

Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

Chemical Engineering Research and Design

IChemE

journal homepage: [www.elsevier.com/locate/cherd](http://www.elsevier.com/locate/cherd)

# Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process

Marina O.S. Dias<sup>a,\*</sup>, Adriano V. Ensinas<sup>a,b</sup>, Silvia A. Nebra<sup>c</sup>, Rubens Maciel Filho<sup>a</sup>, Carlos E.V. Rossell<sup>a</sup>, Maria Regina Wolf Maciel<sup>a</sup>

<sup>a</sup> School of Chemical Engineering, University of Campinas, Brazil

<sup>b</sup> CECS, Federal University of ABC, Brazil

<sup>c</sup> Interdisciplinary Centre for Energy Planning, University of Campinas, Brazil

## A B S T R A C T

Ethanol may be produced using sugarcane bagasse as raw material through the Organosolv process with dilute acid hydrolysis, thus increasing ethanol production with the same cultivated sugarcane area. In this work simulations of bioethanol production from sugarcane juice and bagasse are carried out using software UniSim Design. A typical large scale production plant is considered: 1000 m<sup>3</sup>/day of ethanol is produced using sugarcane juice as raw material. A three-step hydrolysis process (pre-hydrolysis of hemicellulose, Organosolv delignification and cellulose hydrolysis) of surplus sugarcane bagasse is considered. Pinch analysis is used to determine the minimum hot utility obtained with thermal integration of the plant, in order to find out the maximum availability of bagasse that can be used in the hydrolysis process, taking into consideration the use of 50% of generated sugarcane trash as fuel for electricity and steam production. Two different cases were analyzed for the product purification step: conventional and double-effect distillation systems. It was found that the double-effect distillation system allows 90% of generated bagasse to be used as raw material in the hydrolysis plant, which accounts for an increase of 26% in bioethanol production, considering exclusively the fermentation of hexoses obtained from the cellulosic fraction.

© 2009 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

**Keywords:** Bioethanol; Sugarcane; Distillation; Acid hydrolysis; Simulation

## 1. Introduction

Increase on world's energy demand and the progressive depletion of oil reserves motivate the search for alternative energy resources, especially for those derived from renewable materials such as biomass (Saxena et al., 2009). Global concern about climate change and the consequent need to diminish greenhouse gases emissions have encouraged the use of bioethanol as a gasoline replacement or additive (Balat et al., 2008). Bioethanol may also be used as raw material for the production of different chemicals, thus driving a full renewable chemical industry.

Bioethanol is produced from the fermentation of sugars obtained from biomass. Bioethanol feedstock can contain

either sucrose (e.g. sugarcane, sugar beet) or starch (e.g. corn, wheat) or be a lignocellulosic material (e.g. sugarcane bagasse, wood and straw). Corn and sugarcane are the feedstock used in the US and in Brazil, respectively, which are the largest ethanol producers in the world. Sugarcane is so far the most efficient raw material for bioethanol production: the consumption of fossil energy during sugarcane processing is much smaller than that of corn (Macedo et al., 2008). Furthermore, optimization of bioethanol production process from sugarcane is still possible, and significant reduction of energy consumption can be achieved.

One of the world's largest ethanol producers, Brazil has been using sugarcane as raw material for large scale bioethanol production for more than 30 years (Goldemberg,

\* Corresponding author at: School of Chemical Engineering, University of Campinas, UNICAMP, P.O. Box 6066, 13083-970, Campinas-SP, Brazil. Tel.: +55 19 3521 3958.

E-mail addresses: [diasmos@feq.unicamp.br](mailto:diasmos@feq.unicamp.br), [diasmos@gmail.com](mailto:diasmos@gmail.com) (M.O.S. Dias).

Received 5 October 2008; Received in revised form 8 May 2009; Accepted 30 June 2009

0263-8762/\$ – see front matter © 2009 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.  
doi:10.1016/j.cherd.2009.06.020

2007). Typically, in the sugarcane processing, large amounts of sugarcane bagasse are produced (approximately 240 kg of bagasse with 50% humidity per ton of sugarcane), which are nowadays burnt in boilers for steam and electricity generation. Better technologies for cogeneration and optimization of bioethanol production process allow it to have a bagasse surplus (Ensinas et al., 2007), which may be used as a fuel source for electricity generation or as raw material for producing bioethanol and other biobased products (Buddadee et al., 2008).

Bioethanol from lignocellulosic materials, such as sugarcane bagasse, has been studied for the past few decades with great interest, but its production in industrial scale has not yet become viable (Balat et al., 2008). Studies taking into account process integration, increase of fermentation yields and integration of unit operations are still needed in order to make hydrolysis a competitive technology (Zaldivar et al., 2001; Cardona and Sánchez, 2007).

Lignocellulosic materials are mainly comprised of cellulose, which is a glucose polymer, hemicellulose, a mixture of polysaccharides composed mainly by glucose, mannose, xylose and arabinose, and lignin (Saxena et al., 2009). In order to be used as raw material for bioethanol production, sugarcane bagasse must be processed to yield fermentable sugars (Mosier et al., 2005). A pre-treatment process is required in order to separate lignin and hemicellulose from the cellulose, reduce cellulose crystallinity and increase the porosity of the bagasse, thus improving cellulose hydrolysis (Kuo and Lee, 2009). One possible way to achieve that is through the Organosolv process with dilute acid hydrolysis (Rossell et al., 2005). In this process, pre-hydrolysis of the hemicellulose, Organosolv delignification and cellulose hydrolysis may be carried out on three separate steps, thus leading to different streams containing pentoses, lignin and hexoses.

In order to increase the amount of bagasse available for bioethanol production through the hydrolysis process, optimization of energy consumption of the conventional bioethanol production process from sugarcane juice must be carried out. The Pinch Point Method (Linnhoff et al., 1982) was used to analyze the process streams that are available for thermal integration, consequently providing a reduction on system consumption. A similar approach was considered for the optimization of energy consumption of the bioethanol production process from corn (Franceschin et al., 2008).

In this work, simulations of bioethanol production process from sugarcane and sugarcane bagasse were carried out using software UniSim Design. Pinch Technology was used to optimize energy consumption and determine the amount of sugarcane bagasse available for hydrolysis, taking into account the production of steam and electrical energy to supply the factory.

## 2. Simulation development

Simulations were carried out using software UniSim Design from Honeywell. Except for the dehydration step, NRTL (Nom-Random Two Liquid) was the model used throughout the simulation for the calculation of the activity coefficient on the liquid phase, and EOS SRK (equation of state Soave–Redlich–Kwong) for the vapor model.

In order to determine the most suitable thermodynamic model to represent the process, calculations for the boiling point of water–sucrose binary mixtures were carried out, since

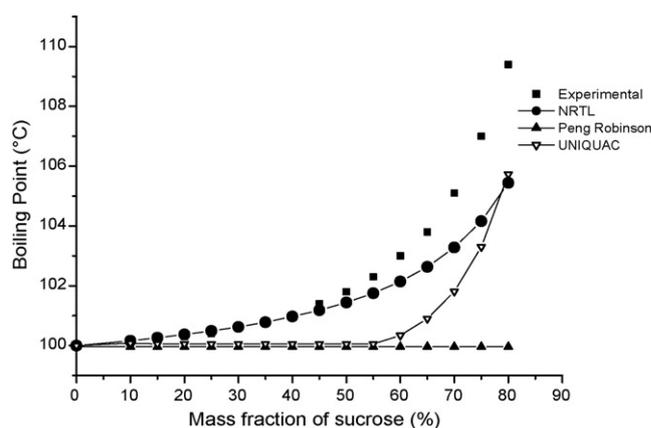


Fig. 1 – Boiling point of the binary mixture sucrose–water, according to experimental data (Hugot, 1972) and estimated using NRTL, EOS Peng-Robinson and UNIQUAC.

sucrose is the most abundant carbohydrate present in sugarcane juice (Mantelatto, 2005). It was verified that the NRTL model provides the best estimations for the boiling temperature of sucrose solutions, when compared either to UNIQUAC or equation of state Peng-Robinson, as shown in Fig. 1.

The extractive distillation process with monoethyleneglycol (MEG) was used for ethanol dehydration (Meirelles et al., 1992), and for this step the model UNIQUAC was used to calculate activity coefficient on the liquid phase, and EOS SRK was used as the vapor model.

The most relevant components usually present in the industrial units were considered, as given in Table 1; it was necessary to create some hypothetical components for those that are not in the process simulator database.

Prior to the simulation, a mass balance of the conventional bioethanol process was made based on data obtained in an industrial plant located in São Paulo state, during the 2006–2007 harvest season, as well as from the literature.

### 2.1. Ethanol production process from sugarcane

The first step of the ethanol production process takes place in the fields, where sugarcane is harvested. The sugarcane plant is composed by roots, stalk, tops and leaves. The stalks contain most of the sugars, thus being the fraction of interest in industrial processing. Upon mechanical harvest, most of the leaves and tops, which constitute the so-called “sugarcane trash”, are separated from the stalks and left on the fields, increasing soil

Table 1 – Components used on the simulation.

Database components	Hypothetic components
Water	Cellulose
Ethanol	Hemicellulose
Dextrose	Lignin
Sucrose	Dirt
Carbon dioxide	Calcium phosphate
Glycerol	Potassium salt
Succinic acid	Minerals
Acetic acid	Aconitic acid
Iso-amyl alcohol	Lime
Sulphuric acid	Phosphoric acid
Furfural	Yeast
Ethylene glycol	HMF
Ammonia	Pentose
Hydrogen	

**Table 2 – Composition of the sugarcane received in the factory.**

Component	Content (wt.%)
Sucrose	13.30
Cellulose	4.77
Hemicellulose	4.53
Lignin	2.62
Reducing sugars	0.62
Minerals	0.20
Impurities	1.79
Water	71.57
Dirt	0.60

protection and inhibiting the growth of weed and other plant species.

Sugarcane received in the factory, comprised mainly by its stalks, contains water, fibre, sugars, impurities and dirt (sand, simulated as silica). The composition considered in this work is based on typical data obtained in the industry and is given in Table 2.

All reducing sugars were simulated as dextrose; fibre (12% of the sugarcane) is comprised by cellulose, hemicellulose and lignin (Wooley and Putsche, 1996); impurities were simulated as acetic acid and potassium salt, since those account for the majority of the impurities (Mantelatto, 2005); minerals were simulated as  $K_2O$  and dirt as  $SiO_2$ . Dirt is dragged along with the sugarcane during harvest; the other components are part of sugarcane structure.

In this work an autonomous distillery, that is, a factory in which sucrose is entirely used as raw material for ethanol production, is considered for the production of 1000 m<sup>3</sup> per day of anhydrous ethanol, using sugarcane juice as raw material. An input of 493 t of sugarcane per hour is necessary. This is compatible with large scale units operating nowadays.

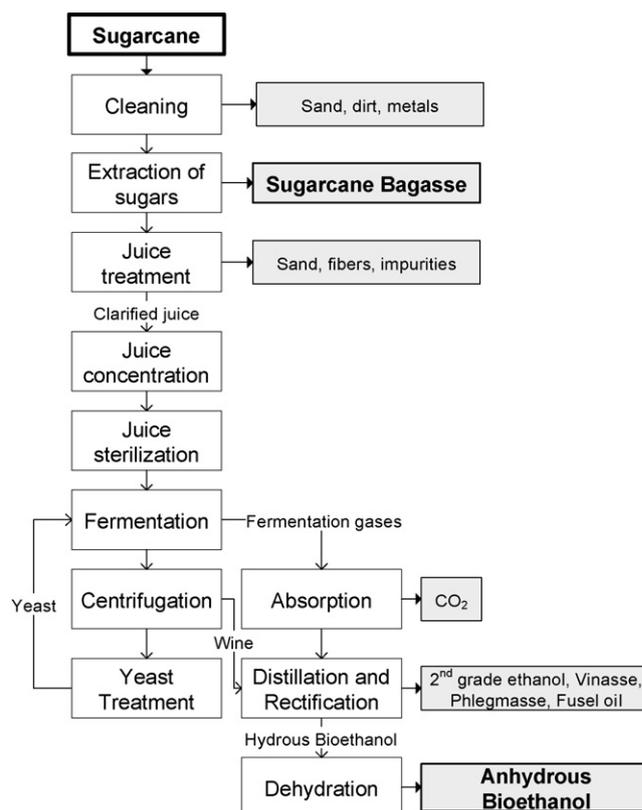
Ethanol production from sugarcane is comprised by the following steps: cleaning of sugarcane and extraction of sugars; juice treatment, concentration and sterilization; fermentation; distillation and dehydration. A detailed description of the simulation of each of these steps is presented, and a block flow diagram is depicted in Fig. 2.

### 2.1.1. Cleaning of sugarcane, extraction of sugars and juice treatment

In order to remove part (70%) of the dirt dragged along with the sugarcane from the fields, a dry-cleaning system is used. Sugar extraction is carried out using mills, in which water at a rate of 28% of sugarcane flow is used to enhance sugar recovery, in a process termed imbibition (Chen and Chou, 1993). Sugars recovery in the mills is considered equal to 96%. In the mills, sugarcane juice and bagasse are obtained. Sugarcane juice, which contains the sugars, is fed to the juice treatment operations, while sugarcane bagasse (50% humidity) is burnt in boilers for generation of steam and electrical energy. In this work bagasse surplus from the cogeneration system is used as raw material for bioethanol production through the hydrolysis process.

Sugarcane juice contains impurities, such as minerals, salts, acids, dirt and fibre, besides water and sugars. In order to be efficiently used as a raw material for ethanol production through fermentation, those impurities must be removed; thus, the juice is submitted to physical and chemical treatments.

Screens and hydrocyclones are used in the physical treatment, where the majority of fibre and dirt particles are



**Fig. 2 – Block flow diagram of the conventional bioethanol production process from sugarcane.**

removed (Chen and Chou, 1993). In a subsequent chemical treatment, phosphoric acid is added to sugarcane juice, to increase juice phosphates content and enhance impurities removal during settlement, followed by the first heating operation in which juice temperature increases from 30 to 70 °C.

Pre-heated juice receives lime and is mixed with a recycle stream containing the filtrate obtained at the cake filter, being then heated up again to 105 °C. Hot juice is then flashed to remove air bubbles, and a flocculant polymer is added to the de-aired juice, which is fed to the settler. In the settler impurities are removed from the juice and two streams are obtained: mud, which contains the impurities, and clarified juice. One of the main impurities removed in the mud is calcium phosphate, which is a precipitate formed in a reaction between lime and phosphoric acid; during settlement it drags many other impurities contained in the juice, thus enhancing clarified juice purity (Mantelatto, 2005).

Besides impurities, the mud obtained in the settler contains sugars, thus a filter is used to enhance sugars recovery. In this filter water and fine particles of bagasse are added to increase filtration efficiency. The filtrate is then recycled to the process and mixed with the limed juice prior to the second heating operation, while the filter cake is used as fertilizer in the fields (Chen and Chou, 1993).

### 2.1.2. Juice concentration and sterilization

Clarified juice contains around 15 wt.% diluted solids, so it must be concentrated before fermentation in order to achieve an adequate ethanol content that allows reduction of energy consumption during product purification steps. Concentration is carried out in a five-stage multiple effect evaporator (MEE) up to 65 wt.% sucrose (Chen and Chou, 1993). Sucrose concentration in the juice fed to the fermentation reactor is

**Table 3 – Pressure and temperature on the MEE.**

Evaporator	Pressure (kPa)	Temperature (°C)
1st effect	169.6	115.5
2nd effect	135.4	108.8
3rd effect	101.0	100.6
4th effect	52.9	83.8
5th effect	20.0	64.6

considered equal to 22 wt.%, thus only a fraction of the clarified juice is concentrated on the MEE; concentrated juice obtained on the MEE last effect is mixed with the remaining clarified juice. The amount of clarified juice for concentration is calculated using the Adjust tool of the simulator. The UniSim simulator used does not have the operation that represents the MEE in its database, so a system comprised by a separator, valve and heat exchanger was used to represent this operation. Vapor purges may be done if needed. Low pressure steam and concentrated juice are obtained on the last effect of the MEE.

Pressure and temperature on each effect of the MEE is shown in Table 3.

Juice is sterilized prior feeding the fermentation reactor, in order to avoid contamination, which would decrease fermentation yields. During sterilization juice is heated up to 130 °C during about 30 min and then rapidly cooled down to fermentation temperature.

### 2.1.3. Fermentation

Yeast suspension containing about 28% yeast cells (*v*) is fed to the fermentation reactor, along with sterilized juice. Yeast accounts for approximately a quarter of the reactor capacity. During the fermentation reactions, sucrose is hydrolyzed into fructose and glucose, which are converted into ethanol and carbon dioxide, as represented in Eq. (1):

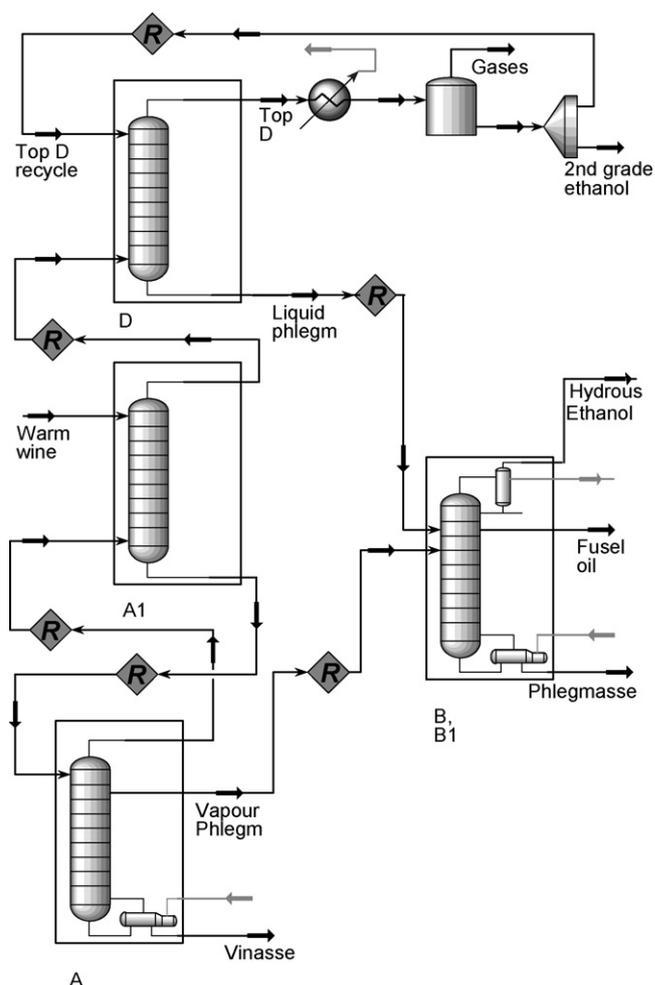


A conversion reactor was used in the simulation, and the conversion for Eq. (1) is equal to 90.48%, based on sugar consumption. Some by-products are formed as well, as a result of parallel fermentation reactions, cells growth and impurities in the sugarcane juice, among other factors. In addition, around 4% of the glucose is not consumed by the yeast. Conversion parameters for the by-products, based on industrial data of large scale units, are given in Table 4.

The fermentation temperature represents a critical step in ethanol production, since higher temperatures affect yeast behaviour, diminishing the ethanol content of the final wine, which increases the consumption of energy during distillation as well as the volume of vinasse per volume of ethanol produced (Dias et al., 2007). In this work fermentation was considered to be performed at 28 °C, which is considerably lower than the temperatures usually used in industry (around 34 °C).

**Table 4 – Product formation based on glucose consumption in the fermentor.**

Product	Conversion (%)
Glycerol	2.67
Succinic acid	0.29
Acetic acid	1.19
Isoamyl alcohol	$3.1 \times 10^{-4}$
Yeast	1.37

**Fig. 3 – Configuration of the conventional distillation process for hydrous ethanol production.**

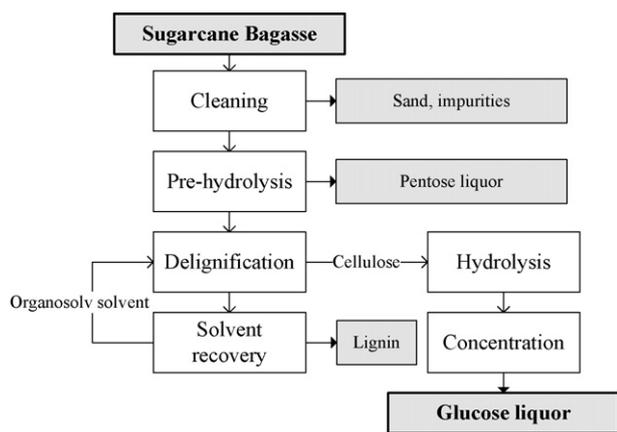
Auxiliary cooling equipments must be used to provide cool water for cooling of the fermentation vats, such as absorption with lithium bromide or steam jet ejectors. This allows the production of wine with higher ethanol content, 10 wt.%, at the expense of higher equipment investments (Dias et al., 2007).

In the fermentor two streams are obtained: wine and gases. Fermentation gases are fed to an absorber column, in order to recover evaporated ethanol, and wine is centrifuged to recover yeast cells. Two centrifuges in series are used: in the first, yeast cell concentration is increased to 35% (*v*); water is added to the second centrifuge, where a concentrated yeast stream (70% cells, volume basis) is obtained. Centrifuged wine is mixed with the alcoholic solution from the absorber and fed to the distillation unit. A purge is made on the concentrated yeast stream, the remaining fraction receives a chemical treatment made up by the addition of sulphuric acid and water, which avoids bacterial contamination and produces a stream of yeast concentrations around 28% (*v*), which is added to the reactor.

### 2.1.4. Distillation and dehydration

Hydrous ethanol is usually produced through conventional distillation, whose configuration is shown in Fig. 3. Hydrous ethanol production, containing between 92.8 and 93.5 wt.% ethanol, is usually achieved in Brazilian industries in a series of distillation and rectification columns operating under atmospheric pressure. Wine is pre-heated and fed to the distillation columns (A, A1 and D), where second grade ethanol





**Fig. 5 – Block flow diagram of the Organosolv process with dilute acid hydrolysis in three separate steps.**

tion and consequent production of fermentation inhibitors such as furfural, leaving cellulose and lignin fractions unaltered (Aguilar et al., 2002). Since hydrolysis reaction uses  $\text{H}_2\text{SO}_4$  as catalyst, this configuration would also allow the production of lignin without traces of sulphates, so lignin recovered could be burnt in conventional boilers with no corrosion risks. This configuration seems to be the most promising strategy for lignocellulosic pre-treatment, since it allows the conversion of the lignin and hemicellulose into valuable co-products, which off-sets the costs of feedstock pre-treatment (Pan et al., 2005). In the biorefinery, in addition to sugarcane juice a fraction of the bagasse produced in the mills are used as raw material for ethanol production in the hydrolysis process. Initially the value of 70% was considered. Process integration and Pinch Technology were used to define the exact amount of bagasse surplus, from which steam and electrical energy are produced to provide the biorefinery energy requirements.

### 2.2.1. Pre-hydrolysis of hemicellulose

The removal and recovery of hemicellulose from lignocellulosic materials are important features of the bioethanol production process (Mosier et al., 2005), and dilute sulphuric acid pre-treatment is one of the most promising approaches (Huang et al., 2008). Sugarcane bagasse with 50 wt.% water is heated by injection of steam up to 122 °C. Sulphuric acid is added to the hot bagasse, and the mixture is fed to the pre-hydrolysis reactor, which operates under 200 kPa and approximately 122 °C. The reactor operates as a flash, in order to maintain a constant temperature. The products of the reactor are washed out and filtered for the recovery of pentoses produced.

Kinetic data for the pre-hydrolysis reactions (conversion to pentose, decomposition to furfural and acetic acid and formation of glucose) are available in Aguilar et al. (2002).

Calculation was made based on data provided by Aguilar et al. (2002) in order to obtain the conversion for the optimum conditions observed in laboratory: 122 °C, 2 wt.%  $\text{H}_2\text{SO}_4$  and residence time in reactor of 24.1 min. For these conditions a conversion of hemicellulose to pentose of 81.4% can be obtained, with decomposition to furfural and acetic acid equivalent to 1.8 and 0.4%, respectively. Glucose is a by-product obtained in the acid hydrolysis of sugarcane bagasse as well, and since process conditions do not usually allow cellulose hydrolysis, the glucose released proceeds from the hemicellulose (Aguilar et al., 2002). Calculation demonstrated

that 1.7% of the hemicellulosic fraction is converted into glucose.

The pentose liquor obtained in the filter contains about 9 wt.% pentose. Since there is no commercial technology available so far for the fermentation of pentoses into ethanol, this stream may be used as raw material for other processes, such as xylitol production (Cheng et al., 2009).

### 2.2.2. Delignification

Pan et al. (2005) and Pan et al. (2006) demonstrated that an Organosolv delignification (40–60 wt.% ethanol and sulphuric acid as catalyst) of poplar and softwood has decreased residual lignin content of the lignocellulosic material and increased sugars recovery on the following enzymatic hydrolysis step.

After the pre-hydrolysis reactions, the mixture of lignin and cellulose (cellulignin), which contains 50 wt.% water, undergoes a delignification step using an Organosolv solution containing around 60% ethanol (vol. basis). Cellulignin is mixed with the solution at a rate of 5 m<sup>3</sup>/t of pre-hydrolyzed bagasse (Rossell et al., 2005), following pressurization up to 19 bar, in order to maintain the mixture on condensed phase after it is heated up to 180 °C for about 5 min. Afterwards, the mixture is flashed and the liquid phase is filtered, producing a suspension of cellulose of high quality. Dissolved lignin in Organosolv solvent is obtained on the flash and filters and fed to a distillation column for Organosolv solvent recovery.

### 2.2.3. Cellulose hydrolysis and solvent recovery

Cellulose is mixed with water until solids concentration reaches 10 wt.%. Sulphuric acid is added to the diluted cellulose stream to increase acid concentration to 0.07 wt.%. The mixture is pressurized (about 36 bar), heated (205 °C) and fed to the hydrolysis reactor. Under these conditions, a conversion of chemical grade cellulose equal to 80.6% was observed in laboratory (Xiang et al., 2003), so this value was considered as basis in the simulation for the conversion of cellulose into hexoses; all the hexoses produced were simulated as glucose. A decomposition of glucose into hydroxymethylfurfural (HMF) of 2% was considered, as well as hydrolysis of the unreacted hemicellulose remaining in the mixture (conversion of 99%) and decomposition of pentose to furfural (80%) (Rodrigues, 2007). The product of hydrolysis reaction (extract) is cooled by heat exchange with the dissolved lignin stream fed to the distillation column, thus shutting down the hydrolysis reactions. After cooling, the extract is filtered for the removal of unreacted solids and the hexoses liquor is obtained.

The solvent recovery column operates under 5 bar to avoid lignin precipitation. The top product contains recovered Organosolv solvent (ethanol), while the bottom contains lignin dissolved on water. Lignin (50 wt.% water) is obtained after the bottom product is flashed and filtered. The aqueous solution obtained is mixed with the Organosolv solvent, making up the Organosolv solution used on the delignification step.

Hexoses liquor contains approximately 9 wt.% glucose, so it must be concentrated before fermentation. Concentration is carried out on a flash and on multiple effect evaporators, similar to the ones used for the concentration of sugarcane juice. A fraction of the liquor is concentrated up to 65 wt.% glucose and mixed to the flashed liquor, thus producing a liquor of 25 wt.% glucose. This liquor is mixed with the sterilized sugarcane juice, producing a mixture with the same concentration of sugar as the sterilized sugarcane juice, which is fed to the fermentation reactor.

**Table 5 – Parameters of the cogeneration system.**

Parameter	Values
Live steam pressure (bar)	90
Live steam temperature (°C)	520
Boiler thermal efficiency (%) <sup>a</sup>	85
High pressure steam turbines isentropic efficiency (%) <sup>b</sup>	72
Intermediate pressure steam turbines isentropic efficiency (%) <sup>c</sup>	81
Pump isentropic efficiency (%)	75
Electric engines efficiency (%)	98
1st extraction pressure (bar)	21
2nd extraction pressure (bar)	6
Turbine back-pressure (bar)	2.5
Deaerator operation pressure (bar)	2.5
Electric power demand of distillery (kW h/t of cane)	12
Mechanical power demand—cane preparation and juice extraction (kW h/t of cane)	16
<sup>a</sup> LHV base.	
<sup>b</sup> Outlet pressure 21 bar.	
<sup>c</sup> Outlet pressure 2.5 bar.	

### 2.3. Simulation of the cogeneration system

A steam-based cycle cogeneration system was simulated in the Engineering Equation Solver Software from F-Chart, since the process simulator used (UniSim Design) does not have the necessary tools to perform simulation of the cogeneration system. The system comprises basically boiler, steam turbine, deaerator and pumps. A back-pressure steam turbine was simulated with two extractions of steam (21 and 6 bar) to attend the process requirements. De-superheaters are used to reduce the temperature of the steam consumed by the process to saturation condition. Electric engines are being considered as prime movers for the juice extraction system. The parameters adopted for the simulation of the cogeneration system is based on data obtained from the industry and are presented in Table 5, as well as the electric consumption of the process. Thermal and electrical energy requirements are supplied and the surplus electricity generated would be available for sale to the grid.

This work considers that 50% of the sugarcane trash available at the field could be recovered and transported to the mill in order to be used as fuel in the cogeneration system, supplying steam to the bioethanol production. Only 50% is used because a fraction of the trash must remain in the fields in order to provide some weed control, coupled to the use of herbicide if needed (Hassuani et al., 2005). Even though efficient equipments for the recovery of sugarcane trash from the fields are yet to be developed, this figure is considered feasible in the years to come, since growing interest on sugarcane trash recovery for use as fuel in the production of renewable energy has been observed and thus investigation of more efficient equipments has been encouraged.

Some bagasse should be diverted for energy production as well, since 50% of trash recovery is not enough to produce the steam required by the distillery. Lignin recovered in the hydrolysis plant is also used as fuel complementing the energy available for the boilers. Table 6 presents data of biomass availability and fuels' Low Heating Values (LHV).

**Table 6 – Parameters considered for the fuels.**

Parameters	Bagasse	Trash	Lignin
Availability <sup>a</sup>	120	140	220 <sup>b</sup>
Moisture	50%	15%	50%
LHV (MJ/kg) <sup>c</sup>	7.52 <sup>d</sup>	12.96 <sup>d</sup>	12.36 <sup>b</sup>
<sup>a</sup> Dry basis, as kg/t cane for bagasse and trash, and as kg/t of hydrolyzed bagasse for lignin.			
<sup>b</sup> Calculated based on data presented by Silva (1995).			
<sup>c</sup> As burned, i.e., with moisture.			
<sup>d</sup> Source: Larson et al. (2001).			

#### 2.3.1. Process integration procedure

The amount of bagasse available for the hydrolysis process was calculated based on the steam consumption of the biorefinery. Process integration procedure was used to minimize hot utility requirements, increasing the bagasse surplus which can be delivered to the hydrolysis plant.

The Pinch Point Method described by Linnhoff et al. (1982) was used to analyze the process streams that are available for thermal integration. The method developed by the works of Hohmann (1971), Umeda et al. (1978, 1979) and Linnhoff and Flower (1978a,b) uses enthalpy-temperature diagrams to represent the streams of the process and to find the thermal integration target for them, considering a minimum approach difference of temperature ( $\Delta t_{\min}$ ) for the heat exchange.

The thermal integration target obtained indicates the minimum requirements of external hot and cold utilities for the process. This analysis is useful to represent all the streams available for heat exchange in one diagram, being possible to evaluate the effect of modifications in the process parameters before the heat exchange network design.

For the integration of the biorefinery the procedure considered initially that 70% of the bagasse produced in the extraction system is available for the hydrolysis process. Afterwards, an iterative procedure is used to find the maximum amount of bagasse that can really be delivered to the hydrolysis process, considering the steam demand of the whole plant. Data obtained in the simulation of an autonomous bioethanol distillery, presented in the previous sections of this work, were used in the process integration procedure.

As it was previously said, two cases of process integration were compared. The first one considers a conventional distillation system with atmospheric pressure columns, as shown in Fig. 3, and the second one a double-effect distillation system, in which the integration between rectification and distillation columns is possible (Fig. 4). This option has an important impact on the distillery steam balance, promoting changes in the integration possibilities as can be seen in the analyses. Data of hot and cold streams available for thermal integration are presented in Tables 7 and 8, respectively.

Some assumptions were made in order to simplify the analysis, as follows:

- Some streams with less than 1000 kW of heat flow were not taken into consideration because of their low thermal integration potential.
- A single-effect absorption system was used to supply the cold utility requirements of those streams with final temperature lower than 28 °C. A COP of 0.65 was assumed for this system, which was integrated in the background process as a cold stream operating with constant temperature of 90 °C. These conservative assumptions can assure the

**Table 7 – Initial ( $T_{\text{initial}}$ ) and final temperature ( $T_{\text{final}}$ ) and heat flow of the hot streams used for the process integration.**

Stream description	Conventional distillation			Double-effect distillation		
	$T_{\text{initial}}$ (°C)	$T_{\text{final}}$ (°C)	Heat flow (kW)	$T_{\text{initial}}$ (°C)	$T_{\text{final}}$ (°C)	Heat flow (kW)
Sterilized juice	130	28	–27,650	130	28	–27,650
Fermented wine	28	24	–6,491	28	24	–6,491
Vinasse	112	35	–32,338	65	35	–13,006
Anhydrous ethanol cooling	78	35	–10,741	78	35	–10,707
Column D condenser	83	35	–1,853	41	26	–4,869
Column B condenser	82	82	–24,565	–	–	–
Extractive column condenser	78	78	–10,948	–	–	–
Hydrolyzed liquor cooling	93	28	–3,348	93	28	–3,348
Organosolv solvent cooling	133	99	–70,120	133	99	–70,120
Organosolv column condenser	134	133	–6,765	134	133	–6,765
1st effect condensate	115	35	–5,350	115	35	–5,350
2nd effect condensate	108	35	–5,166	108	35	–5,166
3rd effect condensate	100	35	–4,810	100	35	–4,810
4th effect condensate	83	35	–3,773	83	35	–3,773
5th effect vapor	60	35	–54,444	60	35	–54,444
Pre-hydrolysis vapor	124	35	–22,372	124	35	–22,372
Lignin recovery vapor	100	35	–9,131	100	35	–9,131
Hexoses liquor vapor	100	35	–7,899	100	35	–7,899

**Table 8 – Initial ( $T_{\text{initial}}$ ) and final temperature ( $T_{\text{final}}$ ) and heat flow of the cold streams used for the process integration.**

Stream description	Conventional distillation			Double-effect distillation		
	$T_{\text{initial}}$ (°C)	$T_{\text{final}}$ (°C)	Heat flow (kW)	$T_{\text{initial}}$ (°C)	$T_{\text{final}}$ (°C)	Heat flow (kW)
Raw juice	30	70	21,061	30	70	21,061
Limed juice	74	105	20,553	74	105	20,553
Juice for sterilization	96	130	9,292	96	130	9,292
Centrifuged wine	28	82	27,060	28	48	10,342
Column A reboiler	112	112	44,774	–	–	–
Column B reboiler	108	108	4,502	108	108	8,905
Extractive column reboiler	111	135	9,829	110	138	13,605
Recovery column reboiler	150	150	2,193	150	150	2,198
Delignification	97	180	29,752	99	180	29,126
Cellulose-hydrolysis	75	205	23,699	88	205	21,257
Organosolv column reboiler	152	152	38,760	152	152	38,546
Pentose wash water	25	65	8,948	25	65	8,948
Cellulose wash water	25	65	5,961	25	65	5,961
Hydrolysis water	25	65	6,594	25	65	6,594
Imbibition water	25	50	7,927	25	50	7,927
Filter cake water	25	80	2,147	25	80	2,147
Absorption system	90	90	9,986	90	90	17,477

integration of the absorption system using process available heat as heating source.

- The integration of the evaporation station with the background process was evaluated in a second step. This procedure previously applied by Ensinas (2008) in sugarcane mills allows the simplification of the analysis and evaluation of the possibility of vapor bleeding use as heating source for other parts of the process.

### 3. Results and analyses

After implementing the thermal integration procedure described above it was possible to determine the hot and cold

utilities requirements for the conventional and double-effect distillation cases.

The grand composite curve (GCC) of the background process can be plotted out (Figs. 6 and 7) and the targets determined following the procedure presented by Linnhoff et al. (1982). The software presented by Elsevier (2007) was used for the calculation of the targets and drawing the GCC curves. Table 9 shows the results for the Pinch analysis.

As can be seen in Figs. 6 and 7, the integration of the evaporation system with the background process is not interesting from the energy recovery point of view, once the Pinch Point is located above the operation temperature of the first effect of evaporation in both cases. In such case the use of vapor bleeding as heating source for other parts of the process is

**Table 9 – Pinch analysis results.**

	$T_{\text{pinch}}$ (°C)	Hot utilities target (kW)	Cold utilities target (kW)
Single-pressure distillation case	116.9	114,615	142,144
Double-effect distillation case	129.4	104,942	124,349

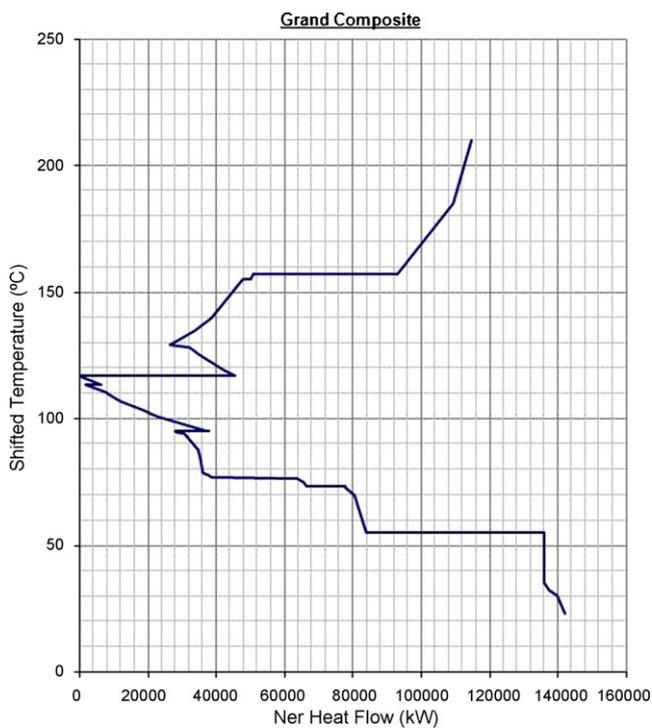


Fig. 6 – Grand composite curve—single-pressure distillation case.

not recommended, since it would increase the hot utilities demand.

The hot utility demands of both cases are shown in detail in Tables 10 and 11, where the amount of turbine extraction steam consumed in each part of the process is reported.

The steam demand of the process after thermal integration and energy balance in the cogeneration system showed that 76% of the total bagasse would be available for the production of bioethanol for the case with conventional distillation.

The use of a double-effect system increases the integration possibilities, reducing the hot utilities targets and consequently raising the availability of bagasse up to 90%. Since more bagasse is available for hydrolysis, the amount of lignin burnt in the boiler increases, which makes up for the fraction of bagasse that is not used as a fuel. Energy input in the boilers for both conventional and double-effect distillation configurations for each fuel is provided in Table 12.

The surplus electricity generated is reduced, due to the consumption of electrical energy of the steam compressors in the double-effect distillation columns, but the increased amount of bagasse used as raw material for ethanol production is clearly an advantage in this case. Considering

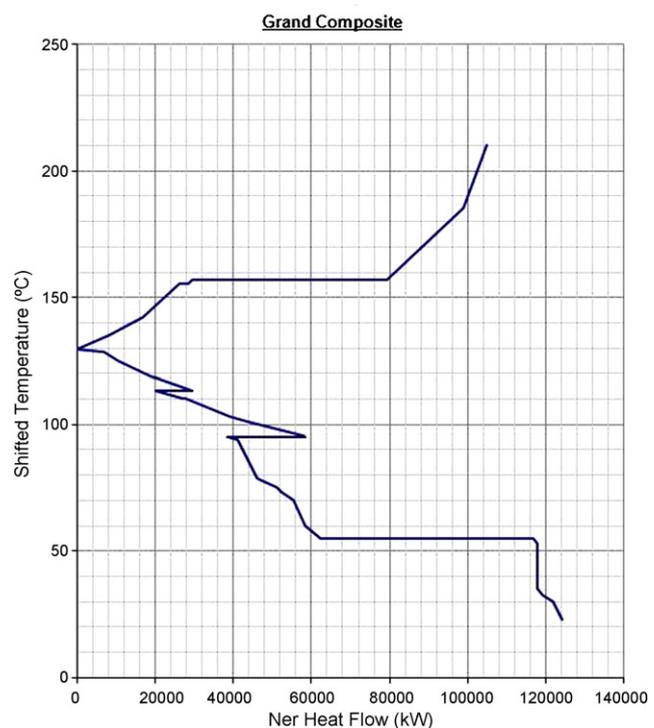


Fig. 7 – Grand composite curve—double-effect distillation case.

an input of 493 t cane/h in the biorefinery and the use of 90% of sugarcane bagasse generated on the mills as raw material for the hydrolysis process, approximately 17 t/h of hexoses are produced from the cellulosic fraction of bagasse. The hexoses are mixed with sugarcane juice and fermented, producing ethanol. Hydrolysis of this fraction of bagasse produces approximately 22 t lignin/h, which are burnt in boilers in order to enhance steam and electrical energy production.

The pentose obtained from the hemicellulose fraction is separated in the pre-hydrolysis step, and may be used in different chemical feedstock routes for the production of renewable materials, such as furfural, xylitol, butanol and other substances. Amount of pentose and other products of the biorefinery, for an input of 493 t/h of sugarcane and hydrolysis of 76% and 90% of bagasse in conventional and double-effect distillation, respectively, are presented in Table 13.

Thus, fermentation of the hexoses obtained solely from the cellulose fraction of 90% of the sugarcane bagasse generated on the mills can increase the production of ethanol in the biorefinery by 26.3%, using the same cultivated area. To

Table 10 – Final saturated steam consumption of the conventional distillation case.

	Steam 2.5 bar (kg/h)	Steam 6 bar (kg/h)	Steam 21 bar (kg/h)
Multi-effect evaporator (conventional plant)	50,687	–	–
Juice sterilization	–	4,764	–
Column A reboiler	22,348	–	–
Column B reboiler	–	–	–
Extractive column reboiler	–	17,611	–
Recovery column reboiler	–	3,895	–
Delignification	–	24,842	23,032
Cellulose heating	–	12,741	21,340
Organosolv solvent recovery column reboiler	–	72,573	–
Multi-effect evaporator (hydrolysis plant)	20,499	–	–
Pre-hydrolysis	15,313	–	–

**Table 11 – Final saturated steam consumption of the double-effect distillation case.**

	Steam 2.5 bar (kg/h)	Steam 6 bar (kg/h)	Steam 21 bar (kg/h)
Multi-effect evaporator (conventional plant)	50,687	–	–
Juice sterilization	–	2,830	–
Column A reboiler	–	–	–
Column B reboiler	–	–	–
Extractive column reboiler	–	11,634	–
Recovery column reboiler	–	4,011	–
Delignification	–	19,529	27,306
Cellulose heating	–	9,977	25,200
Reboiler Organosolv solvent recovery column	–	86,041	–
Multi-effect evaporator (hydrolysis plant)	17,861	–	–
Pre-hydrolysis	17,475	–	–

**Table 12 – Fuel energy input in the boiler for the processes with conventional and double-effect distillation systems.**

Energy input (kW)	Bagasse	Trash	Lignin	Total
Conventional distillation	42,830	146,160	69,407	258,397
Double-effect distillation	12,370	146,160	80,412	238,942

**Table 13 – Final products of the biorefinery.**

Product	Conventional distillation	Double-effect distillation
Anhydrous bioethanol from sugarcane juice (L/t cane)	83.7	83.7
Anhydrous bioethanol from bagasse (L/t cane)	18.8	22.0
Total anhydrous bioethanol produced (L/t cane)	102.5	105.7
Pentose liquor (t/h, in a 9% mass basis solution)	143.2	169.6
Non reacted solids (kg/h, 50% water)	6.5	7.7
Surplus electricity produced (kW h/t cane)	33.0	13.5

achieve these figures, sugarcane trash and lignin are used as fuels in the boilers, in order to provide the amount of steam and electrical energy required by the biorefinery and increase the availability of surplus bagasse.

#### 4. Discussion and conclusions

The main objective of this paper was to perform a simulation and thermal integration analysis of the traditional distillery, in which bioethanol is produced from sugarcane juice, with an Organosolv process with dilute acid hydrolysis, by which ethanol is produced from sugarcane bagasse, in order to evaluate the availability of bagasse and the requirements of external fuels, such as sugarcane trash.

Two configurations for the distillation columns were considered, namely, conventional (single-pressure) and double-effect distillation columns. It was shown that 76% of the bagasse generated in the mills is available for hydrolysis when a conventional distillation system is used, while 90% is available in the double-effect distillation. In the first case, an amount of 102.5 L of anhydrous ethanol per ton of sugarcane and 33.0 kW h/t cane are obtained, while in the second case figures of 105.7 L/t and 13.5 kW h/t are reached for these parameters, respectively. So, in the first case there is an increment of 22.5% in the ethanol production (compared to conventional bioethanol production) and 33.0 kW h/cane of electric energy disposable for sale, while in the second case there is an increase of 26.3% in the ethanol production, but a decrease of more than a half in the electric energy disposable for sale.

The results have shown the importance of the process integration for the feasibility of the biorefinery comprised by conventional sugarcane mills and hydrolysis plants. The multi-pressure distillation columns may be pointed out as the

most important measure for the process integration, allowing at the same time the reduction of hot utilities requirements and bagasse savings, notwithstanding the reduce of the electric energy disposable for sale.

It must also be emphasized that the use of sugarcane trash and lignin as auxiliary fuels are fundamental to fulfil the energy requirements of the biorefinery with hydrolysis plants.

#### Acknowledgments

The authors acknowledge FAPESP and FINEP for financial support and Usina da Pedra for providing industrial data.

#### References

- Aguilar, R., Ramírez, J.A., Garrote, G. and Vázquez, M., 2002, Kinetic study of the acid hydrolysis of sugar cane bagasse. *Journal of Food Engineering*, 55: 309–318.
- Balat, M., Balat, H. and Öz, C., 2008, Progress in bioethanol processing. *Progress in Energy and Combustion Science*, 34: 551–573.
- Buddadee, B., Wirojanagud, W., Watts, D.J. and Pitakaso, R., 2008, The development of multi-objective optimization model for excess bagasse utilization: a case study for Thailand. *Environmental Impact Assessment Review*, 28: 380–391.
- Cardona, C.A. and Sánchez, Ó.J., 2007, Fuel ethanol production: process design trends and integration opportunities. *Bioresource Technology*, 98: 2415–2457.
- Chen, J.C.P. and Chou, C.C., (1993). *Cane Sugar Handbook: A Manual for Cane Sugar Manufacturers and Their Chemists*. (John Wiley and Sons), p. 1090
- Cheng, K.-K., Zhang, J.-A., Ling, H.-Z., Ping, W.-X., Huang, W., Ge, J.-P. and Xu, J.-M., 2009, Optimization of pH and acetic acid concentration for bioconversion of hemicellulose from corncobs to xylitol by *Candida tropicalis*. *Biochemical Engineering Journal*, 43: 203–207.

- Dias, M.O.S., Maciel Filho, R. and Rossell, C.E.V., 2007, Efficient cooling of fermentation vats in ethanol production—Part I. *Sugar Journal*, 70: 11–17.
- Elsevier Ltd., (2007). *Pinch Analysis Spreadsheet*. Available online from <<http://books.elsevier.com/companions/0750682604>>, retrieved on 20 November 2007
- Ensinas, A.V., 2008, Thermal integration and thermoeconomic optimization applied to sugar and ethanol industrial process, PhD Thesis (School of Mechanical Engineering, State University of Campinas (in Portuguese)).
- Ensinas, A.V., Nebra, S.A., Lozano, M.A. and Serra, L.M., 2007, Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. *Energy Conversion and Management*, 48: 2978–2987.
- Franceschin, G., Zamboni, A., Bezzo, F. and Bertucco, A., 2008, Ethanol from corn: a technical and economical assessment based on different scenarios. *Chemical Engineering Research and Design*, 86: 488–498.
- Goldemberg, J., 2007, Ethanol for a sustainable energy future. *Science*, 315: 808–810.
- Hassuani, S.J., Leal, M.R.L.V., & Macedo, I.C. (eds) 2005, *Biomass Power Generation—Sugarcane Bagasse and Trash*.
- Hohmann, E.C., 1971, Optimum networks for heat exchange, PhD Thesis (University of Southern California).
- Huang, H.-J., Ramaswamy, S., Tschirner, U.W. and Ramarao, B.V., 2008, A review of separation technologies in current and future biorefineries. *Separation and Purification Technology*, 62: 1–21.
- Hugot, E., (1972). *Handbook of Cane Sugar Engineering*. (Elsevier, Amsterdam).
- Kuo, C.-H. and Lee, C.-K., 2009, Enhanced enzymatic hydrolysis of sugarcane bagasse by N-methylmorpholine-N-oxide pretreatment. *Bioresource Technology*, 100: 866–871.
- Larson, E.D., Willians, R.H. and Leal, M.R.L.V., 2001, A review of biomass integrated gasifier/gas turbine combined cycle technology and its application in sugarcane industries, with an analysis for Cuba. *Energy for Sustainable Development*, 1: 54–76.
- Linnhoff, B. and Flower, J.R., 1978, Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. *AIChE Journal*, 24: 633–642.
- Linnhoff, B. and Flower, J.R., 1978, Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality. *AIChE Journal*, 24: 642–654.
- Linnhoff, B., Townsend, D.W., Boland, D. and Hewitt, G.F., (1982). *User Guide on Process Integration for the Efficient Use of Energy*. (The Institution of Chemical Engineers, Warks, England), p. 247
- Macedo, I.C., Seabra, J.E.A. and Silva, J.E.A.R., 2008, Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, 32(7): 582–595.
- Mantelatto, P.E., 2005, Study of the Crystallization process of impure sucrose solutions from sugarcane by cooling, MSc Dissertation (School of Chemical Engineering, Federal University of São Carlos, Portuguese).
- Meirelles, A., Weiss, S. and Herfurth, H., 1992, Ethanol dehydration by extractive distillation. *Journal of Chemical Technology and Biotechnology*, 53: 181–188.
- Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M. and Ladisch, M., 2005, Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresource Technology*, 96: 673–686.
- Pan, X., Arato, C., Gilkes, N., Gregg, D., Mabee, W., Pye, K., Xiao, Z., Zhang, X. and Saddler, J., 2005, Biorefining of softwoods using ethanol organosolv pulping: preliminary evaluation of process streams for manufacture of fuel-grade ethanol and co-products. *Biotechnology and Bioengineering*, 90: 473–481.
- Pan, X., Gilkes, N., Kagla, J., Pye, K., Saka, S., Gregg, D., Ehara, K., Xie, D., Lam, D. and Saddler, J., 2006, Bioconversion of hybrid poplar to ethanol and co-products using an organosolv fractionation process: optimization of process yields. *Biotechnology and Bioengineering*, 94: 851–861.
- Rodrigues, F.A., 2007, Evaluation sugarcane bagasse acid hydrolysis technology, MSc Dissertation (School of Chemical Engineering, State University of Campinas, Portuguese).
- Rossell, C.E.V., Lahr Filho, D., Hilst, A.G.P. and Leal, M.R.L.V., 2005, Saccharification of sugarcane bagasse for ethanol production using the Organosolv process. *International Sugar Journal*, 107: 192–195.
- Saxena, R.C., Adhikari, D.K. and Goyal, H.B., 2009, Biomass-based energy fuel through biochemical routes: a review. *Renewable and Sustainable Energy Reviews*, 13: 167–178.
- Silva, F.T., 1995, Production of chemical feedstock from sugarcane bagasse, Campinas: PhD Thesis (Institute of Chemistry, State University of Campinas (in Portuguese)).
- Umeda, T., Itoh, J. and Shiroko, K., 1978, Heat exchange system synthesis. *Chem. Eng. Progr.*, 74: 70–76.
- Umeda, T., Harada, T. and Shiroko, K., 1979, A thermodynamic approach to the synthesis of heat integration systems in chemical processes. *Comput. Chem. Eng.*, 3: 273–282.
- Wooley, R.J. and Putsche, V., 1996, Development of an ASPEN PLUS Physical Property Database for Biofuels Components, Report No. NREL/MP-425-20685 (National Renewable Energy Laboratory, Golden, Colorado). Available online at: <<http://www.p2pays.org/ref/22/21210.pdf>>, retrieved on 12 March 2007.
- Xiang, Q., Kim, J.S. and Lee, Y.Y., 2003, A comprehensive kinetic model for dilute-acid hydrolysis of cellulose. *Applied Biochemistry and Biotechnology*, 105–108: 337–352.
- Zaldivar, J., Nielsen, J. and Olsson, L., 2001, Fuel ethanol production from lignocellulose: a challenge for metabolic engineering and process integration. *Applied Microbiology and Biotechnology*, 56: 17–34.