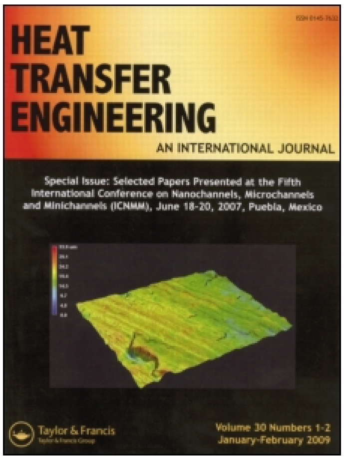

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Ethanol Production from Sugar Cane: Assessing the Possibilities of Improving Energy Efficiency through Exergetic Cost Analysis

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The sugar and ethanol production is one of the most important economical activities in Brazil, mainly due its high efficiency and competitiveness. Ethanol production is done by a series of steps: juice extraction, treatment, fermentation, and distillation. The juice extraction and treatment is a common operation of both the sugar and ethanol industries. The process begins with the sugar cane juice extraction, usually done by mills, where the cane is compressed between large cylinders for the separation of the juice from the bagasse. Recently, a juice extraction system, called a diffuser, was introduced in some sugar and ethanol plants. In diffusers, after the sugar cane preparation stage was completed with knives and shredders, the cane passes through a bed where the juice is separated from bagasse by the addition of imbibition water and steam, resulting in a leaching process. The present study evaluates different possibilities of decreasing the thermal energy consumption through exergetic cost analysis. The base case is a traditional ethanol production plant, for which the unitary exergetic cost of ethanol and electrical energy are determined. In the following cases, two proposals were assessed: the use of the diffuser as an extraction system and the use of pinch technology to perform an energetic integration between distillation and extraction (diffuser) systems. The results of exergetic efficiency, irreversibility generation, and unitary exergetic cost of products of the three cases are analyzed and compared. The results show the feasibility of using diffusers and heat recovery to decrease thermal energy consumption in ethanol production plants.

INTRODUCTION

Sugar cane plants can be found with three basic arrangements: plants that produce either sugar or ethanol, and those that produce sugar and ethanol simultaneously. For all three, the industrial process begins with the preparation of the cane and the extraction of the juice, which will be used in the sequence as the principal raw material for the final product.

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The preparation systems consist of feed tables for whole-stick cane discharge, carrier rollers, leveler knives, and a set of knives and shredders. Heavy-duty knives may be necessary, depending on the kind of extraction system. The extraction systems usually adopted in sugar cane plants are milling and/or diffuser. The former is largely used in Brazilian sugar cane sector, as it is a technology well known by the factory operators. It is based on the use of mechanical work of the mills to extract the juice by compression. Mills are generally connected to drive turbines that consume medium pressure steam (typically 20 bar) as driving force.

The diffuser is another option for juice extraction, but has been rarely used in Brazil. The first plant to install this device was Galo Bravo in Ribeirão Preto (São Paulo State) in 1985. A few problems with the new technology were detected at the beginning, and so diffusers were not generally adopted in spite of their advantages. The condition of the bagasse at the output of the diffuser was a serious problem, presenting impurities and high moisture levels that made combustion in boilers difficult. This problem was mainly due to the fact that the equipment was imported and originally designed for beet sugar factories [1].

The principle of the diffuser is the application of hot water on the cane for the extraction of the juice through a leaching process. The water and the juice re-circulated in the equipment are heated with low-pressure steam (2 bar or lower). There are also dewatering mills at the exit that are used as pre-dryers, reducing the moisture of the bagasse to approximately 50% and extracting the remaining juice for re-circulation. Today, there are only 10 diffusers installed in Brazilian sugar cane plants, out of 324 plants in operation [1]. The problems that occurred in the past inhibited the application of the diffusion process, but new experiences show that they present many advantages when compared with milling.

First, the extraction efficiency of the diffuser is 2–3% higher than milling, reaching 99% in the nominal load, whereas the milling maximum possible efficiency is 97% [2]. However, the high efficiency in the diffuser can only be obtained by adequate preparation of the cane, with heavy-duty knives being required to reach open cells values between 90 and 92% [1].

Moreover, the maintenance costs with a diffuser are 70% lower than with milling, and the operation can be done with three operators, instead of the eight or nine that milling requires [2]. Comparing milling and diffuser systems under operation, it was observed that sand and dust in cane can seriously reduce percolation rates and extraction performance in a diffuser, but could be avoided with correct cane preparation and storage [3]. The installation of a combination of diffuser and the sand/stones removal systems in a South African sugar plant in 1994 resulted in acceptable low values of suspended solids in mixed juice from the diffuser. The equipment removed stones, gravel, and sand with a variable-speed spiked roller that picked up cane from the feeder table before discharge into the main cane carrier [4].

The energy consumption of both extraction systems shows some important differences that affect the sugar cane plant energy balance. Mills require medium pressure steam into drive turbines for all equipment, while diffusers use low-pressure steam for imbibition water heating. This steam can be obtained with vapor bleeds from first and/or second effects of the evaporation train in a sugar production process, or from turbine extractions at low pressure in an ethanol production process.

Comparisons of the energy consumption between milling and diffusers have been carried out by various authors [3, 5, 6], and according to published reports, the change of traditional milling systems to diffusers should increase 3–6% the sugar production at very reasonable cost [5].

DESCRIPTION OF THE SYSTEM

In order to compare the performance between mills and diffusers, a simple cogeneration system has been proposed and simulated. The system uses cane bagasse as fuel and produces electricity and steam for the process. The cogeneration and juice extraction systems are shown in Figure 1.

The plant is composed of a boiler, steam turbine, deaerator, juice extraction system (mill or diffuser), two pumps, a fermentation plant, heat exchangers for heating the wine (ethanol-water mixtures), and a distillation system. The thermodynamic data of this system are shown in Table 1. The sugar cane (stream 13) is introduced in the extraction system together with the leaching water (stream 14). The bagasse produced (stream 15) is used as fuel in the boiler (I), and the juice (stream 16) will be used in the ethanol production. In the cogeneration system, the bagasse is used as a fuel produced steam at a temperature of 480°C and a pressure of 80 bar. The steam from the boiler is expanded in a steam turbine with extractions of steam at pressures of 22 and 2.5 bar. The intermediate-pressure steam is used to generate mechanical energy for the extraction systems, and the low-pressure steam is used for the deaerator and extraction system (in the case of use of diffuser). Streams 4 and 12 (turbine exhausts) supply the thermal demand for heating the imbibition water and wine, as well as for the reboilers of the distillation system. All condensate flows are joined and returned to the cogeneration system by stream 6, pressurized in the electric pump 1 (VII), passed through the deaerator (VI), further pressurized in the electric pump 2 (V), and fed back to the boiler, closing the cycle.

For the process simulation, the following hypotheses are assumed:

- The cane mass flow was calculated as the sum of bagasse and juice flow as shown in Eq. (1):

$$\dot{m}_{\text{cane}} = (1 - x)\,\dot{m}_{\text{juice}} + (x)\,\dot{m}_{\text{bagasse}} \tag{1}$$

  where x is a percentage of fiber in the cane, adopted as 14% [7].
- The bagasse that leaves the extraction system was considered with 50% of moisture.
- The juice enters in the extraction system with a Brix value of 18.5% and leaves with a value of 13.5% and a purity of 83.5%.
- The mass flow 40, imbibition water consumption per tc (ton of cane) was estimated based on [8] for the mill and [9] for the diffuser.

Mechanical work consumption adopted for the mill and the diffuser were obtained from [10], [9], and [7], respectively.

Three different situations were analyzed. In the first case, a traditional ethanol production plant using a mill as an extraction system was simulated. In the second case, the mill extraction system was replaced with a diffuser. In the third case, the mechanical drive is replaced with an electrical one, and pinch technology was used to integrate the hot streams of the distillation system with the cold streams from extraction and fermentation system. Figure 1 shows cases I and II, and Figure 2 shows case III. The thermodynamic data for all three cases considered are shown in Table 1.

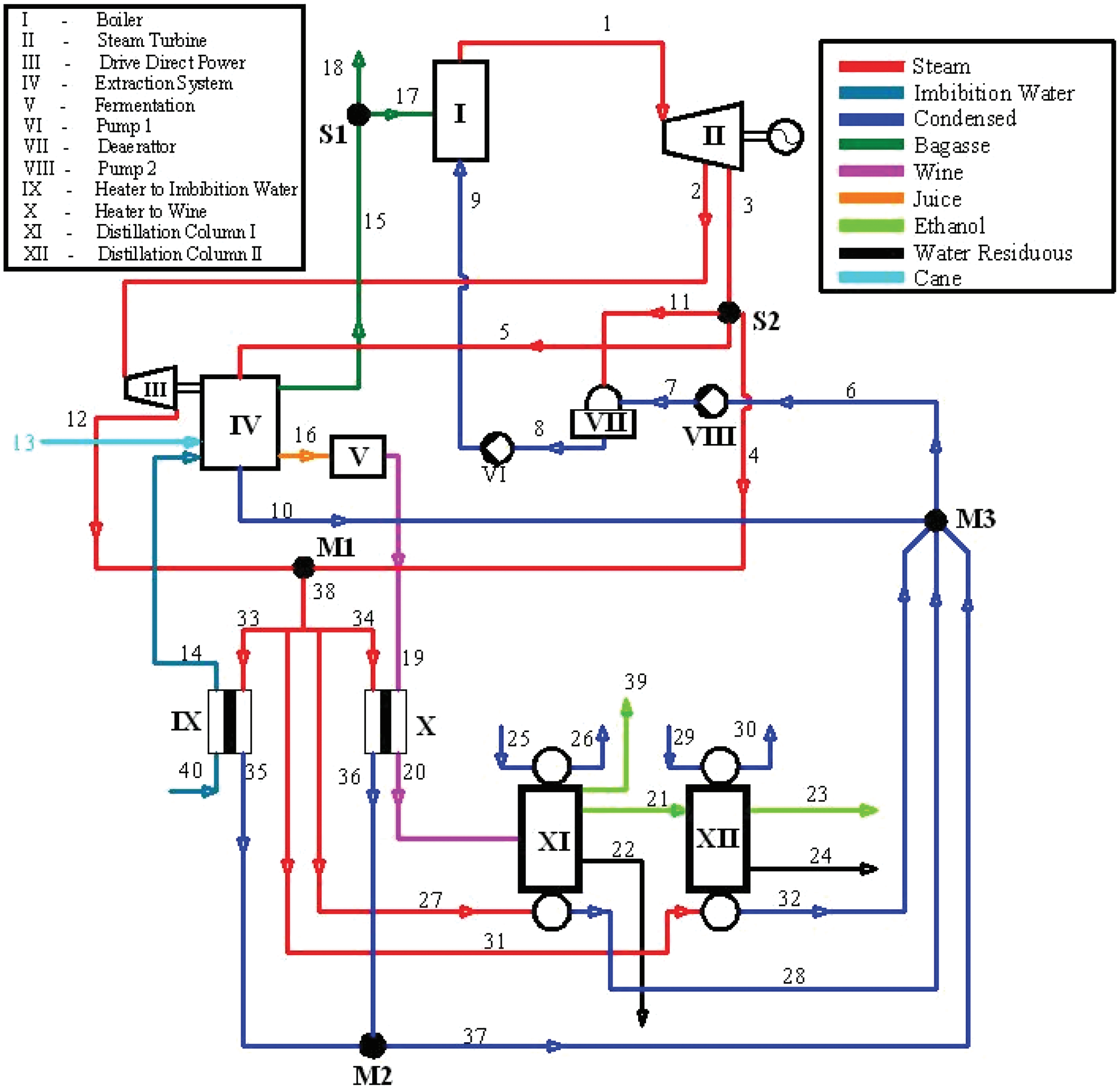

Figure 1 Sketch of cogeneration, extraction, and distillation systems.

THERMODYNAMIC ANALYSIS

The classic evaluation of thermal power plant performance is done through the energetic analysis based on the first law of thermodynamics. Such an analysis allows, from an energetic point of view, a quantitative determination of the entire plant performance and also of each one of its devices. However, through the first law analysis, it is not possible to determine the quality of energy used and where exergy losses are located. In order to determine and quantify these exergy losses due to irreversibilities, analysis by the second law of thermodynamics must be used [11].

This type of analysis is essential when the system includes cogeneration. Equations (2–4) show mass, energy, and exergy balances for a generic control volume, not considering the variation of kinetic and potential energy/exergy, respectively.

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{2}$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \tag{3}$$

$$\dot{Q}\left(1 - \frac{T}{T_o}\right) - \dot{W} + \sum \dot{m}_{in} e_{in} - \sum \dot{m}_{out} e_{out} = \dot{I} \tag{4}$$

The variable *e* represents the specific exergy of a stream and can be calculated with the following equation:

$$e = h_i - h_o - T_o(s_i - s_o) + e_{ch} \tag{5}$$

where h_i = enthalpy of the stream at point i; h_o = enthalpy of reference; s_i = entropy of the stream at point I; s_o = entropy of reference; and e_{ch} = standard chemical exergy.

In order to determine the sugar cane bagasse exergy, a methodology used for wood [12] was adopted, with the required changes in the composition and its low heat value (LHV). For bagasse at reference environment conditions, its total exergy is

Table 1 Thermodynamic data of the cogeneration, extraction and distillation system in three cases studied

	$\dot{m}\,(kg/s)$			$T(°C)$			$P(bar)$			$e(kJ/kg)$		
	I	II	III	I	II	III	I	II	III	I	II	III
1	0.330	0.457	0.377	480	480	480	80	80	80	1896	1896	1896
2	0.291	0.158	—	317.8	317.8	—	22	22	—	1568	1568	—
3	0.038	0.299	0.377	132.4	132.4	127.4	2.5	2.5	2.5	1150	1150	1147
4	0.036	0.227	0.306	132.4	132.4	127.4	2.5	2.5	2.5	1150	1150	1147
5	—	0.068	0.068	—	132.4	127.4	—	2.5	1.05	—	1150	1150
6	0.328	0.453	0.374	121.8	121.8	121.8	2.1	2.1	2.1	582	582	81
7	0.328	0.453	0.374	121.8	121.8	121.8	4	4	4	582	582	582
8	0.330	0.457	0.377	121.8	127.4	125	2.5	2.5	2.5	586	588	588
9	0.330	0.457	0.377	125	128.7	126.3	88	88	88	595	598	598
10	—	0.068	0.068	—	121.8	121.8	—	2.1	2.1	—	582	27, 660
11	0.002	0.005	0.002	132.4	132.4	127.4	2.5	2.5	2.5	1150	1150	1147
12	0.291	0.158	0.901	172.6	172.6	40	2.5	2.5	1.05	1175	1175	55
13	1.000	1.000	1.000	25	25	25	1.01	1.01	1.01	—	—	—
14	0.235	0.361	0.361	98	98	98	1.01	1.01	1.01	82	82	82
15	0.260	0.260	0.260	25	25	25	1.01	1.01	—	9959	9959	9959
16	0.975	1.101	1.101	25	25	25	1.01	1.01	—	2416	2416	2416
17	0.155	0.214	0.176	25	25	25	1.01	1.01	—	9959	9959	9959
18	0.105	0.046	0.084	25	25	25	1.01	1.01	1.01	9959	9959	9959
19	0.975	1.101	1.101	25	25	25	1.01	1.01	1.01	2486	2486	2486
20	0.975	1.101	1.101	90	90	90	1.01	1.01	1.01	2512	2512	2512
21	0.167	0.192	0.192	78	78	78	1.01	1.01	1.01	12, 058	12, 058	12, 058
22	0.793	0.901	0.901	99	99	99	1.01	1.01	1.01	98	98	98
23	0.069	0.073	0.073	78	78	78	1.01	1.01	1.01	27, 674	27, 674	27, 674
24	0.097	0.119	0.119	99	99	99	1.01	1.01	1.01	122	122	122
25	2.433	2.530	2.530	25	25	25	1.2	1.2	1.2	527	527	527
26	2.433	2.530	2.530	30	30	30	1.15	1.15	1.15	528	528	528
27	0.168	0.204	0.209	121.8	148.7	127.4	2.5	2.5	2.5	1148	1159	1159
28	0.168	0.204	0.209	121.8	121.8	121.8	2.1	2.1	2.1	582	582	582
29	15.329	18.336	18.336	25	25	25	1.2	1.2	1.2	527	527	527
30	15.329	18.336	18.336	30	30	30	1.15	1.15	1.15	528	528	528
31	0.015	0.002	0.002	121.8	148.7	127.4	2.5	2.5	2.5	1148	1159	1147
32	0.015	0.002	0.002	121.8	121.8	121.8	2.1	2.1	2.1	582	582	582
33	0.031	0.049	0.037	121.8	148.7	127.4	2.5	2.5	2.5	1148	1159	1147
34	0.113	0.130	0.015	121.8	148.7	127.4	2.1	2.1	2.1	1148	1159	1147
35	0.031	0.049	0.044	121.8	121.8	127.4	2.5	2.5	2.5	582	582	1147
36	0.113	0.130	0.037	121.8	121.8	121.8	2.1	2.1	2.1	582	582	582
37	0.144	0.179	0.015	121.8	121.8	121.8	2.1	2.1	2.1	582	582	582
38	0.328	0.385	0.044	121.8	148.7	121.8	2.5	2.5	2.5	1148	1159	582
39	0.008	0.008	0.008	88	88	88	1.01	1.01	1.01	26397	26101	26, 397
40	0.235	0.361	0.361	25	25	25	1.01	1.01	1.01	50	50	50
41	—	—	0.096	—	—	121.8	—	—	2.1	—	—	582
42	—	—	0.14	—	—	41.71	—	—	1.05	—	—	2488
43	—	—	0.977	—	—	81.92	—	—	1.2	—	—	2517
44	—	—	0.124	—	—	90	—	—	1.05	—	—	2512
45	—	—	0.977	—	—	90	—	—	1.05	—	—	2512
46	—	—	0.361	—	—	44.53	—	—	1.01	—	—	53
47	—	—	0.124	—	—	25	—	—	1.05	—	—	2486
48	—	—	0.977	—	—	25	—	—	1.05	—	—	2486
49	—	—	0.119	—	—	40	—	—	1.05	—	—	81
50	—	—	0.073	—	—	40	—	—	1.05	—	—	27, 660

equal to its chemical exergy; thus, its exergy can be calculated by the referred methodology. The following composition for the bagasse was assumed: 47% carbon, 6.5% hydrogen, 44% oxygen, and 2.5% ash [13]. In flow 15, the bagasse was considered with 50% of humidity to calculate the properties of stream 13, and the bagasse was considered dry. The juice exergy was calculated following the methodology described in [14], and the exergy of ethanol-water mixture by the method proposed in [15].

First Law Analysis

In order to assess the juice extraction system, mass, and energy balances in each component of the cogeneration, juice

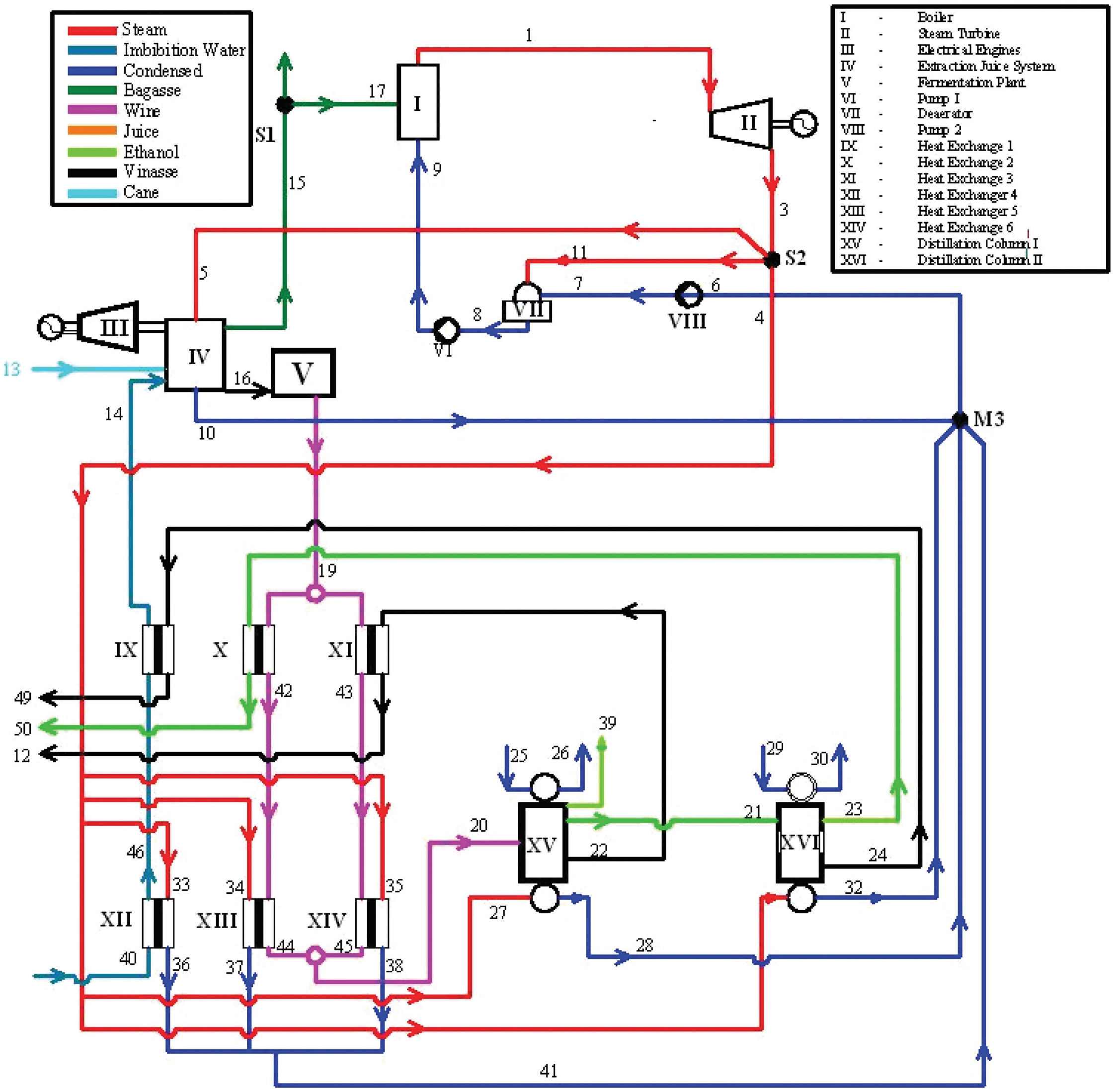

Figure 2 Sketch of cogeneration system integrated with extraction and distillation systems.

extraction, and distillation systems were modeled, and the simulations were performed using the EES® software. From the simulation results, the energy requirements of the pumps, direct drive turbines, and other energy consumers can be computed. Parameters used for the extraction system are shown in Table 2, and the following efficiency values were adopted:

- $\eta_{boiler} = 0.8$: energetic efficiency of boiler
- $\eta_{ST} = 0.812$: isentropic efficiency of steam turbine
- $\eta_{pumps} = 0.8$: isentropic efficiency of pumps
- $\eta_{DT} = 0.55$: isentropic efficiency of drive turbine
- $\eta_{ger} = 0.98$: efficiency of electrical generator and electric engines

The energetic consumption of the systems is shown in Table 3. The hydrated ethanol production using mills reached 85.93 liters/tc consuming 261.1 kWh/tc. For the process using a diffuser, ethanol production increased to 87.33 liters/tc, but with an energy requirement of 282.20 kWh/tc. Heat integration then reduced the energy requirement to 178 kWh/tc.

This energy is supplied from steam generated in the boiler through bagasse utilization as fuel. The surplus of electrical energy reached 24.30 kWh/tc (mill), 46.55 kWh/tc (diffuser), and 48.36 kWh/tc (diffuser with energy integration), while cane bagasse surplus reached 40.56% (mill), 17.52% (diffuser), and 32.12% (diffuser with energy integration).

Table 2 Parameters adopted for the extraction system

	Case I	Case II & III
Bagasse fiber (%)	13	
Direct drive power (kWh/tc)	20	10.85
Consumption of electric energy (kWh/tc)	14.83	14.15
Imbibition water (kg/tc)	235	360.8
Juice production (kg/tc)	0.995	1.101

Table 3 Specific energetic consumptions

Power	I	II	III
Energy generated (kWh/tc)	29.48	64.25	66.08
Pumps (kWh/tc)	1.06	1.85	1.21
Net electrical power (kWh/tc)	24.30	47.83	48.36
Ethanol production (liters/tc)	85.93	90.41	90.41
Cold utilities (m^3/tc)	17.81	20.93	20.93
Thermal energy (kWh/tc)	261.1	282.20	178.00
Available bagasse excess (%)	40.56	17.52	32.12

The electrical energy surplus is directly proportional to the steam produced in the boiler. The greater steam consumption in the diffuser system provides the possibility of increasing the electricity generated. In this case, the bagasse surplus decreases with the use of a diffuser system. However, with the use of heat integration and the replacement of the mechanical turbine by electrical engines, the bagasse surplus reaches a value near that of the process using a mill as an extraction system. The utilization of heat recovery to integrate the extraction and distillation system leads to a decrease of thermal energy consumption of 37%, maintaining a similar level of bagasse surplus.

Depending on the final utilization of bagasse, it can be more advantageous to increase its surplus for its use in another process (syngas production, ethanol production from hydrolysis of bagasse, or gasification). These other utilizations will be analyzed in future studies.

The bagasse surplus is directly proportional to boiler efficiency. The increase of boiler first law efficiency through the use of a bagasse dryer, the pre-heating of air or boiler feed water, and the increase of pressure and temperature of steam allow an increase of bagasse surplus. Another possibility for increasing bagasse surplus is the utilization of cane varieties with a higher percentage of fibers.

For the same conditions, the juice extraction system based on diffuser has an electric net power generation 97% larger than the system based on mills. The direct drive power requirement in mills is 84% larger than diffuser, while the electric power consumption for pumps is similar. The energy consumption with diffuser is 8.8% larger than with mills; the bagasse excess for mills is 135% larger than in diffusers. But with the use of heat integration, a diffuser has an energy consumption 31% lower than mills, with a bagasse surplus only 20% lower.

In order to improve the diagnostics of the three cases considered, an exergetic analysis was performed for the determination of exergetic efficiency and irreversibilities generated in both systems.

Second Law Analysis

The exergy balances (Eq. [4]) were applied to each component of the plant to determine the irreversibility and efficiency of each control volume considered. In the special case of the extraction system, the exergy balance equation is written for the diffuser (Eq. [6]) and the mill (Eq. [7]) as follows:

$$\dot{m}_{14}e_{14} + \dot{m}_{juice}e_{juice\_13} + \dot{m}_{bagasse}e_{bagasse\_13} + \dot{W}_{dif\_ele} + \dot{m}_5e_5 - \dot{m}_{10}e_{10} - \dot{m}_{15}e_{15} - \dot{m}_{16}e_{16} = \dot{I}_{IV} \quad (6)$$

$$\dot{m}_{14}e_{14} + \dot{m}_{juice}e_{juice\_13} + \dot{m}_{bagasse}e_{bagasse\_13} + \dot{W}_{mill} - \dot{m}_{15}e_{15} - \dot{m}_{16}e_{16} = \dot{I}_{IV} \quad (7)$$

where W_{dif_ele} is the electrical power consumption in the diffuser (kW), and W_{mill} is the mechanical power consumption in the diffuser (kW).

The set of equations of exergy balance was solved using the EES® software, determining the irreversibility generated in each component of the system. The efficiency of each component was calculated according as suggested [11, 12], considering Figures 1 and 2 and the exergetic efficiency of the global plant, which is written by:

$$\varepsilon = \frac{\dot{W}_{net} + \dot{m}_{23}e_{23} + \dot{m}_{18}e_{18}}{\dot{m}_{13}e_{13}} \quad (8)$$

The exergetic analysis is a powerful tool to compare different types of thermal systems. This analysis allows one to quantify and identify the components that produce the largest irreversibility in the system. For the ethanol plant under consideration, the main difference between the two systems is the juice extraction device. The mill generates 96% more irreversibility than the diffuser and has an exergetic efficiency 6% lower. The juice extraction system is responsible for 13% (diffuser) and 30% (mill) of the total irreversibility generated in the system. Overall, the cogeneration system and juice extraction system with diffuser produce 14% more irreversibility than the juice extraction with mills. This result is mainly due to the irreversibility generated in the boiler, as more steam is required for the use of a diffuser (but, at the same time, more cogeneration level is reached). The global efficiency of the plant using a mill is larger than plant using a diffuser. Equation (8) shows that the parameters that influence this value are the net power and bagasse surplus (stream 18). The influence of bagasse surplus is large due of its high value of exergy, so the system using a mill has a greater efficiency mainly due the high surplus of bagasse for this system. However, the exergetic efficiency of the mill component is lower than with a diffuser in the extraction system. The value of global efficiency obtained with a diffuser using energy integration is similar when a mill is used as an extraction system. The values of efficiency and irreversibility for each component of the plant are shown in Table 4.

Table 4 Exergetic efficiency and irreversibility

	Exergetic efficiency (%)			Irreversibility (kW)		
	I	II	III	I	II	III
I	27.87	27.91	27.87	1110.21	1533.64	1267.78
II	83.52	84.21	84.32	15.74	43.45	44.23
III	62.76	62.76	—	42.73	23.18	—
IV	88.02	93.67	93.81	672.81	345.20	346.63
VI	85.07	85.16	85.07	0.56	0.77	0.01
VII	99.96	99.96	99.96	0.07	0.11	0.08
VIII	84.91	84.91	84.91	0.01	0.02	0.64
IX	42.93	41.36	19.29	10.13	16.60	1.24
X	38.89	37.47	18.77	39.04	46.82	66.68
XI	93.42	93.39	80.50	258.4	289.16	9.94
XII	99.12	97.80	52.00	81.90	263.48	5.44
XIII	—	—	35.28	—	—	29.92
XIV	—	—	19.32	—	—	288.55
XV	—	—	93.35	—	—	263.48
XVI	—	—	97.80	—	—	4.76
Total	55.36	48.12	54.92	2231.6	2562.43	2329.38

Theory of Exergetic Cost

The methodology used to perform the exergetic cost analysis is the *theory of exergetic cost,* as proposed in [16]. This methodology can be used to determine the exergetic and monetary cost of each of the streams that compose the system. In [17], the determination of the exergetic and monetary costs of a cogeneration system in a sugar plant evaluating the influence of the price of the main fuel (cane bagasse) on steam production and electricity costs was presented. In [8], the exergoeconomic methodology to assess the exergetic cost of sugar in the production process was used.

The exergetic cost calculation is made applying cost balance equations for each component, as shown by Eq. (9)

$$\sum k_{in} E_{in} - \sum k_{out} E_{out} = 0 \qquad (9)$$

where k defines the unitary exergetic cost and E the total flow exergy, while the subscripts *in* and *out* indicate the streams that enter and leave the control volume, respectively.

The application of Eq. (9) to all control volumes forms a linear set of equations, where the variable number is greater than the equation number. In order to obtain a set with a unique solution, it is necessary to add some additional equations to equalize the number of equations and variables. In [18], the postulates of the methodology were reported in a simple way to define the additional equations below.

In the special case of the extraction system, the exergetic cost balance equation can be written for the diffuser (Eq. [10]) and the mill (Eq. [11]) as follows:

$$\dot{m}_{14}e_{14}k_{14} + \dot{m}_{\text{juice\_13}}e_{\text{juice\_13}}k_{\text{juice\_13}} + \dot{m}_{\text{bagasse\_13}}e_{\text{bagasse\_13}}k_{\text{bagasse\_13}} + \dot{W}_{\text{DF\_ele}}k_P + \dot{m}_5 e_5 k_5 - \dot{m}_{10}e_{10}k_{10} - \dot{m}_{15}e_{15}k_{15} - \dot{m}_{16}e_{16}k_{16} = 0 \qquad (10)$$

$$\dot{m}_{14}e_{14}k_{14} + \dot{m}_{\text{juice\_13}}e_{\text{juice\_13}}k_{\text{juice\_13}} + \dot{m}_{\text{bagasse\_13}}e_{\text{bagasse\_13}}k_{\text{bagasse\_13}} + \dot{W}_{\text{mill}}k_m - \dot{m}_{15}e_{15}k_{15} - \dot{m}_{16}e_{16}k_{16} = 0 \qquad (11)$$

This set of additional equations was added following the considerations proposed by Lozano and Valero [16]. To the unitary exergetic costs of the inputs (juice and bagasse), a unitary value is assigned; therefore:

$$k_{\text{juice\_13}} = k_{\text{bagasse\_13}} = k_{40} = 1 \qquad (12)$$

All the irreversibility generation in the turbines must be carried out by the unitary exergetic cost of electric or mechanical power; consequently, the unitary exergetic costs of the steam entering and leaving these turbines are considered equal. Therefore, we have:

$$k_1 = k_2 = k_3 = k_{12} \qquad (13)$$

In the splitters, where no irreversibility generation takes place, streams entering and leaving the valves have the same exergetic cost.

$$S1: \quad k_3 = k_4 = k_5 = k_{11}$$

$$S2: \quad k_{15} = k_{17} = k_{18} \qquad (14)$$

In the diffuser, the following considerations were made:

- The unitary exergetic cost of the steam that enters the diffusers (stream 5) is the same of the condensed that leaves the diffuser (stream 10);

$$k_5 = k_{10} \qquad (15)$$

- The unitary exergetic cost of bagasse (flow 15) is the same as that of the cane that enters in the diffuser; consequently, the entire irreversibility generation is carried by the unitary exergetic cost of the juice that leaves the diffuser, flow 16. The same hypothesis is adopted for the mill. Thus:

$$k_{15} = k_{\text{bagasse\_13}} \qquad (16)$$

With the additional set of equations above, the number of equations is equal to the number of variables. The system was solved using the EES® software [19], and the result is the unitary exergetic cost for the different plants. Table 5 shows the values of the unitary exergetic cost for both systems.

The products of the cogeneration and juice extraction system are the electrical power (k_P), juice (k_{16}), mechanical power (k_m), and ethanol (k_{23}) unitary exergetic costs. The juice extraction system using a mill has a value of k_p 3.21% lower than using a diffuser. Similarly, the cane juice cost (k_{16}) is 14.4% higher, mechanical power (k_m) has a similar value, and for ethanol (k_{23}), the value is 9.2% higher than for a diffuser.

Table 5 Unitary exergetic cost of main flows of cogeneration, extraction, and distillation systems

Flow	I	II	III
Steam from boiler [1]	3.633	3.595	3.331
Cane: juice [13]	1.000	1.000	1.000
Cane: bagasse [13]	1.000	1.000	1.000
Bagasse to boiler [17]	1.000	1.000	1.000
Juice [16]	1.457	1.272	1.253
Wine [20]	1.498	1.321	1.263
Ethanol [23]	1.882	1.876	1.787
Electrical energy (k_P)	4.246	4.356	4.030
Mechanical energy (k_m)	5.789	5.728	—

Considering that the juice is a main product of the juice extraction system, the diffuser produces a sugar cane juice with a higher efficiency and is exergetically cheaper than the mill, and this juice cost spreads the ethanol production cost, decreasing the ethanol exergetic cost. When the energy integration scheme between extraction and distillation systems is used, all values decrease.

When compared with the mill, the extraction system based on diffuser decreases the juice exergetic cost in 12.6%. This reduction of juice cost results in a decrease of exergetic ethanol production cost of 3.8%. In case III, the cost decreases are 14% and 8%, respectively. The values of mechanical and electrical power and imbibition of water remain unchanged as the operation conditions (pressure and temperature) of cogeneration system remain the same. However, the most important information obtained from exergoeconomic analysis is the decrease of the influence of the extraction system on the ethanol production cost.

The participation of the extraction step starts with 51.81% (case I), decreases to 33.5% (case II), and reaches 34.8% in case III. In this step, the main difference occurs due to the replacement of the extraction component mill by the diffuser. With the use of a diffuser the participation of the extraction system decreases by about 14%.

The step of wine heating has the lowest contribution on the composition of ethanol cost in case III. In this case, the use of heat integration reduced the requirement of thermal energy in this step. Overall, the contribution of this step is quite small.

Finally, the distillation system has an increased contribution on the composition of ethanol cost. As there were made no modifications in this system (in any of the three cases), the contribution of this step on the ethanol cost tends to increase.

The variation of values of unitary exergetic cost of ethanol when moving from mills to diffuser and diffuser with energy integration is shown in Figure 3. The use of a diffuser decreases the unitary exergetic cost by 0.32%, and by 5% when combined with heat integration.

A complete exergoeconomic analysis of the integrated system has still to be performed in future work, considering the monetary costs of ethanol production, like investment, and operational and maintenance costs, reaching a monetary value of ethanol production cost based on exergy concepts.

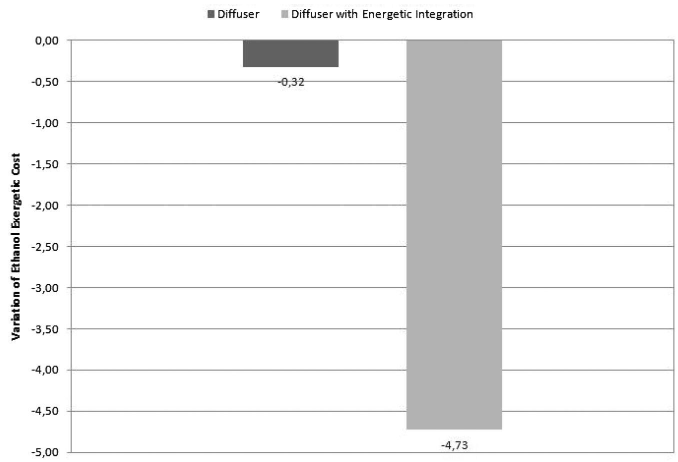

Figure 3 Variation of unitary exergetic cost of ethanol.

CONCLUSIONS

This study analyzed a cogeneration and distillation integrated system with a juice extraction scheme using a mill or a diffuser, as well as a diffuser coupled with energy integration. The three cases were compared using the first and second thermodynamic laws and exergetic cost analysis. The mill has a higher consumption of mechanical energy than the diffuser, which decreases the electric energy generated by the steam turbine. In spite of its lower mechanical energy consumption, the diffuser needs more thermal energy, so more steam is required from the boilers. Consequently, more electric energy is generated, but more fuel (bagasse) is also spent. However, the use of energy integration allows for the increase of extraction efficiency while keeping a similar level of bagasse surplus as when using a mill.

The simulation of the process showed that a mill generates more irreversibility than a diffuser, as it requires much more mechanical energy, and therefore consuming steam at high pressure and temperature in direct drive turbines with low isentropic efficiencies and increasing the irreversibility generation. The diffuser, on the other hand, requires less mechanical power and consumes steam at lower pressure and temperature for the leaching processes, reaching higher exergetic efficiency than the mill.

Due to its work principle, which requires more steam at high pressure and temperature, mills present a higher value of unitary exergetic cost of juice produced than the diffuser, representing higher consumption of the energy available in the plant and consequently higher costs for the production of the final product, ethanol.

A future exergoeconomic analysis comparing both juice extraction systems will show the differences considering the operational cost, including maintenance, and investment cost to obtain the monetary juice cost in each case, thus providing an additional tool for the decision of which extraction system is the best to invest.

NOMENCLATURE

Brix	proportion of solids in juice cane, %
e	exergy, kJ/kg
E	total exergy, kW
h	enthalpy, kJ/kg
I	irreversibility, kW
k	unitary exergetic cost
LHW	lower heating value, kJ/kg
$\dot{m}$	mass flow, kg/s
Q	heat rate, kW
s	entropy, kJ/kg-K
tc	ton of cane
W	work, kW
x	percentage of fiber, %

Greek Symbol

η	efficiency

Subscripts

ch	chemical
DT	direct turbine
in	inlet
o	reference
out	outlet
st	steam turbine

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