered for the ejector.

The most important relation of a thermo-compressor is its “drag relation” (μ), given by the ratio of bled steam mass to the high pressure steam mass. According to Hugot (1986), this relation might be calculated through the Truffault formula:

$$(\mu_0 + 1) = \frac{80}{t_{low\ pressure\ steam} - t_{bled\ steam}} \cdot \left[\log \left(\frac{P_{high\ pressure\ steam}}{P_{low\ pressure\ steam}} \right) - 0.01 \cdot \left(t_{bled\ steam} - 100 \right) \right] \quad (31)$$

$$\mu = \frac{\dot{m}_{bled\ steam}}{\dot{m}_{high\ pressure\ steam}} = 0.95 \cdot \mu_0 \quad (32)$$

Thus, it is possible to set the mass, energy and exergy balances, and also to apply the second law to the control volume shown in Fig. 5.

Mass Balance:

$$\dot{m}_{high\ pressure\ steam} + \dot{m}_{bled\ steam} = \dot{m}_{low\ pressure\ steam} \quad (33)$$

Energy Balance (First Law):

$$\dot{m}_{\text{high pressure steam}} \cdot h_{\text{high pressure steam}} + \dot{m}_{\text{bled steam}} \cdot h_{\text{bled steam}} = \dot{m}_{\text{low pressure steam}} \cdot h_{\text{low pressure steam}} \quad (34)$$

Second Law:

$$\dot{m}_{\text{low pressure steam}} \cdot s_{\text{low pressure steam}} - \dot{m}_{\text{high pressure steam}} \cdot s_{\text{high pressure steam}} - \dot{m}_{\text{bled steam}} \cdot s_{\text{bled steam}} = \dot{S}_g \quad (35)$$

Exergy Balance:

$$\dot{m}_{\text{high pressure steam}} \cdot b_{\text{high pressure steam}} + \dot{m}_{\text{bled steam}} \cdot b_{\text{bled steam}} = \dot{m}_{\text{low pressure steam}} \cdot b_{\text{low pressure steam}} + \dot{I} \quad (36)$$

5. Simulation Considerations

The balances just introduced have been implemented in EES software (Klein and Alvorado, 2005), and the following considerations were made:

- ✓ The pressure distributions used for the triple, quadruple and quintuple effects was those given in Hugot (1986);
- ✓ Only water is present in vapor phase;
- ✓ Only water and sucrose are present in the solution ($P_z = 100\%$);
- ✓ The solution leaves each equipment in equilibrium with its vapor. In this way, the Modified Raoult's Law was used to model this equilibrium:

$$p_t = y_w \cdot \gamma_w \cdot p_{\text{sat}}(T_{\text{sol}}) \quad (37)$$

- ✓ The heating steam leaves each effect as saturated liquid;
- ✓ The energetic efficiency of each effect (η_e) is 0.98;

It has been analyzed three different scenarios:

- Comparison of the number of effects with no bleeding;
- Comparison of different configurations with various bleedings;
- Use of thermo-compression for a real mill.

For the comparisons, four exergetic indexes have been used:

- ✓ Exergy Destroyed Rate ($\dot{B}_{\text{destroyed}}$) – related to the thermodynamic inefficiencies of the system. This index makes reference to the Gouy-Stodola Theorem (Bejan, 1996):

$$\dot{B}_{\text{destroyed}} = \dot{W}_{\text{lost}} = T_0 \cdot \dot{S}_g \quad (38)$$

- ✓ Exergy Lost Rate (\dot{B}_{lost}) – related to mass flow rates leaving the control volume without being in equilibrium with the environment, and that are not used any further (Bejan, Tsatsaronis e Moran, 1996).
- ✓ Exergy Efficiency (η_{ex}) – defined as the ratio between the exergy spent for the separation process to the exergy made available by the backpressure steam condensation. Following Bejan, Tsatsaronis e Moran (1996), the product would be the separation process, and the fuel would be the condensation of backpressure steam:

$$\eta_{\text{ex}} = \frac{\left(\dot{m}_{\text{syrup}} \cdot b_{\text{syrup}} + \sum_{\text{out}} \dot{m}_{\text{steam}} \cdot b_{\text{steam}} + \dot{m}_{\text{condensate}} \cdot b_{\text{condensate}} \right) - \dot{m}_{\text{juice}} \cdot b_{\text{juice}}}{\left(\dot{m}_{\text{backpressure steam}} \cdot b_{\text{backpressure steam}} - \dot{m}_{\text{condensate from backpressure steam}} \cdot b_{\text{condensate from backpressure steam}} \right)} \quad (39)$$

- ✓ Improvement Potential (IP) - described in Rivero (1997), this index tries to bring together qualitative aspects (efficiency) and quantitative ones (exergy destroyed and lost rates, i.e., irreversibilities). According to that

author, in some components of thermal systems, in which the irreversibilities are very high, even a small efficiency gain might lead to great operational advantages. At the same time, there are components which “produce” low irreversibility rates; hence its reduction would not lead to a real gain. This index is defined by:

$$IP = (1 - \eta_{ex}) \cdot \dot{B}_{destroyed} + \dot{B}_{lost} \quad (40)$$

6. Results

6.1. Influence of the number of effects and flash tanks

Table 1 shows the results of the simulations for 1 kg/s of juice with 15% mass fraction of solids entering the first effect, and leaving with 65% mass fraction of solids (no bleeding or flash tanks were considered).

Table 1. Simulation results for different number of effects with no bleeding or flash tanks.

Number of Effects	Backpressure Steam Mass Flow Rate (kg/s)	Exergy Destroyed Rate (kW)	Exergy Lost Rate (kW)	Exergy Efficiency (%)	Improvement Potential (kW)
3	0.253	95.20	126.84	35.48	188.26
4	0.190	73.96	113.09	34.22	161.74
5	0.152	61.20	104.77	32.92	145.82

Although the exergy efficiency does decrease with the number of effects, this result might be misleading. The exergy content of the condensates for a triple effect is greater than for a quadruple effect, which is greater than for a quintuple effect. Thus, more exergy is lost in a triple effect than in the others. Also, as more backpressure steam is needed for a triple effect in order to achieve the same mass fraction of solids at the outlet, more exergy is destroyed in the process. Also, as the pressures in the first and last effects are set, as more effects are added the temperature difference between the juice and the heating steam become smaller, and less entropy is generated due to heat transfer (less exergy is destroyed). These results might, as well, be seen with Improvement Potential Index. As more effects are added, fewer opportunities for improvements exist.

One possible manner to use the exergy of the condensates is the use of flash tanks between two consecutive effects. For instance, condensate from the 2nd effect might pass through a flash tank “producing” steam to be used in the 3rd effect (see Fig. 1). Table 2 summarizes the results obtained with flash tanks.

Table 2. Simulation results for different number of effects with flash tanks, but no bleeding.

Number of Effects	Backpressure Steam Mass Flow Rate (kg/s)	Exergy Destroyed Rate (kW)	Exergy Lost Rate (kW)	Exergy Efficiency (%)	Improvement Potential (kW)
3	0.249	96.27	124.13	33.96	187.71
4	0.185	75.71	108.54	30.74	160.98
5	0.145	63.37	98.99	27.25	145.09

The use of flash tanks reduce in almost 2% the mass flow rate of backpressure steam for a triple effect, almost 3% for a quadruple, and almost 5% for a quintuple. The exergetic indexes show a trade-off between an increase in the exergy destruction rate (addition of a new equipment) and a decrease in the exergy lost rate (the condensate streams leaves the system closer to the environmental conditions). As for the exergy efficiency, its decrease is a result of the lower exergetic contents of the condensate streams leaving the flash tanks. All in all, the Improvement Potential has decreased, what indicates a better operation of the system.

6.2. Influence of bleeding

The influence of bleeding has been analyzed based on the use of the steam produced only for heating purposes (take the juice from 30°C to 100°C). It has not been analyzed the heating needs for the crystallization (cooking) process or for distillation processes of the alcohol production. Table 3 indicates the conditions of the available steam streams, the range of operation of the heat exchangers (based on Hugot, 1977), and the amount of bleeding needed in each effect for the three systems considered.

Table 3. Amount of bleed to used for heating the juice from 30°C to 100°C

Pressure (bar)	Temperature (°C)	Range of Operation (°C)	Amount of steam needed (kg of steam/kg of juice)
Triple Effect			
1.657	114.63	70 – 100	0.052
0.89	96.62	30 – 70	0.067
0.2	60.24	-	-
Quadruple Effect			
1.868	118.34	80 – 100	0.035
1.274	106.77	65 – 80	0.026
0.718	90.83	30 – 65	0.058
0.2	60.24	-	-
Quintuple Effect			
1.994	120.40	85 – 100	0.026
1.511	111.83	75 – 85	0.017
1.051	101.25	60 – 75	0.025
0.614	86.74	30 – 60	0.050
0.2	60.24	-	-

These values were set in the model considering the same input conditions of the previous section, with no flash tanks. Table 4 brings the results.

Table 4. Simulation results for different number of effects with different bleedings and no flash tanks.

Number of Effects	Backpressure Steam Mass Flow Rate (kg/s)	Exergy Destroyed Rate (kW)	Exergy Lost Rate (kW)	Exergy Efficiency (%)	Improvement Potential (kW)
3	0.313	86.44	103.12	53.03	143.73
4	0.248	65.33	89.08	55.89	117.90
5	0.208	52.78	80.86	58.23	102.91

The results indicate a better performance of the system, even though more backpressure steam is needed. However, if no bleeding was employed, then 0.12 kg of backpressure steam would be required to heat 1 kg of juice from 30°C to 100°C. Thus, the total amount of backpressure steam required for a triple effect with no bleeding would be 0.372 kg/s (almost 20% more), 0.308 kg/s for a quadruple effect (24% more), and 0.268 for a quintuple effect (29% more).

As the same amount of water is separated from the juice, and the more steam is used for other processes, the exergy lost rate decreases.

The main source of entropy generation in multiple-effect evaporators is due to heat transfer, and it is higher in the last effects, where the temperature differences are higher. The use of bleeding in different effects decreases the heating needs of the last effects (especially in the last one), reducing the entropy generation rate. This result indicates that it would be better to use as much bleeding as possible.

To illustrate this conclusion, a quintuple-effect might be considered. Table 5 compares the results of bleeding each effect to attend a heating demand of 267 kW.

Table 5. Simulation results for bleeding each effect separately.

Effect with bleeding	Backpressure Steam Mass Flow Rate (kg/s)	Exergy Destroyed Rate (kW)	Exergy Lost Rate (kW)	Exergy Efficiency (%)	Improvement Potential (kW)
1 st	0.253	56.81	88.64	62.83	109.76
2 nd	0.230	53.16	85.08	62.01	105.27
3 rd	0.205	50.94	80.76	59.33	101.48
4 th	0.179	51.53	75.62	52.80	99.94
5 th	0.152	61.20	70.13	32.92	111.18

The results show a trade-off relation between the place of bleeding, consumption of backpressure steam and exergy destroyed rate. For a quintuple-effect the use of bleeding in the third effect would generate less entropy than in the others. Recalling Tabs. 3 and 4, it is clear that steam from the third effect can be used instead of the steam from the fourth. Hence, a new simulation was done based on Tab.3, considering no bleeding in the fourth effect, and a greater amount of steam bled from the third. There has been a decrease of less than 1% in the exergy destruction rate, and an increase of 5% in the backpressure steam consumption. The exergy lost rate has also increased.

Thus, a good integration of the multiple-effect evaporator with the heating needs of the mill leads to the best operating point for that system.

Another interesting remark might be made regarding the use of different indexes based on exergy to analyze a system. As it has been shown so far, the use of a single index might be misleading; thus an integrated analysis seems to be a better approach.

6.3. Use of thermo-compression

The methodology described in parts 3 and 4 of this paper has been applied to a real multiple-effect evaporator by Pellegrini and Oliveira Jr (2006). Tables 6 and 7 show the operational data of the mill considered and the simulation results.

Table 6. Operation data of the mill.

Amount of sugarcane crushed (t/day)	18,720
Bagasse production (t/h)	195
Juice production (t/h)	780
Steam production (t/h)	435
Specific steam consumption (kg/tc)	557
Specific electro-mechanical energy consumption (kWh/tc)	33.8

Source: Pellegrini and Oliveira Jr. (2006)

Table 7. Simulation results.

Backpressure steam consumption (kg/s)	114
Exergy Destruction Rate (kW)	11080
Exergy Lost Rate (t/h)	8695
Exergy Efficiency (%)	84
Improvement Potential (kW)	10468

Source: Pellegrini and Oliveira Jr. (2006)

The mill considered is capable of crushing 20,000 t of cane a day, what would require an extra amount of steam in the evaporation systems. As there are no more turbines available to expand steam from the boilers, reduction valves are used.

A new simulation was performed (see Tab. 8), maintaining the same mass fraction of solids at the inlet and outlet of each effect of Pellegrini and Oliveira Jr (2005).

Table 8. Simulation results for 20,000 t of cane/day.

Backpressure steam consumption (kg/s)	121
Exergy Destruction Rate (kW)	11838
Exergy Lost Rate (t/h)	9290
Exergy Efficiency (%)	84
Improvement Potential (kW)	11184

There has been an increase of 6% in the consumption of backpressure steam (7 kg/s), representing an exergy destruction rate of 2.7 MW in the valves. Table 9 gives the results for the same conditions of Tab. 8, but using a thermo-compression device instead of reduction valves.

Table 9. Simulation results for 20,000 t of cane/day, using thermo-compression.

High Pressure steam consumption (kg/s)	7
Backpressure steam consumption (kg/s)	112
Exergy Destruction Rate (kW)	12430
Exergy Lost Rate (t/h)	8069
Exergy Efficiency (%)	82
Improvement Potential (kW)	10306

The results show that there is a net decrease in the steam consumption of almost 2% (from 121 to 119 kg/s), an increase in the exergy destruction rate of 5% (relative to the use of new equipment), a decrease of the exergy lost rate of 13% and of 2% in the exergy efficiency. However, the Improvement Potential has decreased (almost 8%), what indicates a net gain in the operation of the system.

Comparing only the exergy destroyed in the thermo-compression process with the one destroyed in the valve, the first destroys less (1.7 MW) than the later (2.7 MW).

Nevertheless, the use of thermo-compression is only recommended for mills that have a consumption of backpressure steam greater than its "production" in the turbines, in order to replace reduction valves that are less efficient from a thermodynamic point of view.

7. Conclusion

A methodology for the exergy analysis of multiple-effect evaporators has been introduced and applied to study different options of configurations for the system.

The results showed that the use of more effects reduces the rates of exergy destruction (less backpressure steam is required) and exergy lost (streams leaving the system are closer to the environmental conditions). The use of flash tanks contributes to the decrease of the exergy lost rate, as they recover energy from the condensates.

It has been pointed out that the use of bleeding presents a trade-off relation between the consumption of backpressure steam, and the rates of exergy destruction. If more water is evaporated in the first effects, than less exergy will be destroyed in last one (the most irreversible one). However, evaporating water in the early effects requires a greater amount of backpressure steam. Thus, a balanced bleeding (according to pinch point methodology, for instance) represents the best configuration, from a thermodynamic perspective.

The use of thermo-compression should be considered whenever reduction valves are employed to deliver low pressure steam to the evaporators. Thermo-compression gives a new use to high pressure steam that would be expanded in the valves, improving the performance of the system.

The integrated analysis of exergetic indexes proved to be more reliable than the use of a single index.

Future works will integrate this methodology to a model of a cogeneration plant of a sugarcane mill in order to evaluate the interaction of the systems.

8. References

- Baloh T., 1968, "Wärmewirtschaft". In: Schneider, F (org.), "Technologie des Zuckers", M & H Schaper, 2nd Edition, Hannover, Germany.
- Bayrak, M., Midilli, A., Nurveren, K., 2003. "Energy and Exergy Analysis of Sugar Production Stages", International Journal of Energy Research, Vol. 27, pp. 989-1001.
- Bejan, A., 1996, "Entropy Generation Minimization: the method of thermodynamic optimization of finite-size systems and finite-time processes", Boca Raton: CRC Press, 362 p.
- Bejan, A., Moran, M. e Tsatsaronis, G., 1996. "Thermal Design and Optimization", John Wiley & Sons, New York, USA, 542 p.
- Calvo A.E., 1990, "Application of Exergetic Method of Analysis to the Sugar Industry" (Aplicación del Método Exergetico de Análisis a la Industria Azucarera). Ph.D Thesis, Instituto Superior Politécnico José Antonio Echeverría, Havana, Cuba (in Spanish).
- Christodoulou, P., 1996, "Energy Economy Otimization in the Separation Processes: Optimizing the Separation of Sucrose/Water and Non-Sugars", International Sugar Journal, Vol. 98, pp.419-430.
- FAPESP (many authors)., 2002, "Technical, Economical and Environmental Analysis of the Use of Sugarcane to the Sustainable Electricity Generation (Análise Técnica, Econômica e Ambiental do Uso da Cana de Açúcar para Geração Sustentável de Energia Elétrica)", Thematic Project, Brazil.
- Fernández-Parra M. I., Nebra S.A., 2001, "Energetic, Exergetic and Exergoeconomic Analysis of Multiple-effect Evaporation Systems of a Sugarcane Industry", Proceedings of the 16th Brazilian Congress of Mechanical Engineering, Águas de Lindóia, Brazil, in CD-ROM (in Portuguese).
- Fundora, A. J. B., 2002, "Thermoeconomic Method Applied to New Energetic Proposals for Sugarcane Industry", Proceedings of 16th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Vol. 2, Berlin, Germany, pp. 250-257.
- Goutte, D., 1987, "Exergy Analysis, Management and Economy of Energy in Sugar Mills (Analyse Exergetique, Gestion et Économie d'Énergie en Sucrerie et Sucrerie-Distillerie)", Ph.D Thesis, Institut National Polytechnique de Lorraine, École Nationale Supérieure des Industries Chimiques, Nancy, Franch (in French).
- Guallar J., Valero A. 1989, "Thermodynamic and Costs in the Sugar Industry (Termodinámica y Costes en la Industria Azucarera. I. Actividades en Disoluciones Técnicas de Sacarosa, II. Exergia de sus Flujos, III. Análisis Termodinámico)", Alimentación, Equipos y Tecnología, pp. 213-220, 155-159, 199-210 (in Spanish).

- Higa M., 2003, "Cogeneration and Thermal Integration in Sugar and Alcohol Plants (Cogeração e Integração Térmica em Usinas de Açúcar e Álcool)", Ph.D Thesis, Mechanical Engineering Department, State University of Campinas, Campinas, Brazil (in Portuguese).
- Hugot, E., 1977, "Manual da Engenharia Açucareira", Editora Mestre Jou, 1ª edição em português, São Paulo, Brazil, 1198 p.
- Klein S. A., Alvarado F. L., 2005, "EES – Engineering Equation Solver for Microsoft Windows Operating Systems", F-Chart Software.
- Kotas T. J., 1985, "The Exergy Method of Thermal Plant Analysis". Butterworths, London, England, 328 p.
- Modesto, M., Ensinas, A. V., Nebra, S. A., 2005, "Sugar Cane Extraction System Comparison – Mill vs Diffuser, Proceedings of the 18th Brazilian Congress of Mechanical Engineering, Ouro Preto, Brazil (in CD-ROM).
- Nebra S. A., Fernández-Parra M. I., 2005, "The Exergy of Sucrose-Water Solutions: Proposal of a Calculation Method", 18th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Vol. 1, Trondheim, Norway, pp. 385-392.
- Paz D., Cárdenas G.J., 1997, "Exergy Analysis of a Heating-Evaporation-Cooking System (Análisis Exergético de um Sistema de Calentamiento-Evaporación-Cocimiento)", Int. Sugar Journal, Vol. 98, pp.263-267 and 317-320.
- Peacock S., 1995, "Predicting Physical Properties of Factory Juices and Syrups", Int. Sugar Journal, Vol. 97, pp. 571-577.
- Pellegrini L.F., Oliveira Jr, S. "Exergy Analysis of Sugarcane Bagasse Gasification", Proceedings of the 18th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Vol. 1, Trondheim, Norway, pp. 393-400.
- Prieto, M. G. S., 2003, "Cogeneration Alternatives in Sugar and Alcohol Factories (Alternativas de Cogeração na Indústria Sucroalcooleira, Estudo de Caso)", Ph.D Thesis, Mechanical Engineering Department, State University of Campinas, Campinas, Brazil (in Portuguese).
- Rivero, R., 1997, "The Exergoecologic Improvement Potential of Industrial Processes", in: Thermodynamic Analysis and Improvement of Energy Systems, World Publishing Corporation, Beijing, pp. 299-304.
- Smith J. M., Abbot M. M., Van Ness H. A., 2000, "Introduction to Chemical Engineering Thermodynamics (Introdução à Termodinâmica da Engenharia Química)", LTC – Livros Técnicos e Científicos Editora SA. 5th Edition, Rio de Janeiro, Brazil, 697 p.
- Starzak M., Peacock S.D., 1997, "Water Activity Coefficient in Aqueous Solutions of Sucrose – A Comprehensive Data Analysis", Zuckering, Vol. 122, pp. 380-387.
- Szargut, J, Morris DR, Steward FR., 1988, "Exergy Analysis of Thermal, Chemical and Metallurgical Processes", Hemisphere Publishing Corporation, New York, USA, 332 p.
- Tekin, T., Bayramoğlu, M., 1998, "Exergy Analysis of the Sugar Production Process from Sugar Beets", International Journal of Energy Research, Vol. 22, pp. 591-601.
- Tekin, T., Bayramoğlu, M., 2001, "Exergy and Structural Analysis of Raw Juice Production and Steam-Power Units of a Sugar Production Plant", Energy, Vol. 26, pp. 287-297.
- Zanetti, A. A., Pellegrini, L. F., Oliveira Jr., S., "Evaluation of exergetic indexes of an utilities plant of a sugarcane mill (Avaliação de Índices Exergéticos de uma Planta de Utilidades de uma Usina Sucroalcooleira), 13^o International Symposium of Scientific Initiation, São Carlos, Brazil in CD-ROM.