REDUCING STEAM DEMAND IN BIOETHANOL PRODUCTION THROUGH PROCESS INTEGRATION

Marina O.S. Dias, diasmos@feq.unicamp.br
FEQ, State University of Campinas, Cid. Universitária Zeferino Vaz, Campinas-SP, Brazil, P.O. Box 6066.
Adriano V. Ensinas, adrianov@fem.unicamp.br
FEM, State University of Campinas, Cid. Universitária Zeferino Vaz, Campinas-SP, Brazil, P.O. Box 6122
Silvia A. Nebra, silvia.nebra@pesquisador.cnpq.br
NIPE, State University of Campinas, Cid. Universitária Zeferino Vaz, Campinas-SP, Brazil, P.O. Box 6192.
Carlos E.V. Rossell, crossell@bioetanol.org.br
NIPE, State University of Campinas, Cid. Universitária Zeferino Vaz, Campinas-SP, Brazil, P.O. Box 6192.
Rubens Maciel Filho, maciel@feq.unicamp.br
FEQ, State University of Campinas, Cid. Universitária Zeferino Vaz, Campinas-SP, Brazil, P.O. Box 6066.

Abstract. *The sugarcane industry is one of the most important activities of the Brazilian economy, producing simultaneously sugar, ethanol and electricity. These industries are characterized historically by their low energy efficiency, consuming a large fraction of the bagasse produced as fuel for the cogeneration system to attend the process energy requirements. A new scenario, with the possibility of selling surplus electricity to the grid or even using surplus bagasse as raw material for other processes, has motivated investments on more efficient cogeneration systems and process thermal integration. Bioethanol production is an interesting case of process integration, with many possibilities of plant design. This work intends to show a procedure of process design applied to bioethanol production, comparing two different situations for the purification step: conventional distillation columns and double effect distillation system. Integrations of the plant were made according to concepts of the Pinch Analysis, permitting the identification of the best options of thermal integration of the plant, in order to reduce hot and cold utilities demand. Simulation of the processes were carried out including the cogeneration system, evaluating the steam demand and the surplus of bagasse and/or electricity generated. It is shown that a reduction on steam consumption around 30 % is possible when using thermal integration, for conventional and double effect distillation. The use of double effect distillation and a cogeneration system with extraction-condensation turbines, where all bagasse in consumed, provides the largest production of electricity surplus, equivalent to 77.1 kWh/ton cane, while the maximum bagasse surplus (52.8 %) is obtained with the cogeneration system with back-pressure steam turbines, but in this case the use of an extra fuel source such as sugarcane trash is necessary.*

Keywords*: bioethanol, distillation, process integration.*

1. INTRODUCTION

The rise in oil prices and increasing global concern about climate change have motivated the use of bioethanol as a gasoline additive or substitute for reduction of greenhouse gases emissions. Sugarcane is the most efficient raw material for bioethanol production nowadays, and the great potential of increase on bioethanol international demand and on production of sugarcane in Brazil motivate the investigation and development of more efficient process configurations.

In order to be used as a gasoline substitute or additive bioethanol must be concentrated to 92.6 – 93.8 % and 99.3 % ethanol (mass basis), respectively. When ethanol is produced from fermentation of sugars, a wine containing from 5 to 12 % ethanol (mass basis) is produced, depending on process conditions, raw materials, fermentation efficiency, etc, so a purification step must take place. Usually hydrous ethanol, containing from 92.6 to 93.8 % ethanol (mass), is produced using conventional distillation columns, while anhydrous ethanol, with at least 99.3 % ethanol, is produced using alternative separation methods, since water and ethanol form an azeotrope with concentration equal to 95.6 % ethanol (mass basis) at 1 atm.

Separation is the step where major costs are generated in process industry (Cardona and Sánchez, 2007). In the case of bioethanol production, distillation process may be optimized to reduce steam consumption on column reboilers, therefore reducing production costs. A distillation process commonly employed in Brazilian distilleries is based on the same configuration used for decades: in this configuration, wine is fed to distillation columns (A, A1 and D), where phlegms containing from 40 to 50 % ethanol (mass basis) are produced; phlegms are fed to rectification columns (B and B1), where hydrous ethanol is produced. Reduction of steam consumption on distillation column reboilers may be achieved by the use of a double effect distillation system, since different temperature levels are obtained in column condensers and reboilers, allowing the thermal integration of these equipments.

In this work simulations of bioethanol production processes considering both conventional and double effect distillation systems were carried out using software UniSim Design from Honeywell. A process design procedure was applied to bioethanol production and thermal integration was done using Pinch Analysis, in order to minimize hot and cold utilities requirements. Steam demand was determined for each case, as well as production of surplus bagasse and/or electricity generated.

2. SIMULATION OF BIOETHANOL PRODUCTION PROCESS

Production of anhydrous bioethanol from sugarcane is comprised by the following main steps: reception and cleaning of sugarcane, extraction of sugars, juice treatment, concentration and sterilization, fermentation, distillation, dehydration and production of steam and electrical energy.

Simulations were carried out using software UniSim Design from Honeywell. Hypothetic components were created for: bagasse components (cellulose, hemicellulose and lignin); sand, with properties considered equal to those of SiO_2; impurities, represented by potassium salts and aconitic acid, since those constitute the majorities of the impurities present in sugarcane (Mantelatto, 2005); input materials such as phosphoric acid and lime; calcium-phosphate, the main salt formed during liming operation, of great importance in removal of impurities during juice settlement; minerals, represented by K_2O; and yeast, with composition $CH_{1,8}O_{0,9}N_{0,145}$. Properties for bagasse components were obtained in Wooley and Putsche (1996); molecular weight of yeast is calculated directly, and density considered equal to that of water; all other components have their properties available in Perry and Green (1999). All reducing sugars are considered dextrose; all other components (water, sucrose, ethanol, carbon dioxide, glycerol, succinic acid, acetic acid, isoamyl alcohol, sulphuric acid, monoethyleneglycol) are part of Hysys database.

NRTL was chosen for calculating activity coefficient of the liquid phase, and the equation of state SRK for the vapor model. It was verified that the NRTL model was the one that calculated elevation of the boiling point of sugar solutions with larger accuracy, when compared to UNIQUAC or equation of state Peng-Robinson. For the extractive distillation process, the model UNIQUAC and equation of state SRK were used.

Simulation was carried out considering the production of 1000 m³/day of anhydrous bioethanol in an autonomous distillery. Around 12,000 tons of sugarcane per day are crushed, what gives wise to a production of around 85 liters of anhydrous ethanol per ton of sugarcane. Simulation of bioethanol production process was made based on data obtained at the literature and at industrial sites. In the following sections a detailed description of the simulation is made.

2.1. Sugarcane reception and cleaning, extraction of sugars and juice treatment

Upon reception in the factory sugarcane must be cleaned to remove part of the dirt carried along from the field. A dry-cleaning system is used to clean sugarcane, removing 70 % of dirt before it is fed to the mills.

Extraction of sugars is done using mills, where sugarcane juice and bagasse are obtained. Imbibitions water (28 % of sugarcane) is used to improve sugars recovery. Sugarcane juice contains water, sucrose, and reducing sugars, besides impurities such as minerals, salts, organic acids, dirt and fiber particles, which must be removed prior to fermentation. Firstly a physical treatment is used, in which screens and hydrocyclones are used to remove sand and fiber.

Juice without fibers and sand then receives a chemical treatment to remove other impurities. Phosphoric acid is added to the juice prior to a first heating operation, in which juice temperature increases from 30 to 70 ºC, followed by addition of lime and a second heating, up to 105 ºC. Hot juice is flashed to remove dissolved air bubbles, and after addition of flocculant impurities are removed through settlement. In the settler mud and clarified juice are obtained. A filter is used in order to recover some of the sugars carried along with the mud, and a filtrate is recycled to the process prior to the second heating operation. Operations cleaning of sugarcane, extraction of sugars, screens and hydrocyclones, addition of phosphoric acid, 1st heating and limming are represented in Fig.1.

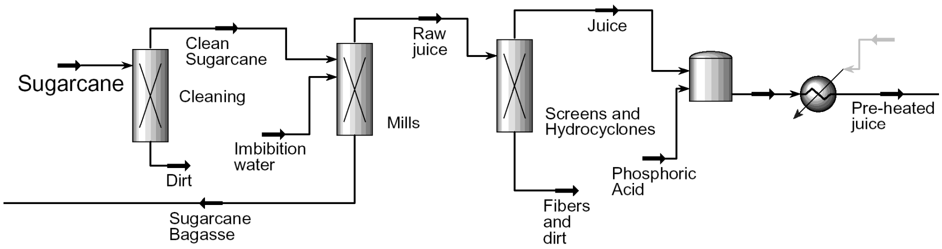

Figure 1. Cleaning of sugarcane, mills, screens and hydrocyclones, addition of phosphoric acid and lime.

The second juice heating, settlement and mud filtration operations are represented in Fig. 2.

2.2. Juice concentration and sterilization

Clarified juice contains around 15 % solids, so it must be concentrated before fermentation in order for the product to contain an adequate ethanol content that allows reduction of energy consumption during purification steps. Concentration is done on a 5-stage multiple effect evaporators (MEE) up to 65 % sucrose (mass basis). The process simulator used does not have the operation that represents the MEE on its database; thus, a system made up of separator, valve and heat exchanger was used to represent this operation, as shown in Fig.3.

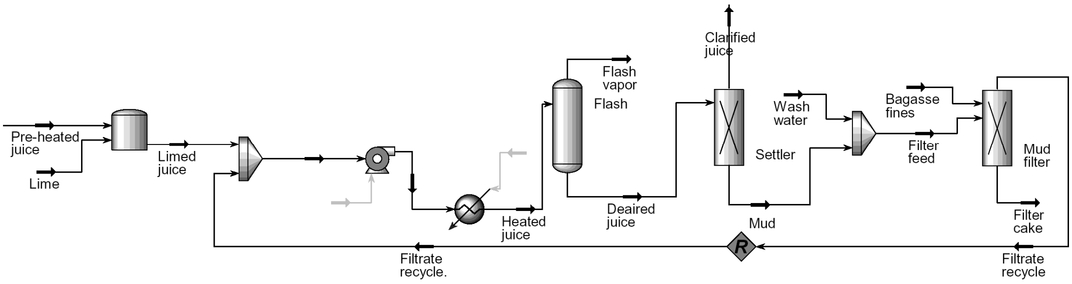

Figure 2: Limed juice heating, flash, decanter and mud filter.

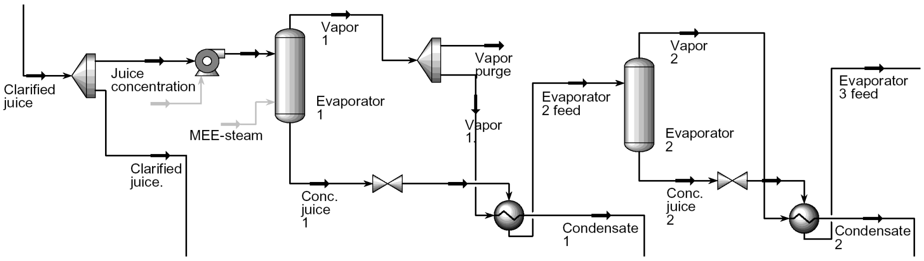

Figure 3. First stages of multiple effect evaporators (MEE) for juice concentration.

Only part of the juice is concentrated, and final juice contains around 22 % sucrose (mass basis). In order to avoid contamination in fermentation the juice is sterilized by heating up to 130 ºC for about 30 minutes, following a rapid cooling to fermentation temperature (28 ºC).

2.3. Fermentation

Simulations were based on the Melle-Boinot (feed-batch with cell recycle) process. Sterilized juice is added to the fermentors along with yeast stream. In the fermentor sucrose is inverted to glucose and fructose, which are consumed by the yeast producing ethanol, CO_2 and other products, such as higher alcohols, organic acids, glycerol and yeast. Fermentation gases are collected and washed in an absorber for ethanol recovery, while wine containing yeast cells are centrifuged to recover yeasts. The yeast stream receives an acid treatment prior to returning to fermentor, and wine is mixed to alcoholic solutions from the absorber before being fed to the distillation columns.

Fermentation was carried at 28 ºC, in order to obtain wine with higher ethanol content (around 10 % mass). An alternative cooling method (absorption with lithium-bromide) was considered to supply cool water to maintain this low fermentation temperature, since glucose conversion to ethanol releases energy into the system. Fermentation system is represented in Fig 4.

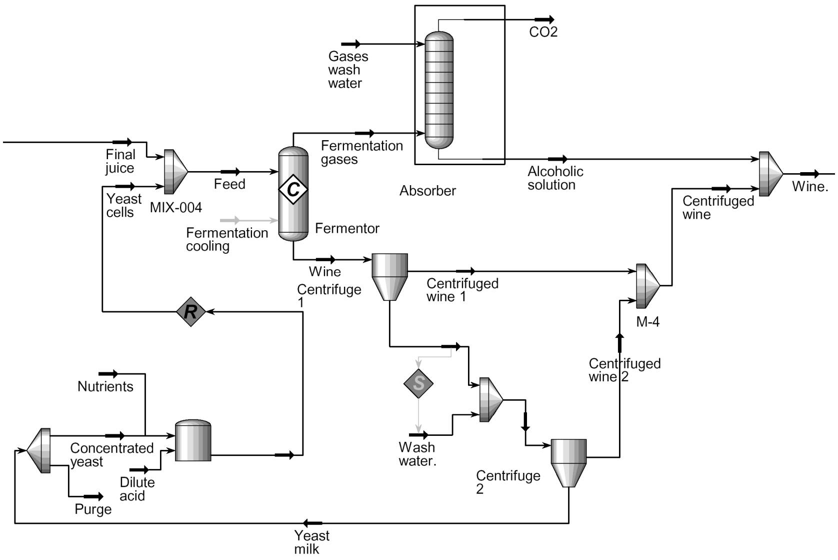

Figure 4. Fermentation of juice, yeast recovery and treatment and absorption column.

2.4. Distillation and Dehydration

The conventional distillation process consists of a distillation column comprised by columns A, A1 and D, and a rectification column comprised by columns B and B1. Since columns B and B1 have the same diameter and type of plates, they were considered as only one column in the simulation.

Wine obtained in fermentation is pre-heated and fed to column A1, which is located above column A and below column D, as shown in

Figure **5**. Pressure on distillation columns range from 133.8 to 152.5 kPa, and on rectification column from 116 to 135.7 kPa.

In the distillation columns phlegm streams containing from 40 to 50 % (w) ethanol are obtained, as well as vinasse and 2nd grade ethanol. In the rectification column hydrous ethanol and residues like phlegmasse and fusel oil are obtained. Hydrous ethanol in vapor phase is produced on top of column B.

Since water and ethanol form an azeotrope with concentration around 95.6 % ethanol (mass basis) at 1 atm, conventional distillation can not achieve the necessary separation that allows the use of ethanol as a gasoline additive. Thus, an extractive separation process with monoethyleneglycol (MEG) was used to produce anhydrous bioethanol. In this process two columns are used: an extractive column, where both hydrous ethanol and solvent get in contact, producing anhydrous bioethanol on the top and a solvent solution on the bottom, and a recovery column, in which extractive solvent is recovered. Extractive column operates at atmospheric pressure (101.325 kPa), while the recovery column operates at 20 kPa, in order to avoid high temperature and solvent decomposition. The solvent is cooled before fed to the extractive distillation. Since the bottom temperatures of both extractive and recovery columns are relatively high (136 and 150 °C, respectively), both reboilers need to operate with high pressure (6 bar) steam. Configuration of conventional distillation and extractive distillation with MEG is shown in Fig 5.

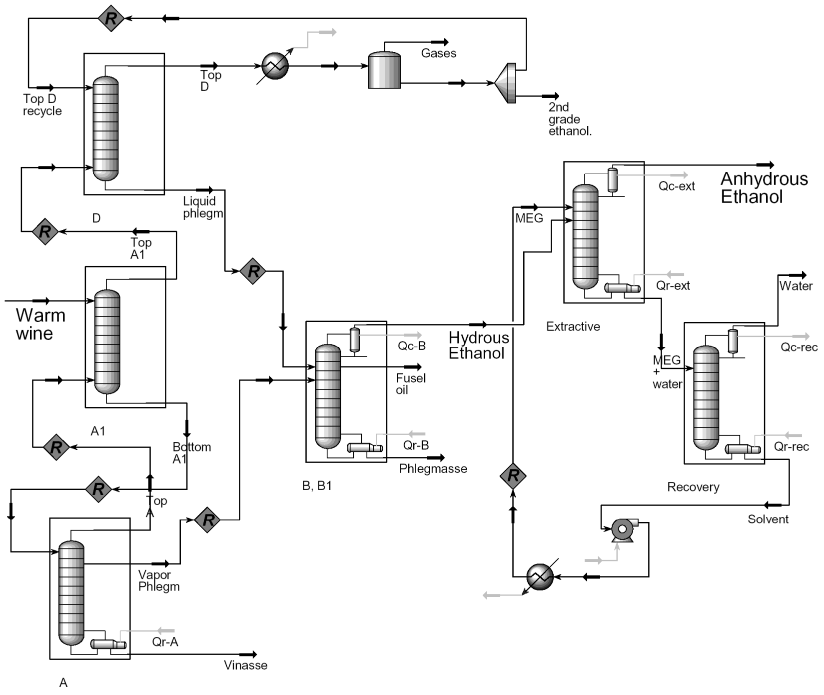

Figure 5. Conventional distillation process configuration and extractive distillation process with monoethyleneglycol (MEG) for anhydrous bioethanol production.

In the double effect distillation system, the distillation columns operate at vacuum pressures (19 - 25 kPa), while the rectification column operates at atmospheric pressures (101.325 - 135.7 kPa), what makes temperature on bottom of column A reach about 65 ºC and temperature on top of column B reach 78 ºC. Consequently, integration of column B condenser and column A reboiler is possible, and the rectification column condenser may work as the distillation column reboiler, what provides a reduction in steam consumption on distillation. Since column A reboiler duty is greater than that of column B condenser, this integration can not supply all the heat necessary to the adequate operation of the distillation columns.

Hydrous ethanol in vapor phase obtained on top of column B is dehydrated in an extractive distillation process with MEG, similarly to the dehydration process used in conventional distillation. Since temperature on top of extractive column reaches 78 ºC, it is possible to use anhydrous bioethanol vapors to provide the remaining heat necessary to an adequate operation of column A. This integration in the double effect distillation is shown in Fig. 6.

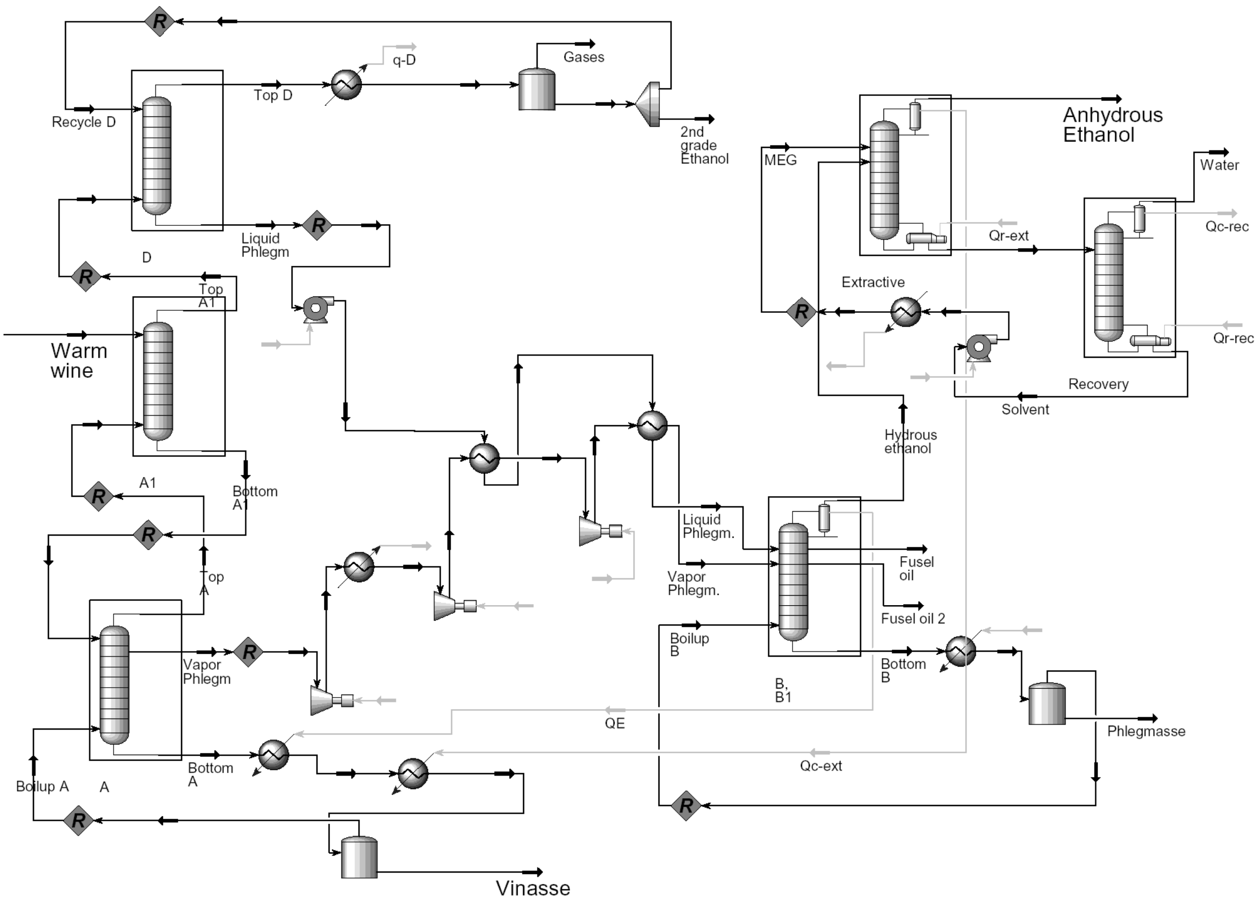

Figure 6. Double effect distillation - integration of column A reboiler to column B and extractive column condensers.

2.5. Production of steam and electrical energy

A steam based-cycle cogeneration system was simulated in the Engineering Equation Solver Software from F-Chart, being basically composed by boiler, steam turbine, deaerator and pumps. Two configurations of cogeneration were simulated, the first (Cogeneration 1) considering back-pressure steam turbine where the steam production is determined by the process requirements and the second (Cogeneration 2) with an extraction-condensation turbine with all the bagasse available consumed for steam and electricity generation. The system was simulated with two extractions of steam to attend the process requirements at 6.0bar and 2.5bar of pressure. Electric engines are considered as prime movers for the juice extraction system. The parameters adopted for the simulation of this system are presented in Tab. 1, as well as the electric consumption of the process. Thermal and electrical energy requirements of the process are supplied by this system and surplus electricity generated is considered available for sale to the grid.

Table 1. Parameters of the cogeneration system.

Parameter	Value	Parameter	Value
Live steam pressure (bar)	90	1st Extraction pressure (bar)	6.0
Live steam temperature (ºC)	520	2nd Extraction pressure (bar)	2.5
Boiler thermal efficiency (%)[1]	85	Deaerator operation pressure (bar)	2.5
High pressure (HP) steam turbine isentropic efficiency (%)[2]	72	Electric power demand of distillery (kWh/t of cane)	12
Medium pressure (MP) steam turbine isentropic efficiency (%)[2]	81	Mechanical power demand of cane preparation and juice extraction (kWh/t of cane)	16
Low pressure (LP) steam turbine isentropic efficiency (%)[2]	78	Bagasse available (kg/t cane)[3]	240
Pump isentropic efficiency (%)	75	Bagasse Low Heating Value (LHV) (MJ/kg)[4]	7.52
Electric engines efficiency (%)	98		

Note:[1]LHV base; [2] outlet pressures: 21bar for HP, 2.5bar for MP and 0.12bar for LP; [3] wet base; moisture content: 50%; [4] as burned, i.e., with moisture.

3. PROCESS INTEGRATION ANALYSIS

The Pinch Point Method described by Linnhoff et al. (1982) was used to analyze the streams of the process which are available for thermal integration. The method developed by works of Hohmann (1971), Umeda et al. (1978-1979) and Linnhoff and Flowers (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 (Δt_{min}) for the heat exchange.

The thermal integration target indicates the minimum requirements of external hot and cold utilities for the process. The 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.

Thermal integration analysis of the bioethanol production process considered the hot and cold streams parameters determined in the simulation of an autonomous bioethanol distillery crushing 493t cane/h. Two different distillation systems where simulated, considering simple and double effect cases. Thermal integration between rectification and distillation columns has an important impact on the distillery steam balance, promoting changes in the integration possibilities. Data of available streams for thermal integration are presented in Tab. 2.

Table 2. Data of considered streams for thermal integration.

Streams		Conventional Distillation Case			Double-effect Distillation Case		
Hot streams		$T_{initial}$ (°C)	T_{final} (°C)	Heat Flow (kW)	$T_{initial}$ (°C)	T_{final} (°C)	Heat Flow (kW)
H1	Sterilized juice	130	28	27,606	130	28	27,602
H2	Fermented wine	28	24	5,440	28	24	5,063
H3	Vinasse	112	35	27,426	65	35	10,547
H4	Anhydrous ethanol cooling	78	35	9,070	78	35	8,983
H5	Vapor condensates	107	50	10,499	109	50	12,418
H6	Condenser Column B	82	82	24,297	-	-	-
H7	Condenser Extractive Column	78	78	9,224	-	-	
H8	Condenser Column D	-	-	-	41	26	4,482
Cold streams		$T_{initial}$ (°C)	T_{final} (°C)	Heat Flow (kW)	$T_{initial}$ (°C)	T_{final} (°C)	Heat Flow (kW)
C1	Raw juice	30	70	21,062	30	70	21,096
C2	Limed Juice	76	105	20,535	74	105	20,667
C3	Juice for sterilization	96	130	9,287	96	130	9,309
C4	Centrifuged wine	28	82	23,161	28	48	8,636
C5	Reboiler Column A	112	112	38,553	-	-	-
C6	Reboiler Column B	108	108	6,725	108	108	5,248
C7	Reboiler Extractive Column	111	137	8,432	111	137	12,881
C8	Reboiler Recovery Column	150	150	1,704	150	150	1,794

Some streams with less than 1000kW of heat flow were not considered in the analysis because of their low thermal integration potential. The evaporation station was considered as a separated system which is integrated with the background process in a second step. This procedure previously applied by Ensinas (2008) in sugarcane mills permits the simplification of the analysis, maximizing the vapor bleeding use and reducing the total exhausted steam consumption in the process.

In this analysis a single-effect lithium bromide absorption system, with COP 0.65, was considered to provide the cold utility requirements of the fermentation step, consuming for that vapor from the third effect of the evaporation system as heating source to produce the necessary cold water.

Thus, following the procedure presented by Linnhoff et al. (1982) the Composite Curve (CC) and Grand Composite Curve (GCC) of the background process could be drawn (Figure **7** through 10) and the targets determined. The Pinch Point temperature was found at 81°C, considering a global Δt_{min} of 10°C. The software presented by Elsevier (2007) was used for calculation of the targets and drawing of CC and GCC curves.

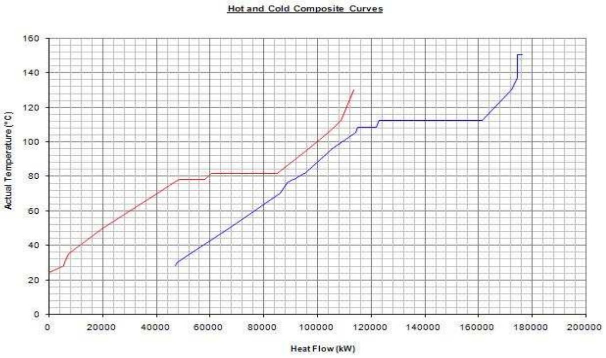

Figure 7. Composite Curves for conventional distillation case.

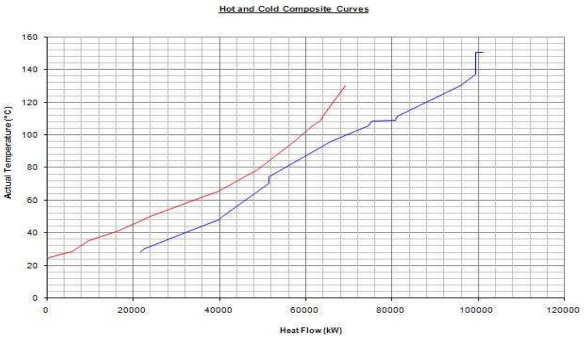

Figure 8. Composite Curves for the double-effect distillation case.

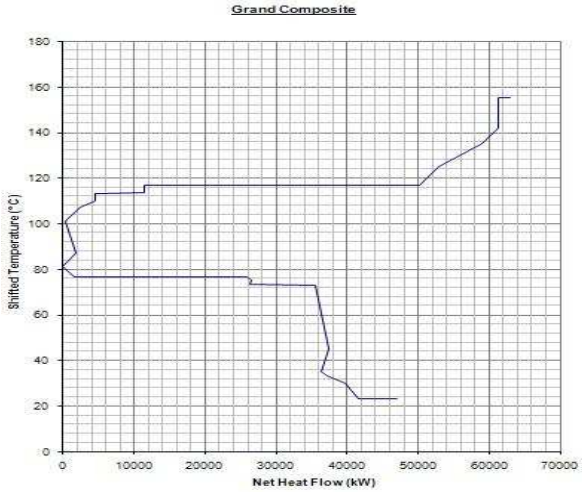

Figure 9. Grand Composite Curves for conventional distillation case.

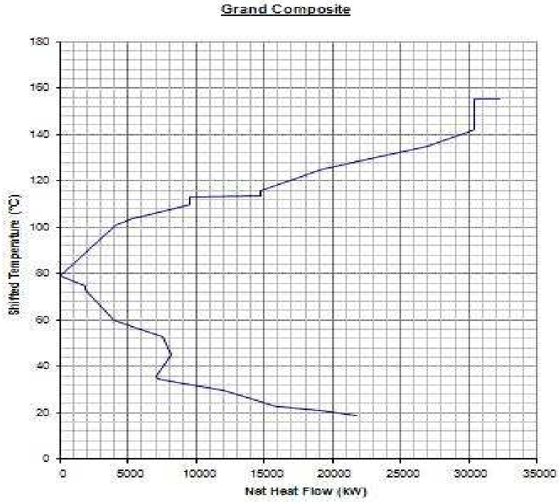

Figure 10. Grand Composite Curves for the double-effect distillation case.

4. RESULTS AND DISCUSSION

After integration of the background process and the distribution of the vapor bleeding the hot utilities requirements could be determined. Two levels of steam pressure were considered for hot utilities, derived from extractions at 6.0bar and 2.5bar of pressure in the steam turbine. Tab. 3 where steam consumption of the analyzed cases is shown summarizes the final results of hot utilities demand for each case. The decrease on steam consumption before and after integration is shown as well.

Table 3. Hot utilities demand before and after thermal integration for both conventional and double-effect distillation.

Operation	Saturated steam consumption (kg/h)							
	Before thermal integration				After thermal integration			
	Conventional distillation		Double-effect distillation		Conventional distillation		Double-effect distillation	
	2.5bar	6.0bar	2.5bar	6.0bar	2.5bar	6.0bar	2.5bar	6.0bar
1st juice heating	34,632	-	34,687	-	-	-	-	-
2nd juice heating	33,765	-	33,981	-	-	-	-	-
Multi-effect evaporation	56,270	-	60,706	-	59,254	-	68,519	-
Juice sterilization	-	15,843	-	15,916	4,056	4,711	5,427	4,729
Reboiler Column A	63,390	-	-	-	63,390	-	-	-
Reboiler Column B	11,058	-	8,629	-	11,058		8,629	-
Reboiler Extractive Column	-	14,426	-	22,039	-	14,426	-	22,039
Reboiler Recovery Column	-	2,915	-	3,069	-	2,915	-	3,069
Total	199,115	33,184	138,003	41,024	137,758	22,052	82,575	29,837
Decrease on steam consumption after thermal integration (%)					30.8	33.5	40.2	27.3

As can be seen in Tab. 3 the distillation system scheme (convention or double effect) has influenced significantly the process integration potential of improvements, since the largest steam consumption in the process takes place at Column A reboiler. Comparing both studied cases after thermal integration, a reduction in steam consumption of nearly 30 % is possible when using a double-effect distillation system for anhydrous bioethanol production.

The surplus of bagasse and electricity generation for both configurations of the cogeneration system and for each process case analyzed before and after thermal integration are shown in Tab. 4.

Table 4. Bagasse and electricity surplus generation.

Cogeneration system Configurations	Before thermal integration				After thermal integration			
	Conventional distillation		Double-effect distillation		Conventional distillation		Double-effect distillation	
	Bagasse (%)	Electricity (kWh/t cane)	Bagasse (%)	Electricity (kWh/t cane)	Bagasse (%)	Electricity (kWh/t cane)	Bagasse (%)	Electricity (kWh/t cane) [1]
Cogeneration 1 – back pressure turbine	8.9	45.0	28.7	26.9	35.5	22. 2	52.8	-2,8
Cogeneration 2 – extraction-condensation turbine	-	57.0	-	65.6	-	69.5	-	77.1

Note: [1]negative electricity surplus indicates that the process consumption is higher than cogeneration system capacity.

The process thermal integration implemented showed to have great impact in the plant surplus of bagasse and electricity. For Cogeneration 1, the bagasse surplus amount increases significantly for the double-effect distillation case, reaching more than 50% of the total bagasse produced. In this case the large quantity of surplus bagasse may be used to provide steam for other by-products processes or as feedstock for other activities. On the other hand, the electricity generation is limited by the low process steam demand and the internal consumption for juice extraction and compression of ethanol stream between distillation columns. The use of an extra fuel source such as sugarcane trash can be an alternative to attend the process electricity requirements, producing at the same time large amounts of bagasse surplus.

For Cogeneration 2, where all the bagasse is consumed, the increase in electricity generation is evident for the double-effect distillation case, reaching 77.1 kWh/t cane, which shows the importance of process integration for the feasibility of cogeneration systems with extraction-condensation turbines.

5. ACKNOWLEDGEMENTS

The authors acknowledge FAPESP and FINEP for financial support.

6. REFERENCES

Elsevier Ltd., 2006. “Pinch Analysis Spreadsheet”. 20 Nov 2007,<http://books.elsevier.com/companions/0750682604>.

Ensinas, A. V., 2008, “Integração térmica e otimização termoeconômica aplicadas ao processo industrial de produção de açúcar e etanol a partir da cana-de-açúcar”. PhD Thesis. School of Mechanical Engineering, State University of Campinas.

Hohmann, E.C. , 1971 “Optimum Networks for Heat Exchange”. Ph.D. Thesis, University of Southern California.

Linnhoff, B., Flower, J.R. , 1978a, “Synthesis of heat exchanger networks: I. systematic generation of energy optimal networks”, AIChE Jl., Vol. 24, pp. 633-642.

Linnhoff, B., Flower, J.R., 1978b, “Synthesis of heat exchanger networks: II. Evolutionary generation of networks with various criteria of optimality”, AIChE Jl., Vol. 24, pp. 642-654.

Linnhoff, B. et al., 1982, “User Guide on Process Integration for the Efficient Use of Energy”. Warks, England: The Institution of Chemical Engineers, 247p.

Mantelatto, P.E., 2005, “Estudo do processo de cristalização de soluções impuras de sacarose de cana-de-açúcar por resfriamento”, Dissertation (Master in Chemical Engineering), Federal University of São Carlos.

Perry, R.H. and Green, D.W., 1999, “Perry's Chemical Engineering Handbook”, McGraw-Hill, 7th edition, New York.

Umeda, T., Itoh, J. and Shiroko, K., 1978, “Heat exchange system synthesis”, Chem. Engng. Progr., v. 74, pp. 70-76.

Umeda, T., Harada, T., Shiroko, K., 1979, “A thermodynamic approach to the synthesis of heat integration systems in chemical processes”, Comput. Chem. Engng., v. 3, pp.273-282.

Wooley, R.J., Putsche, V., 1996 “Development of an ASPEN PLUS Physical Property Database for Biofuels Components”, 12 Nov. 2007, <www.p2pays.org/ref/22/21210.pdf>.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.