Enzymatic Hydrolysis of Sugarcane Biomass and Heat Integration as Enhancers of Ethanol Production

Reynaldo Palacios-Bereche[1], Adriano Ensinas[2], Marcelo Modesto[1] and Silvia Nebra[1,3,*]

[1] *Centre of Engineering, Modelling and Applied Social Sciences, Federal University of ABC (CECS/UFABC), Santo André, SP, Brazil*
[2] *Energy Department, Federal University of Lavras, Lavras MG, Brazil*
[3] *Interdisciplinary Centre of Energy Planning, University of Campinas (NIPE/UNICAMP), Campinas, SP, Brazil*

Received April 18, 2017; Accepted October 9, 2017

ABSTRACT: The aim of this study is to assess the possibility of increasing ethanol production by introducing the bagasse hydrolysis process into conventional distilleries. Simulations were performed for mass and energy balances using Aspen Plus® software. It was assumed that sugarcane trash and lignin cake—hydrolysis process residues—are available as supplementary fuel. Several cases were evaluated, including: (a) conventional ethanol distillery, (b) conventional plant combined with a hydrolysis process without heat integration, with different solid contents in the hydrolysis reactor, and (c) conventional plant combined with the hydrolysis process applying heat integration by pinch analysis. The highest ethanol yield was achieved in the case of heat integration and concentration of cellulose hydrolysate by the membrane system with a solid content of 5% in the hydrolysis reactor. This represents an increase of 22% over conventional distilleries currently found in the industry.

KEYWORDS: Ethanol, sugarcane, enzymatic hydrolysis, heat integration

1. INTRODUCTION

In Brazil, ethanol is produced from sugarcane on a large scale by fermentation of sugars and distillation. The world consumption of ethanol is projected to grow in the coming years because of the interest of many countries in the replacement of fossil fuels by biofuels, due to such considerations as environmental damage (avoidance of greenhouse gas emissions); energy security (energy source diversification and reduction in oil dependence); and support to farmers [1]. In this context, sugarcane bagasse is the major by-product of sugar and ethanol production; it is usually burnt in boilers to cover the steam and power requirements of the process. Nevertheless, sugarcane bagasse, as well as other lignocellulosic materials, could alternatively be used as raw material for ethanol production by introducing a hydrolysis process into the current ethanol production system. However, in practice, this is likely to be a challenge, because less bagasse would then be available as fuel.

In the literature, there are several studies evaluating the incorporation of bagasse hydrolysis in current distilleries. Thus, the CGEE [1] accomplished a prospective study evaluating the increase of ethanol production by means of an enzymatic hydrolysis process under projected scenarios for the years 2015 and 2025. In this context, Dias *et al.* [2] studied the incorporation of the organosolv hydrolysis process with diluted acid into the current ethanol production process. Dias *et al.* [3] also performed a simulation study of ethanol production by enzymatic hydrolysis and different pretreatment processes. In their study, the authors assumed a reduction of 30.8% in steam consumption, which would be obtained from heat integration, though no details about heat integration were presented. In addition, Walter and Ensinas [4] also accomplished a preliminary analysis of two technological routes of biofuels production from cellulosic materials (based on hydrolysis and on gasification + Fischer-Tropsch conversion processes). Nevertheless, these authors considered a future scenario assuming glucose and xylose fermentation (the latter being a technology not yet fully developed). Along these lines, Macrelli et al. [5] carried out a techno-economic evaluation of the ethanol production by enzymatic hydrolysis, assuming the production of biogas from pentose

---

Corresponding author: sanebra@gmail.com

DOI: 10.7569/JRM.2017.634175

liquor and its use in boilers as fuel. Furthermore, Furlan *et al.* [6] carried out the modeling and simulation of the integrated production process of first- and second-generation ethanol, including the optimization of bagasse use by employing an equation-oriented simulator. Recently, Albarelli *et al.* [7] studied supercritical water, and compared it with the enzymatic hydrolysis applied to sugarcane bagasse.

Concerning the hydrolysis process, previous studies showed that cellulose hydrolysate (glucose liquor) has a rather low glucose content, which depends on the solid content adopted in hydrolysis reactors. Hence, the hydrolysate must be concentrated until the appropriate condition for the fermentation process. In this context, an alternative method, based on membranes, is proposed. That being so, pressure-driven membrane processes, such as reverse osmosis (RO), have the capability of removing water from aqueous solutions without changing their phase, consuming less energy than other separation techniques [8–10]. According to some authors [11, 12], RO membranes are suitable for concentrating glucose-water solutions; besides, several studies report their use in the food industry for fruit juice concentration [13–15].

Thus, the aim of this study is to evaluate the possibilities of an increase in ethanol production by the bagasse hydrolysis process, taking into account the limitations of bagasse use as raw material, and evaluating two technologies of glucose liquor concentration (multiple-effect evaporators and RO membranes). To achieve this objective, simulations were performed using Aspen Plus software to establish the mass and energy balances.

A detailed modeling of the cogeneration system was carried out, including the main elements of the steam generator and the steam cycle. Moreover, in order to appropriately calculate the surplus electricity of the mill, the electricity consumption related to each stage of the hydrolysis process was carefully estimated [16, 17]. Finally, pinch analysis was applied to determine the minimum hot and cold utilities required by the integrated process. Moreover, a procedure to incorporate the multiple-effect evaporation system into the grand composite curve, in order to optimize the vapor bleedings in each effect, is presented [18–20].

2. METHODS

2.1. Modeling and Simulation of the Conventional Ethanol and Electricity Production Process from Sugarcane

This study looks into a plant producing anhydrous ethanol and electricity using sugarcane as raw material.

Sugarcane is essentially composed of water, sugars, and fibers [21]. The sugarcane composition adopted for this study is shown in Table 1. Because the fiber main components—cellulose, hemicellulose, and lignin—are not found in the Aspen Plus simulator database, they were created, and their properties specified with the parameters reported in [22].

Figure 1 shows the flow sheet assumed for simulation of the conventional ethanol production process.

Thus, this study assumed a dry cleaning operation to remove the soil coming from the harvesting operation. Following that, the sugarcane is sent to the extraction system, where juice and bagasse are separated. For simulation purposes, an extraction system with mill tandems was selected. From the specifications assumed for the extraction system, the composition of bagasse (dry basis, wt) resulted in: cellulose 36.8%, hemicelluloses 35%, lignin 20.3%, and ashes 2.3%; while the bagasse moisture content (wet basis, wt) was 50% [21].

The bagasse goes to the cogeneration system, while the raw sugarcane juice undergoes a physicochemical treatment, where the following operations were adopted: screening, heating, liming, decantation, and mud filtration. Thereafter, the treated juice is sent to the concentration stage, which takes place in a multiple-effect evaporation system to achieve a sucrose content of approximately 17% (suitable for the fermentation process).

The must sterilization is then carried out through a HTST-type (high-temperature short-time) treatment, by heating the must to 130 °C, followed by a fast cooling to reach the fermentation temperature of 32 °C [23]. The fermentation was based on the Melle-Boinot process (fed-batch fermentation with cell recycle); the fermentation yield and its by-products were assumed according to [24]. At the end of the fermentation, the resulting wine is centrifuged to recover most of the yeast.

Following that, the wine is sent to distillation and rectification columns where hydrous ethanol (93.7% wt of ethanol) and vinasse (0.02% wt of ethanol) are separated [25].

Table 1 Sugarcane composition specified in simulation [16].

Component	% Mass
Sucrose	13.85
Fibers	13.15
Reducing sugars	0.59
Minerals	0.20
Other non-saccharides	1.79
Water	69.35
Soil	1.07

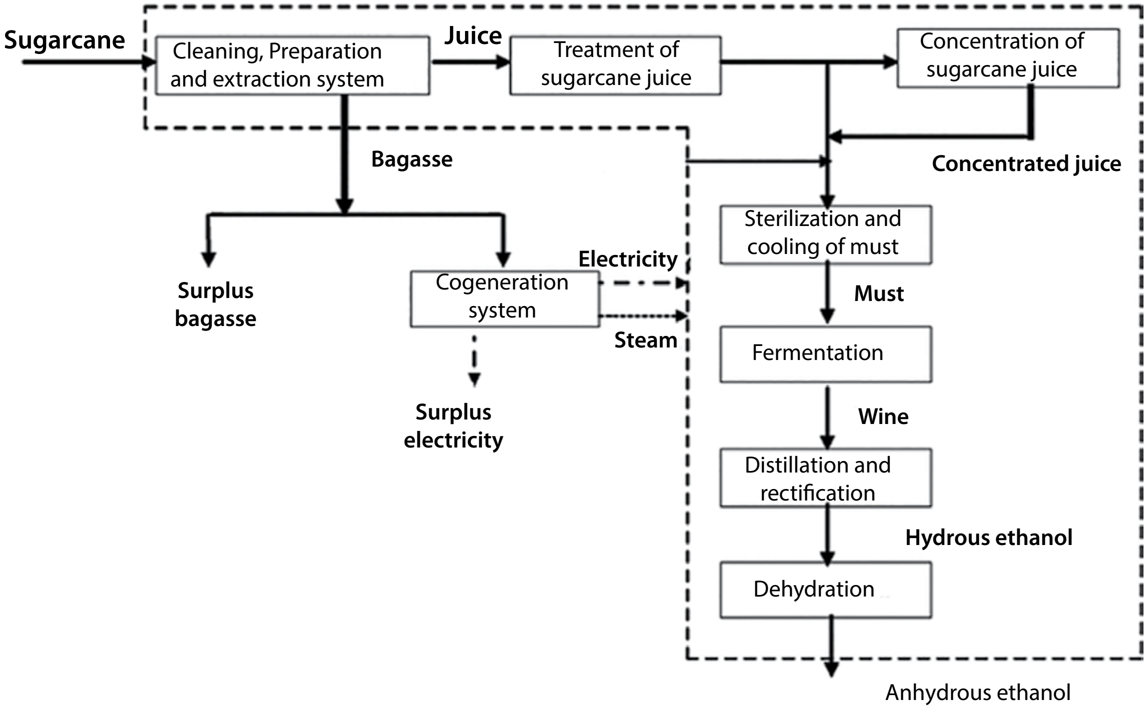

Figure 1 Flow sheet of conventional ethanol production process.

A process of extractive distillation with monoethylene glycol (MEG) was then simulated, according to [2, 23], to obtain anhydrous ethanol with an ethanol content of 99.4% (mass basis).

The cogeneration system adopted in the simulation consists of a steam cycle with backpressure steam turbines. This configuration is used to generate only the necessary process steam, leaving a surplus of bagasse that can be used in an enzymatic hydrolysis process [26].

Table 2 shows the mean parameters adopted in the ethanol production process simulation.

2.2 Modeling and Simulation of the Ethanol Production through Enzymatic Hydrolysis

Figure 2 shows the flow sheet of the ethanol production process by enzymatic hydrolysis as addressed by this study. Sugarcane bagasse (stream B2) was considered as raw material for the hydrolysis process.

Some authors [27] point out the need for cleaning (washing) the raw material before sending it to the pretreatment reactor; however, this operation would reduce the amount of reactants in subsequent stages. Since this study is an initial assessment, previous washing of bagasse and trash was not envisaged. Thus, bagasse (stream B2) is sent to the pretreatment reactor (PRE-TRAT).

Researchers and engineering companies have proposed several pretreatment methods, which can be physical, physicochemical, chemical, and biological in nature [28]. In this study, the steam explosion process was adopted because of its efficiency and low cost when compared to other chemical pretreatments.

Although some authors indicate that an acidic catalyst is not necessary during the pretreatment, this study assumed the addition of SO_2, as a catalyst, in the pretreatment reactor at the rate of 2% w/w, to keep consistency with the conversion yields reported by [27].

In the pretreatment reactor, formation of xylose ($C_5H_{10}O_5$), acetic acid ($C_2H_4O_2$), furfural, and glucose ($C_6H_{12}O_6$) was assumed, in accordance with [23]. In order to remove xylose and other components that might inhibit the subsequent processes of enzymatic hydrolysis and fermentation, the pretreated bagasse is washed in the unit block SEPA-PE. After that, two fractions remain: the liquid fraction L-PE (xylose liquor), and the solid fraction CEL-LIG. In this study, the use of xylose liquor was not contemplated.

For the next stage, water is added to the process (stream H2O-HIDR) in the tank T-MIST, in order to adjust the concentration of water-insoluble solids in the hydrolysis reactor. In the present study, three levels of solid content in the hydrolysis reactor were simulated: 5%, 8%, and 10%. In the next step, the stream

Table 2 Parameters adopted for the simulation of the ethanol production process.

Parameter	**Value**
Conventional process	
Sugarcane crushing rate, t/h	500
Efficiency of soil removal in cleaning operation, %	70
Efficiency of sugar extraction in extraction system, %	97
Conversion yield from sugars to ethanol, %	89
Ethanol content in vinasse and phlegmasse, %	0.02
Ethanol content in anhydrous ethanol, wt%	99.4
Cogeneration system	
Pressure of boiler live steam, bar	67
Temperature of boiler live steam, °C	480
Lower heating value of bagasse, MJ/kg	7.63
Isentropic efficiency of electricity generation in steam turbines, %	80
Alternator efficiency of turbine generator, %	97.6
Turbine mechanical efficiency, %	98.2
Isentropic efficiency of direct drive steam turbines, %	50
Pump isentropic efficiency, %	70
Boiler thermal efficiency, % (LHV base)	85
Mechanical power demand of cane preparation and extraction system, kWh/t of cane	16
Electric power demand of the conventional ethanol production process, kWh/t of cane	12
Process steam pressure, bar	2.5
Process steam temperature, °C	127.4

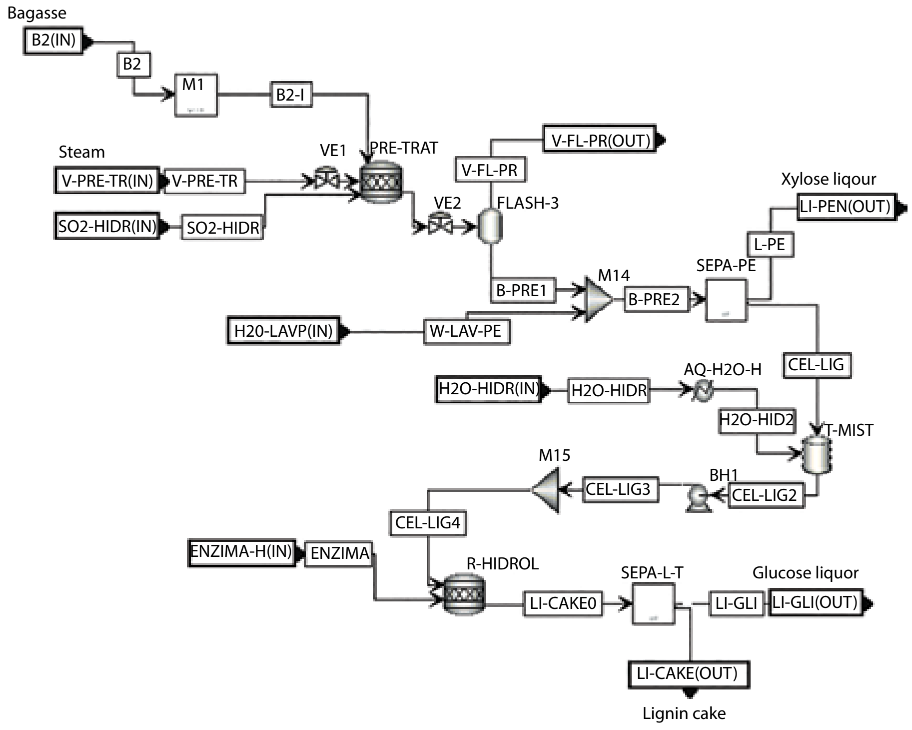

Figure 2 Flow sheet of the enzymatic hydrolysis process.

CEL-LIG4 goes to the hydrolysis reactor R-HIDROL, where enzymes (stream ENZIMA) are added to catalyze the hydrolysis reactions.

Following the hydrolysis stage, the hydrolysate is sent to a filter in order to separate the lignin cake (LI-CAKE) from the cellulose hydrolysate (LI-GLI).

Table 3 shows the yields assumed for the pretreatment and hydrolysis reactors, calculated from data reported in [27].

Table 4 shows the main parameters assumed in the simulation of the ethanol production through enzymatic hydrolysis.

Table 3 Yields assumed for reactions in pretreatment and hydrolysis reactors for different solid contents (5%, 8%, and 10%), according to [27].

Reaction	**From**	**Product**	**Yield (%)**		
Pretreatment reactor					
$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$	Hemicellulose	Xylose		61.4	
$C_5H_8O_4 + H_2O \rightarrow 2.5\ C_2H_4O_2$	Hemicellulose	Acetic acid		9.2	
$C_5H_{10}O_5 \rightarrow C_5H_4O_2 + 3\ H_2O$	Xylose	Furfural		5.1	
$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$	Cellulose	Glucose		4.1	
Hydrolysis reactor					
Solid content in hydrolysis			**5%**	**8%**	**10%**
$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$	Cellulose	Glucose	69.2	60.6	55.8
$C5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$	Hemicellulose	Xylose	46.9	44.4	40.6

Table 4 Parameters adopted for the simulation of the hydrolysis process.

Parameter	**Value**
Hydrolysis process	
Pretreatment reactor temperature, °C[a]	190
Pretreatment reactor pressure, bar	12.5
Pretreatment reactor steam consumption, kg of steam/kg of raw material[b]	0.55
Pressure at unitary block FLASH-3, bar	1.01
Efficiency of solid removal from solution in unit block SEPA-PE, %[a]	90
Loss of soluble lignin in unit block SEPA-PE, %[a]	6.3
Moisture content of solid fraction CEL-LIG, %[c]	60
Water for xylose washing, l/kg of dry materialc	15
Hydrolysis reactor temperature, °C[d]	50
Enzymatic load – cellulose, FPU/g dry biomass[a]	53
Enzymatic load – b glucosidase, IU/g dry biomass[a]	83
Moisture content in solid fraction TORTA-LI0, %	70
Lignin cake, kg of lignin cake/kg of hydrolyzed bagasse [g] (50% of moisture content)	0.455
Solid content in concentrate hydrolysate, %	19
Energy consumption in trash shredder, kWh/t of trash[e]	82.03
Energy consumption in cleaner station, kWh/t of trash[f]	13.6
Energy consumption in bagasse feeder, kWh/t of bagasse	0.459
Energy consumption in xylose separator SEPA-PE, kWh/t of material	2.3
Energy consumption in separator SEPA-L-T, kWh/m^3	0.4
Energy consumption in lignin cake dewatering press, kWh/kg of dry matter	56.09

[a]Carrasco *et al.* [27]; [b]Kling *et al.* [33]; [c]Palacios-Bereche [16]; [d]Galbe and Zacchi [34]; [e]Hassuani *et al.* [32]; [f]Cella [35]; [g]Average value, it varies from 0.426 to 0.481 depending on the solid content in hydrolysis

2.3. Integration of an Enzymatic Hydrolysis Plant into a Conventional Distillery

Figure 3 shows a block diagram of the hydrolysis plant inserted into the conventional ethanol production process as proposed.

The glucose liquor (cellulose hydrolysate) obtained in the hydrolysis process has a rather low glucose content—1.8% to 3.4% (w/w). Therefore, in order to integrate the enzymatic hydrolysis into a conventional distillery, this liquor must be concentrated, aiming to achieve a glucose content suitable for the fermentation process. After concentrating, it can be mixed with must from sugarcane juice.

This study evaluates two concentration technologies: a multiple-effect evaporation system, and a membrane system.

2.3.1 *Multiple-Effect Evaporation System*

Glucose liquor is preheated with flash steam recovered from the pretreatment decompression (PH-X) before sending it to a five-effect evaporation system, which operates with exhaust steam at 2.5 bar. Figure 4 shows the evaporation system modeled with the Aspen Plus software, where each stage of the evaporation system was represented using two-unit operation: a heat exchanger, and a flash separator [29, 30].

2.3.2 *Membrane System*

In this study, reverse osmosis (RO) was also assumed for the concentration of the glucose liquor. According to [9], a driving pressure of 28 to 32 bar is enough to achieve a sucrose content of 20 to 25 wt%; hence, a driving pressure of 30 bar was adopted in this study. Nevertheless, the osmotic pressure of the glucose

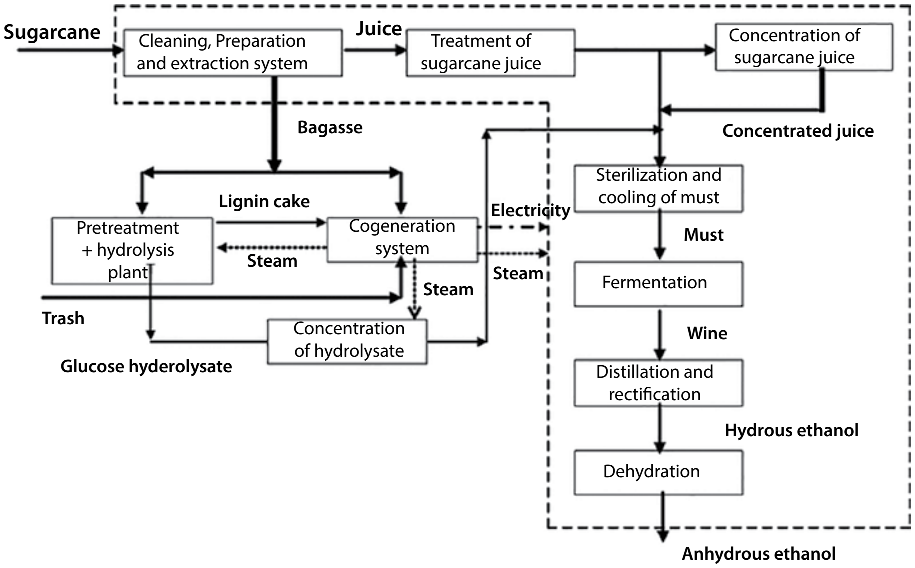

Figure 3 Ethanol production process – conventional process integrated with hydrolysis process.

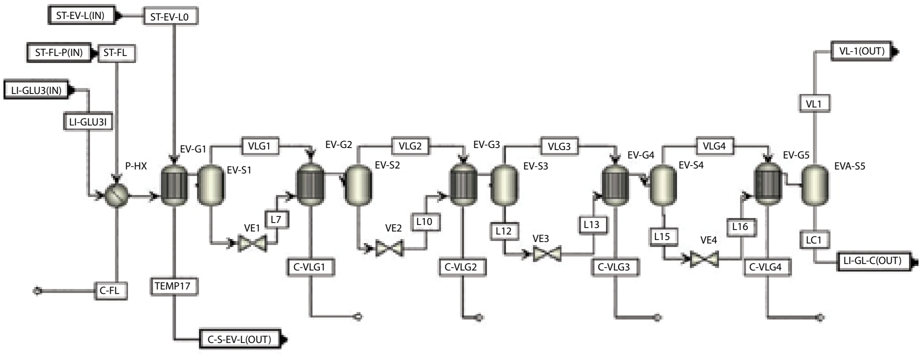

Figure 4 Evaporation system for concentration of cellulose hydrolysate.

Table 5 Description of evaluated cases.

Case	Name	Solid content in hydrolysis, %	Method for glucose liquor concentration	Description
I	Base case			Conventional distillery without hydrolysis
II	EV5	5	EV	Hydrolysis process coupled with conventional distillery
III	EV8	8	EV	
IV	EV10	10	EV	
V	ME5	5	ME	
VI	ME8	8	ME	
VII	ME10	10	ME	
VIII	$E10_{INT}$	10	EV	Hydrolysis process coupled with conventional distillery and heat integration
IX	$M5_{INT}$	5	ME	

EV: Evaporation system. ME: Membrane system

solution depends on its composition, temperature, and viscosity; therefore, further research is necessary in order to improve the results. The energy consumption in RO systems is mainly due to high-pressure pumps. The pump efficiency adopted in the simulation was 60% [16].

The steam used in pretreatment (steam explosion) should be supplied by the cogeneration system. It was assumed that steam is taken at the operation pressure of direct drive turbines (22 bar and 300 °C); thus, this steam must pass through an expansion valve before entering the pretreatment reactor, to reduce its pressure to 12.5 bar [31].

Sugarcane trash and lignin cake were regarded as fuels, thus freeing a larger amount of bagasse to be used in the hydrolysis process.

In such a way, the lignin cake (LI-CAKE) is burnt to contribute to the steam generation in the cogeneration system. Wet lignin cake at the outlet of the hydrolysis reactor has a moisture content of 70%. In order to improve its heating value, the wet lignin cake is sent to a dewatering press, where its moisture content is reduced to 50%, and its lower heating value reaches values between 8.3 MJ/kg and 8.5 MJ/kg (calculated from the lignin cake composition and data from [22]).

Regarding sugarcane trash, an average trash potential of 140 kg of dry residues per tonne of cane stalks was assumed [1, 32]. In addition, 50% of the total trash potential was assumed to be available for its use as fuel in the cogeneration system (38.9 t/h of wet trash). The moisture content of trash was assumed at 10%, thus its lower heating value was 13.9 MJ/kg.

Although the sugarcane trash and lignin cake were regarded as fuels, it is still necessary to burn part of the bagasse in the boilers to cover the energy requirements of the integrated process. The amount of bagasse for hydrolysis was calculated by an iterative process, because an increase in raw material for hydrolysis increases the plant steam consumption.

Owing to the lack of specific data, the trash and lignin cake were assumed to burn in the boiler with an efficiency of 86% (LHV base) [16].

2.4 Evaluated Cases

Table 5 shows the cases evaluated in this study.

2.5 Heat Integration through Pinch Analysis

The pinch method was used to accomplish the heat integration procedure, which allows the determination of minimal energy consumption targets, thereby maximizing the ethanol production from bagasse hydrolysis. The minimum approach temperature difference (ΔT_{min}) adopted in this study for the process streams was 10 °C, except for streams coming from evaporation systems, where 4 °C was selected. Because of the existence of evaporation systems; the heat integration procedure is carried out in steps. Moreover, vapor bleedings from the concentration systems were used to cover process heating requirements. Because their mass flows change according to process characteristics, the heat integration procedure was carried out by an iterative process according to the following sequence:

Step 1. Calculation of the amounts of trash and bagasse to be burnt in the boiler, from an initial assumption of the steam consumption of the overall process.

Step 2. Heat integration of the available process streams except the evaporation systems (sugarcane juice and glucose liquor). Construction of a previous grand composite curve (GCC).

Step 3. Integration of the evaporation systems and calculation of the appropriate vapor bleeding according to the procedure reported in [18–20].

Step 4. Recalculation of the steam consumption of the overall process until convergence is obtained.

The heat integration procedure was applied to Cases $E10_{INT}$ and $M5_{INT}$, which were selected for giving the best results in terms of ethanol production among the many cases analyzed by [16].

Table 6 shows the process streams data selected for heat integration.

Figure 5 shows the final grand composite curves for Cases $E10_{INT}$ and $M5_{INT}$.

3 RESULTS AND DISCUSSION

Table 7 shows the results of the anhydrous ethanol production, surplus electricity, bagasse sent to the hydrolysis process, and steam consumption for the evaluated cases.

3.1 Ethanol Production

Table 7 reveals that a higher solid concentration in the hydrolysis process in Cases EV5, EV8, and EV10 corresponds to a lower steam consumption in the glucose liquor concentration step. This fact allows larger amounts of bagasse to be sent to the hydrolysis process, leading to a higher ethanol production (for instance, in Case EV10 the increase in ethanol production was 12.3%; while in Case EV5, the increase was 9.7%).

Table 6 Streams selected for heat integration, solid content of 10% in hydrolysis reactor (Case $EV10_{INT}$).

Hot streams	Ti °C	Tf °C	ΔH MW	Cold streams	Ti °C	Tf °C	ΔH MW
Sterilized juice	130.0	32	50.8	Juice treatment	34.2	105.0	44.9
Fermented wine	32.0	28	13.2	Juice preheating	98.1	115.0	2.8
Phlegmasse	103.8	35	3.7	Juice for sterilization	89	130.0	22.5
Vinasse	109.3	35	45.9	Final wine	31.2	90.0	41.4
Anhydrous ethanol	78.3	35	10.2	Reboiler column A	109.3	109.3	53
Vapor Condensates	83.2	35	16.8	Reboiler column B	103.4	103.8	35.4
Condenser column B	81.6	81.6	30.5	Reboiler extractive column	112.1	137.1	8.0
Condenser extractive column	78.3	78.3	8.7	Reboiler recovery column	149.6	149.6	2.9
Condenser column D	85.1	35	34.6	Hydrolysis water	25	50	9.7
Vapor recovered from steam explosion	100.7	100	17.9	Glucose liquor preheating	50	115	27.2
				Imbibition water	25	50	4.7

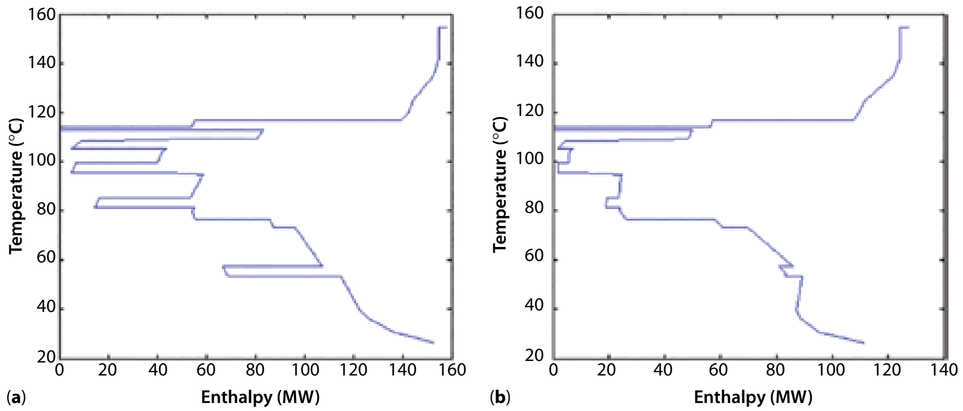

Figure 5 Grand composite curves including evaporation systems – GCC (Cases $E10_{INT}$ and $M5_{INT}$).

Table 7 Simulation results: Anhydrous ethanol production, l/t of cane; surplus electricity, kWh/t of cane; and steam consumption, kg/t of cane.

Parameter	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
	Base	EV5	EV8	EV10	ME5	ME8	ME10	$E10_{INT}$	$M5_{INT}$
Solid content in hydrolysis reactor	--	5	8	10	5	8	10	10	5
Anhydrous ethanol, (l/t of cane)	79	86.7	88.1	88.7	92.6	91.5	90.9	92.8	96.7
Surplus electricity, (kWh/t of cane)	42.3	62.5	54.6	51.3	25.3	32.9	35.7	30.5	–5.2
Vinasse, (t/t of cane)	0.88	0.98	1.00	1.01	1.07	1.06	1.05	1.06	1.12
Bagasse for hydrolysis, (kg/t of cane)	0	110.3	149.5	172.7	195.9	206.2	212.4	239.7	257.8
Steam generated at boiler, (kg/t of cane)	489.6	794.2	756.9	745.1	690.6	691.6	692.3	661.8	571.8
Increase in ethanol production, (%)[a]	--	9.7	11.5	12.3	17.2	15.9	15.1	17.4	22.4
Increase in ethanol production, (l/t of cane)[a]	--	7.7	9.1	9.7	13.6	12.5	11.9	13.7	17.7

[a] In comparison to Case I.

On the other hand, the use of membranes in Cases ME5, ME8, and ME10 allows further reductions in steam consumption (in comparison to EV cases); and, consequently, sends more bagasse to the hydrolysis. Among these cases, Case ME5 displayed the highest increase in ethanol production, due to the conversion yields assumed in the hydrolysis reactor.

By means of the heat integration procedure, an additional and significant decrease in steam consumption is obtained in Cases $E10_{INT}$ (a decrease of 11% in comparison to EV10), and $M5_{INT}$ (a decrease of 17% in comparison to ME5). As a consequence, the highest increases in ethanol production are achieved in these cases.

Hence, the heat integration promotes a higher increase in ethanol production. However, it must be kept in mind that this is a prospective study; therefore, pilot plant or industrial data would be necessary to confirm the modeling results.

3.2 Bagasse Balance

Figure 6 shows the bagasse balance for each case. The bagasse for hydrolysis increases as we go from Case EV5 to $M5_{INT}$. In Case $M5_{INT}$, all available bagasse is sent to the hydrolysis process (discounting the bagasse for filters and self-consumption), and only trash and lignin cake are burnt in the boilers. In this case, the energy supplied from lignin cake represents half of the total energy, while the other half is supplied by trash.

3.3 Cogeneration System – Surplus Electricity

Figure 7 shows the balance of the generated electricity in a steam cycle. The electricity consumption in the hydrolysis process was estimated from data in Table 4. A significant amount of electricity is consumed by the agitators of the hydrolysis reactors, because of their large volume. The reactor volume was calculated assuming continuous stirred tank reactors (CSRT) and a residence time of 48 h, in agreement with the data in Table 3.

Thus, the highest electricity consumption corresponds to Case $M5_{INT}$, owing to the large volume of the hydrolysis reactor (agitation power) and the large amount of hydrolyzed bagasse. It can be observed that the increase in hydrolysis solid content leads to a reduction in electricity consumption, this fact being more significant in cases that use membranes.

As a result of assuming back-pressure steam turbines in the cogeneration system, the surplus electricity is in direct relationship with the process steam consumption. Thus, the cases with the largest steam consumptions present the highest surplus electricity (for instance, Case EV5 presented an increase of 48% in electricity surplus, in comparison to Base Case). On the other hand, the cases with the lowest steam consumption present the lowest surplus electricity. Nevertheless, the electricity consumption in hydrolysis also influences electricity surplus; thus, even though cases that use membranes present steam

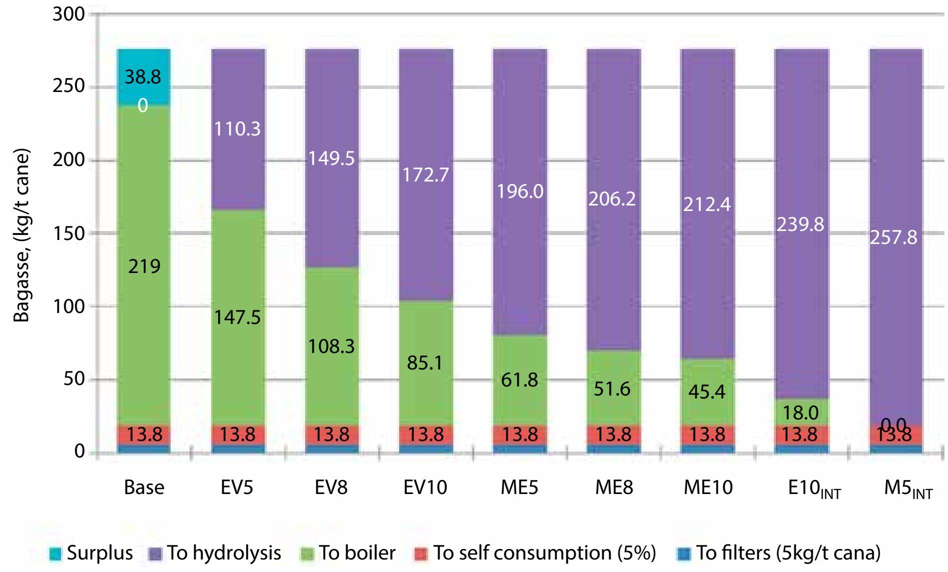

Figure 6 Bagasse balance (kg/t of cane).

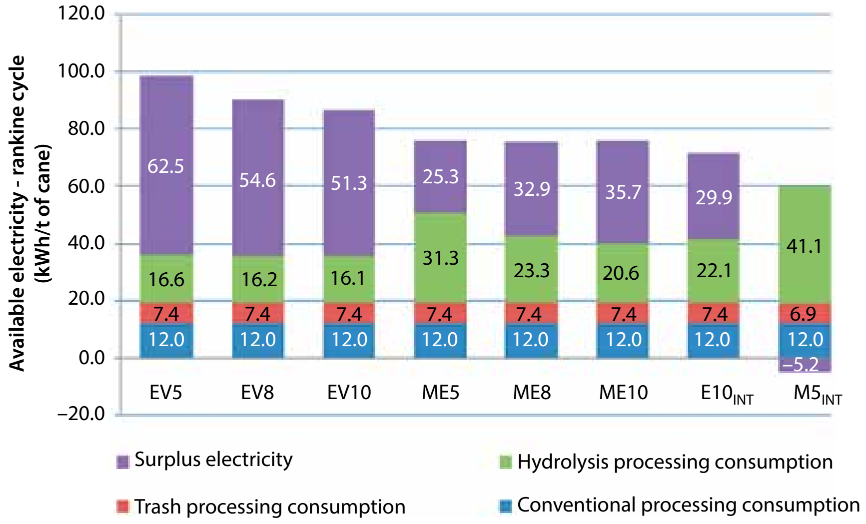

Figure 7 Balance of generated electricity (kWh/t of cane).

consumptions larger than the Base Case, their surplus electricity is lower due to the high electricity consumption in the hydrolysis process for these cases (for instance, Case ME5 presented an surplus electricity 40% lower in comparison to Base Case). Case $M5_{INT}$ deserves mention since it has an electricity deficit of 5.2 kWh/t of cane, which might be bought from the grid; however, other energy management solutions could be proposed as well.

It is interesting to compare the results of the present study with others from the literature.

By way of illustration, Walter and Ensinas [4] indicated an increase of 25.6% in ethanol production, though in a future scenario, assuming glucose and xylose fermentation. Dias *et al.* [2] mentioned ethanol production increases of 22.5% for the conventional distillation case, and 26.33% for the double-effect distillation case; while CGEE [1] indicated ethanol production increases of 12.2% and 25.6% in projected scenarios for the years 2015 and 2025 respectively. Dias *et al.* [3] indicate an ethanol production, in the integrated process, in the range of 107.5 to 120.6 l/t of cane when pretreatment by steam explosion is adopted. It represents an increase of 15.9% and 30% over their base case. Finally, Macrelli *et al.* [5] mentioned ethanol production increases in the range of 15.8% to 53.2%.

4. CONCLUSIONS

The present study shows potential ethanol production increases by introducing bagasse enzymatic hydrolysis into the conventional ethanol production process.

Results were comparatively modest, but it must be borne in mind that this study assumed conservative conversion factors, and did not include pentose fermentation. An optimization of the conventional process is also recommended, aiming at energy consumption reduction. Eventually, biogas production from pentose liquor can be assumed.

The use of membranes to concentrate glucose liquor allowed a significant reduction of steam consumption and a considerable increase in ethanol production. Moreover, heat integration promoted a higher increase in ethanol production, which is important for the feasibility of the introduction of the hydrolysis process into current distilleries.

The cogeneration system energy balance shows that the energy supplied by lignin cake is significant for the integrated process operation. Hence, the study and characterization of lignin cake will be relevant to make ethanol production by enzymatic hydrolysis a viable proposition.

ACKNOWLEDGMENTS

The authors wish to thank CNPq (Process 304820/2009-1), FAPESP (Process 11/05718-1), and FINEP (Contract FINEP – FUNCAMP No. 01/06/004700) for providing financial support.

REFERENCES

1. CGEE – Center for Strategic Studies and Management in Science, Bioetanol combustível: uma oportunidade para o Brasil, CGEE, Brasília (2009).
2. M.O.S. Dias, A.V. Ensinas, S.A. Nebra, R. Maciel Filho, and C.E.V. Rossell, Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chem. Eng. Res. Des.* 87, 1206–1216 (2009).
3. M.O.S. Dias, M.P. Cunha, R. Maciel Filho, A. Bonomi, C.D.F. Jesus, and C.E.V. Rossell, Simulation of integrated first and second generation bioethanol production from sugarcane: Comparison between different biomass pre-treatment methods. *J. Ind. Microbiol. Biotechnol.* 38, 955–966 (2011).
4. A. Walter and A.V. Ensinas, Combined production of second-generation biofuels and electricity from sugarcane residues. *Energy* 35, 874–879 (2010).
5. S. Macrelli, J. Mogensen, and G. Zacchi, Techno-economic evaluation of 2nd generation bioethanol production from sugar cane bagasse and leaves integrated with the sugar-based ethanol process. *Biotechnol. Biofuels* 5, 22 (2012).
6. F.F. Furlan, C.B.B. Costa, G.C. Fonseca, R.P. Soares, A.R. Secchi, A.J.G. Cruz, and R.C. Giordano, Assessing the production of first and second generation bioethanol from sugarcane through the integration of global optimization and process detailed modelling. *Comput. Chem. Eng.* 43, 1–9 (2012).
7. J. Albarelli, D. Santos, A.V. Ensinas, F. Maréchal, F. Mato, M. Cocero, and M. Meireles, Thermo-economic and environmental comparison of supercritical water and enzymatic hydrolysis of sugarcane bagasse in a biorefinery concept. *Energy* 141, 20 (2017).
8. N. Zaghbani, M. Nakajima, H. Nabetani, and A. Hafiane, Modeling reverse osmosis flux of aqueous solution containing glucose. *Korean J. Chem. Eng.* 34(2), 407–412 (2017).
9. S. Gul and M. Harasek, Energy savings in sugar manufacturing with the implementation of a new membrane process, Proceedings of 14th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction. Florence, Italy (2011).
10. S.S. Madaeni and S. Zereshki, Energy consumption for sugar manufacturing. Part I: Evaporation versus reverse osmosis. *Energy Convers. Manage.* 51, 1270–1276 (2010).
11. R.W. Baker, *Membrane Technology and Applications,* 2nd ed., John Wiley & Sons Ltd., West Sussex (2004).
12. G. Zacchi and A. Axelsson, Economic evaluation of preconcentration in production of ethanol from dilute sugar solutions. *Biotechnol. Bioeng.* 34, 223–233 (1989).
13. D. Pepper, A.C.J. Orchard, and A.J. Merry, Concentration of tomato juice and other fruit juices by reverse osmosis. *Desalination* 53, 157–166 (1985).
14. A. Kozák, A. Rektor, and G. Vatai, Integrated large-scale membrane process for producing concentrated fruit juices. *Desalination* 200, 540–542 (2006).
15. B. Jiao, A. Cassano, and E. Drioli, Recent advances on membrane processes for the concentration of fruit juices: A review. *J. Food Eng.* 63, 303–324 (2004).
16. R. Palacios-Bereche, Modelling and energy integration of the ethanol production process from sugarcane biomass, PhD Thesis. Campinas, Mechanical Engineering Faculty, University of Campinas, (in Portuguese) (2011).
17. L.T.C. Pereira, R.S.S.T. Teixeira, E.P.S. Bom, and S.P. Freitas, Sugarcane bagasse enzymatic hydrolysis: Rheological data as criteria for impeller selection. *J. Ind. Microbiol. Biotechnol.* 38, 901–907 (2011).
18. A.V. Ensinas, Thermal integration and thermoeconomic optimization applied to industrial process of sugar and ethanol from sugarcane, PhD Thesis, Campinas: Mechanical Engineering Faculty, University of Campinas, (in Portuguese) (2008).
19. E.A. Pina, R. Palacios-Bereche, M.F. Chavez-Rodriguez, A.V. Ensinas, M. Modesto, and S.A. Nebra, Reduction of process steam demand and water-usage through heat integration in sugar and ethanol production from sugarcane – Evaluation of different

plant configurations. Energy (2015) In press. DOI: org/10.1016/J.ENERGY.2015.06.054

20. E.F. Cortes-Rodríguez, N.A. Fukushima, R. Palacios-Bereche, A.V. Ensinas, and S.A. Nebra, Vinasse concentration and juice evaporation system integrated to the conventional ethanol production process from sugarcane – Heat integration and impacts in cogeneration system. *Renew. Energy* (2017) In press. DOI: org/10.1016/J.RENENE.2017.08.036
21. P. Rein, *Cane Sugar Engineering,* Verlag Dr. Albert Bartens KG, Berlin (2007).
22. R.J. Wooley and V. Putsche, Development of an ASPEN PLUS physical property database for biofuels components, National Renewable Energy Laboratory, 1996. http:// www.p2pays.org/ref/22/21210.pdf (2007).
23. M.O.S. Dias, Simulation of ethanol production processes from sugar and sugarcane bagasse, aiming process integration and maximization of energy and bagasse surplus, Master thesis. Campinas: Chemical Engineering Faculty, University of Campinas, (in Portuguese) (2008).
24. R. Eijsberg, The design and economic analysis of a modern bioethanol factory located in Brazil, Master thesis, Delft, University Delft (2006).
25. J. Finguerut, A.J.A. Meirelles, R. Guirardello, and A. Costa, Fermentation, hydrolysis and distillation, in *Biomass for Energy,* L.A.B. Cortez (Ed.), pp. 436–474, Ed. Unicamp Campinas, Brazil (2008).
26. R. Palacios-Bereche and S.A. Nebra, Thermodynamic modelling of a cogeneration system for a sugarcane mill using ASPEN PLUS, Proceedings of COBEM 2009, Paper N° COB09-2093, Gramado (2009).
27. C. Carrasco, H.M. Baudel, J. Sendelius, T. Modig, C. Roslander, and M. Galbe, SO2-catalyzed steam pretreatment and fermentation of enzymatically hydrolyzed sugarcane bagasse. *Enzyme Microb. Technol.* 46, 64–73 (2010).
28. Y. Sun and J. Cheng, Hydrolysis of lignocellulosic materials for ethanol production: *A review. Bioresour. Technol.* 83, 1–11 (2002).
29. M.O.S. Dias, M. Modesto, A.V. Ensinas, S.A. Nebra, R. Maciel Filho, and C.E.V. Rossell, Improving bioethanol production from sugarcane: Evaluation of distillation, thermal integration and cogeneration systems. *Energy* 36, 3691–3703 (2012).
30. L.M.M. Jorge, A.R. Righetto, P.A. Polli, O.A.A. Santos, and R. Maciel Filho, Simulation and analysis of a sugarcane juice evaporation system. *J. Food Eng.* 99, 351–359 (2010).
31. O.J. Sanchez and C.A. Cardona, Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresour. Technol.* 99, 5270–5295 (2008).
32. S.J. Hassuani, M.R.L.V. Leal, and I.C. Macedo, *Biomass Power Generation: Sugarcane Bagasse and Trash,* 1st ed., Ed. PNUD and CTC, Piracicaba (2005).
33. S.H. Kling, C. Carvalho Neto, M.A. Ferrara, J.C.R. Torres, D.B. Magalhaes, and D.D.Y. Ryu, Enhancements of enzymatic hydrolysis of sugar cane bagasse by steam explosion pretreatment. *Biotechnol. Bioeng.* 29, 1035–1039 (1987).
34. M. Galbe and G. Zacchi, Ethanol production from lignocellulosic materials, in *Sugarcane Bioethanol – R&D for Productivity and Sustainability,* L.A.B. Cortez (Ed.), pp. 697–716, Blucher, São Paulo (2010).
35. N. Cella, Trash use as fuel in biomass boilers, Course Boilers, Environment and Renewable Energy. Ribeirao Preto, 23–24 de June 2010.
36. C.E.V. Rossell, Sugarcane processing to ethanol for fuel purposes, in *Chemistry and Processing of Sugarbeet and Sugarcane,* M.A. Clarke and M.A. Godshall (Eds.), pp. 349–366, Elsevier Science Publishers BV, Amsterdam (1988).
37. H. Magnusson, Process simulation in Aspen Plus of an integrated ethanol and CHP plant, Master thesis, Umea University, Umea (2005).
38. M.B. Michelazzo. Sensitivity analysis of six systems for collection of sugarcane trash (*Saccharum* spp.), Master thesis, Campinas: Agricultural Engineering Faculty, University of Campinas, (in Portuguese) (2005).