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Thermal Integration of Different Plant Configurations of Sugar and Ethanol Production from Sugarcane

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The sugarcane industry represents one of the most important economic activities in Brazil producing sugar and ethanol for the internal and external markets. Most of the sugarcane plants in Brazil have been projected to produce both sugar and ethanol, prioritizing one over the other according to market prices. There are also plants dedicated only to ethanol production. Nevertheless, this change in the production pattern affects parameters in their production such as water consumption, steam demands, bagasse surplus and electricity production. Thus, the aim of this study is to evaluate the production parameters for different configurations of sugarcane plant: (a) all sugarcane juice is destined to produce ethanol without sugar production and (b) distribution of 50 %/50 % of total recoverable sugars in sugar and ethanol production. Simulations in ASPEN PLUS® software were performed in order to evaluate the mass and energy balances and thermal integration using the Pinch Method was applied in order to minimize the utilities consumption.

1. Introduction

Over the recent years as energy security and environmental concerns have risen up various political agendas, there has been a substantial interest in biofuels and their potential contribution to energy security, mitigation of GHGs in the transport sector and also in delivering rural economic development benefits. Many countries around the world have developed or are developing biofuel mandates that require specific and rising contributions within the transport sector in the following years.
World fuel ethanol production in 2012 was estimated at about 107 billion L (RFA, 2014), from which approximately 49 % corresponded to the United States of America, the main world producer since 2006. For more than three decades (from mid-1970s to 2006) Brazil was the world's largest producer and consumer of ethanol. In 2012, the country figured in the third position, with a share of about 20 % (21.11 billion litres of ethanol). According to (EPE, 2014), there has been an increase of 6.3 % in the national sugar production and an increase of 2.4 % in the national ethanol production from 2011 to 2012.
Most of the sugarcane plants in Brazil have been projected to produce both sugar and ethanol, prioritizing one over the other according to market prices. The decision of how to distribute and prioritize ethanol and sugar productions from sugarcane will definitely affect the process water and steam demands, which could have impacts on its sustainability, for example on their water consumption or GHG emissions balances.
Another by-product of Brazilian sugarcane plants is electricity generated by their cogeneration systems. Plants with generating capacities exceeding 28 kWh/t of processed sugarcane are usually able to offer electricity surplus for sale to the public electricity grid. Several works have demonstrated the importance of reducing the energy consumption, namely steam, in the ethanol production process (Dias et al., 2011). Such reduction will allow more surplus bagasse to be used either in the cogeneration system for electricity production, or in the second-generation ethanol production.

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Pinch Analysis can be a powerful tool to achieve energy consumption optimization; for instance, Dias et al. (2011) simulated an ethanol production process from sugarcane and applied the Pinch Analysis in order to minimize utilities consumption, several configurations of cogeneration systems were studied by these authors including a BIGCC cycle (Biomass Integrated Gasification Combined Cycle). On the other hand, Martinez-Hernandez et al. (2013) applied the Pinch Analysis, including Mass Pinch, to the ethanol production process from wheat.

In the present work, the construction of composite curves for Pinch Analysis was carried out through a plug-in implemented in C++ language. The plug-in is an auxiliary module to the main program of the "Virtual 1st Generation Sugarcane Plant", which is being developed using a Brazilian simulation platform called EMSO (Environment for Modelling, Simulation, and Optimization) and that will allow to compare and optimize different technological routes in the production of sugar, ethanol and bioelectricity.

The aim of this work is to evaluate the production parameters for different configurations of sugarcane plant: (a) all sugarcane juice is dedicated to produce ethanol without sugar production and (b) equal distribution of total recoverable sugars in sugar and ethanol production. Simulations in ASPEN PLUS® software were performed in order to evaluate the mass and energy balances and thermal integration using the Pinch Method was applied in order to minimize the utilities consumption. Challenges were found for sugarcane plant simulation due to some sugarcane components which are not present in the simulator's database (Palacios-Bereche, 2013).

2. Methodology

2.1 Ethanol and sugar production process

A sugarcane plant for production of sugar and anhydrous ethanol with crushing rate of 500 t/h was modelled. The main parameters considered for the simulation correspond to a Brazilian standard size plant (CGEE, 2009).

In the simulation, cane dry cleaning, and a mill tandem extraction system driven by electric engines were assumed. The raw juice is separated according to Figure 1. One part is treated for ethanol production, while the other for sugar production. In the juice treatment, the following operations were adopted: screening, sulphitation (only for sugar production), heating, liming, decantation, and mud filtration. The concentration of treated juice for sugar takes place in a multiple-effect evaporation system of 5 effects until sucrose content of 55.4 % (syrup). Vapour bleedings with different pressures and temperatures resulting from the concentration process are used to cover heat demands in other parts of the plant. The syrup obtained in concentration step is sent to the crystallization process, which is accomplished in vacuum pans, in order to maintain low temperatures in *massecuite*, which has high content of soluble solids. In this way, problems of sucrose inversion can be avoided. Vapour bleeding from the first effect is used for heating vacuum pans. Then, sugar is separated from molasses through centrifugal separation. Finally air at 100 ºC heated by turbines exhaust steam is used to reduce the sugar moisture content in the drying process.

For the ethanol production, the must for fermentation is prepared with juice, syrup and residual molasses. The amounts of syrup and juice are determined in order to achieve a distribution of 50 %/50 % of total recoverable sugars in sugar and ethanol production. Sugar concentration of must should not exceed 17 %. Must sterilization is carried out by an HTST-type treatment (High Temperature Short Time), with heating to 130 °C followed by fast cooling down to the fermentation temperature of 32 °C. In this study, fermentation was based on the Melle-Boinot process (cell-recycle batch fermentation). Following that, the wine is sent to distillation and rectification columns where hydrated ethanol (93.7 % wt. of ethanol) and vinasse (0.02 % wt. of ethanol) are separated. For ethanol dehydration, a process of extractive distillation with MEG (monoethylene glycol) was simulated. Anhydrous ethanol is obtained, with an ethanol content of 99.4 % (mass basis).

The different production patterns adopted for analysis correspond to different distributions in the total recoverable sugars (TRS) from sugarcane. For Case I, TRS are destined exclusively for the production of ethanol; in this case, the must for ethanol production is prepared only from sugarcane juice. In Case II, sugar and ethanol are produced equally, considering ethanol production from residual molasses from sugar production and some amount of syrup and treated juice. In both cases it is assumed to have a constant electricity demand of 28 kWh/t of sugarcane crushed.

2.2 Pinch Analysis

The Pinch Analysis was proposed by Linnhoff et al. (1979) and has the purpose of reducing the use of external utilities to its minimum by combining the process hot and cold streams and achieving the optimum heat recovery (target). Lately, it has also been employed for optimisation in heat exchanger networks. Its graphic tools, the Hot and Cold Composite Curves (CCs) and the Grand Composite Curve (GCC), simplify the identification of opportunities of Heat Integration.

However, according to Higa et al. (2009), the addition of a multiple effect evaporator (MEE) system presents a conceptual problem for the construction of both CCs and GCC, because the minimum target

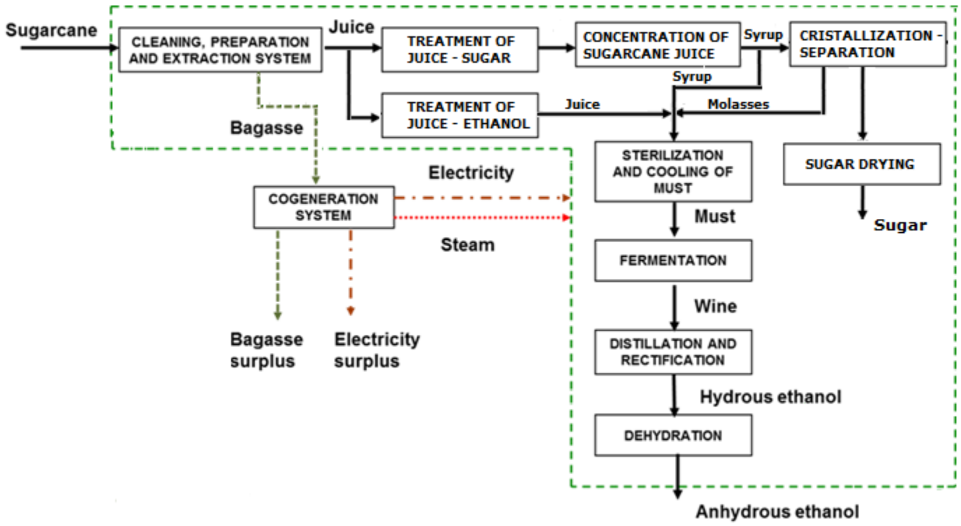


Figure 1: Scheme of the ethanol and sugar production process from sugarcane

Table 1: Hot and cold streams adopted for the process thermal integration

	Ti	Tf	ΔH (MW)	
	(ºC)	(ºC)	Case I	Case II
Hot streams				
Sterilized juice	130	32	41	17.1
Wine from the vats	32	28	12.2	6.2
Flegmass	103.9	35	3	1.4
Vinasse	109.3	35	37.2	16.1
Anhydrous ethanol	78.3	35	8.6	4.3
Condensates of steam	110	35	8.4	22.6
Condensate column D	84.9	35	19.5	9.9
Condensate column B	81.7	81.7	26.4	12.9
Condenser extractive column	78.3	78.3	7.4	3.7
Cold streams				
Imbibition water	25	50	4.4	4.4
Treatment juice	34.2	105	44	-
Treatment juice-etanol 1	42.1	105	-	10.2
Treatment juice-sugar 1	35	70	-	14
Treatment juice-sugar 2	73.3	105	-	15.6
Juice pre-heating	98.1	115	2.7	6.9
Juice for sterilization	95.5	130	14.6	5.7
Final wine	31.2	90	33.7	14.8
Reboiler column A	109.3	109.3	43.7	20.5
Reboiler column B	103.9	103.9	21.8	11.2
Reboiler extractive column	134.5	134.5	6.7	3.4
Reboiler recuperative column	149.6	149.6	2.5	1.3

utility is greatly affected by certain arrangement. To solve such issue Urbaniec et al. (2000) decomposed the thermal system into two sub-systems: the MEE and the remaining of the process. The minimum temperature difference (ΔT_{mi}n) adopted was 10 ºC for the process streams and 4 ºC for the evaporation system streams. The thermal integration can be achieved through four iterative steps as mentioned below:

Step 1: Thermal integration of available process streams excluding evaporation system and construction of the initial GCC.
Step 2: Calculation of appropriate vapour bleedings in each effect of the evaporation system, according to the procedure proposed by Ensinas et al. (2007) later by Ensinas and Nebra (2009) and recently by Palacios-Bereche (2011),
Step 3: Integration of the evaporation system with the appropriate demand including the vapour bleedings optimized in each effect.
Step 4: Update of the mass rates of the evaporation system condensates. Return to Step 2 until convergence. Table 1 shows the streams adopted for the thermal integration process of each case.

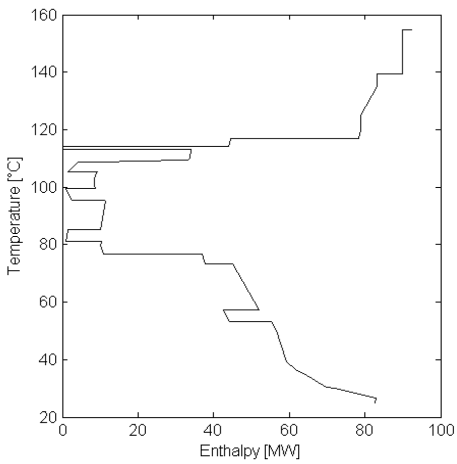
3. Results and discussion

Table 2 shows the steam consumption in each operation of the process for all cases. It can be observed that for both Cases I and II the major steam consumer is the evaporation system (35 and 69 % of the total respectively). In these cases the vapour bleedings are used for juice treatment (Case I and II) and for vapour pans (Case II). It can be noticed that there is no steam consumption for distillation column B-B1 in Case I_{-TI} and Case II_{-TI} owing to these heat requirements are covered by the process streams, which reduces significantly the total steam consumption. Case II_{-TI} presented the lowest total steam consumption which indicates its high thermal integration potential; it can be explained by its largest amount of vapour available for bleedings.
Figure 2 shows the final GCC for the Case I_{-TI} and Case II_{-TI} obtained through the thermal integration procedure. Through the size of horizontal bars in GCC's it can be observed that heat exchanged in evaporator stages of Case II_{-TI} is higher than heat exchanged in Case I_{-TI} . The procedure also allowed to identify the appropriate place and size for vapour bleedings. For this simulation the bleeding adopted in Case I_{-TI} was 44 t/h in first effect, while in Case II_{-TI} was 31 t/h in first effect and 36 t/h in third effect.

Table 2: Steam consumption (kg/t of cane)

		Case I	Case II	Case I_{-TI}	Case II_{-TI}
Steam 6 bar	Juice sterilization	51.2	19.5	15.1	5.2
	Dehydration: extractive column	24.8	11.8	23.0	11.7
	Dehydration: recovery column	8.6	5.6	9.8	5.6
Steam 2.5 bar	Pre-heating of juice	0	0	3.6	22.8
	Treatment juice- ethanol 1	0	0	0	1.9
	Evaporation system	164.2	322.3	112.3	191.4
	Distillation column A	147	67.7	144.3	54.8
	Distillation column B-B1	71.9	37.2	0	0
	Drying sugar	0	1.3	0	1.3
	TOTAL	467.7	465.4	308.1	294.6

Case I_{-TI}; Case II_{-TI}: Cases thermally integrated



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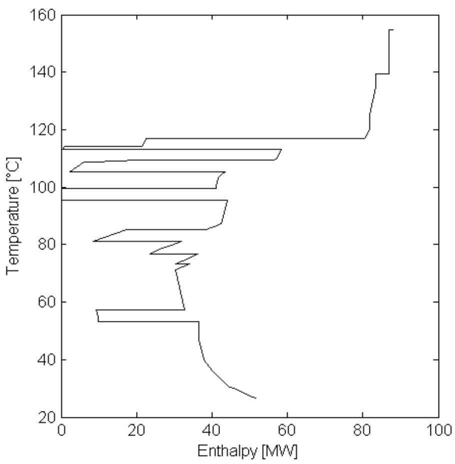

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Figure 2: Grand Composite Curves - GCC for the Case I_{-TI} (a) and Case II_{-TI} (b)

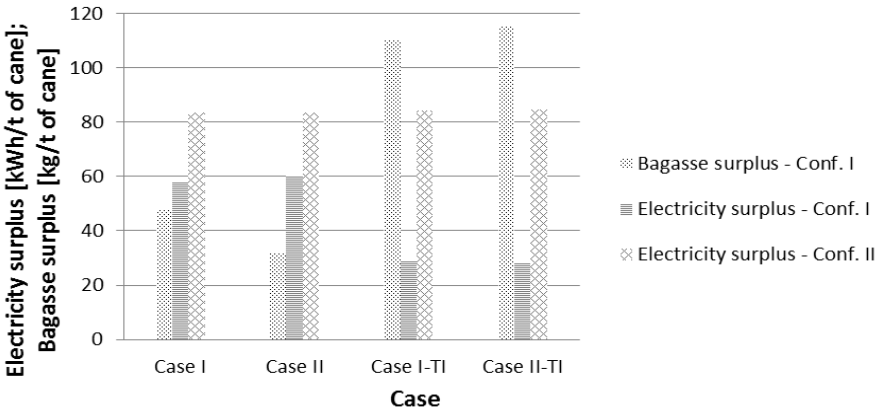

Figure 3: Electricity surplus and bagasse surplus for evaluated cases

Currently, sugarcane plants are self-sufficient in terms of electromechanical energy and heat for their processes. The cogeneration system provides steam at 2.5 and 6 bar for the process requirements according to Table 2. Bagasse generated in the extraction process is sent to the utility plant, where it is burned in boilers. In this study two configurations of cogeneration system were evaluated:
i) Configuration I: Steam cycle with backpressure steam turbines
ii) Configuration II: Steam cycle with condensing-extracting steam turbines
In both of cases it was assumed that steam is generated in boiler at 100 bar and 530 °C. In configuration I, the amount of steam produced in the boiler is that necessary to meet the requirements of the process; on the other hand, in configuration II all available bagasse is burnt in order to maximize the electricity surplus. Figure 3 shows the electricity and bagasse surplus for Configuration II and the electricity surplus for Configuration II.
In Cases I and II there are no great differences in steam consumption and electricity surplus, however bagasse surplus in Case II resulted slightly lower in comparison to Case I. It can be explained by the fact that Case I presents a larger use of steam at 6 bar and this simulation assumed a flash recovery of this steam, thus the steam generated in boiler in Case I resulted lower than in Case II.
Concerning the thermally integrated cases there are no great differences in total steam amounts and consequently electricity and bagasse surplus, however it can also be observed that Case I_{-TI} presented the greatest needs of high pressure steam (6 bar).

4. Conclusion

The thermal integration method promotes a significant reduction in steam consumption. Bagasse surplus is maximised when backpressure steam turbines are used, on the other hand, electricity surplus are the highest when condensing extraction steam turbines are adopted. The combined production of sugar and ethanol (Case II) presented higher potential for thermal integration. The procedure also allow to optimize the vapour bleedings in evaporation system minimizing the use of hot utility in process (exhaust steam of turbines).

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