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6

INCREASING ENERGETIC EFFICIENCY IN SUGAR, ETHANOL, AND ELECTRICITY PRODUCING PLANTS

Adriano V. Ensinas, Juan Harold Sosa Arnao and *Silvia Azucena Nebra*

The sugar-alcohol industry has been one of the most important activities in the Brazilian economy, producing sugar and ethanol for both domestic and foreign markets. This industry has been historically characterized by its low energy efficiency, consuming a considerable part of the bagasse produced as fuel in its co-generation systems, to supply the energy needs of the process. A new scenario, with the possibility of selling surplus electricity to the distribution network, or else, to use bagasse as a raw material for other processes, has motivated several plants into investing in more efficient co-generation systems, as well as in higher process energetic integration.

This chapter discusses the improvement of sugar-alcohol mills co-generation systems by increasing boiler efficiency through the use of bagasse dryers, as well as other design approaches, to these systems. Energy process integration is also included, showing that available thermal energy exploitation may lead to a significant reduction in plant steam intake, thus improving the energy efficiency of the production process.

INTRODUCTION

Through the Brazilian sugar-alcohol industrial history, it is possible to identify efforts to increase mill energy efficiency, as a result of the need to solve actual problems that came up from time to time.

Therefore, one of the first objectives achieved was freeing the industry from any auxiliary fuel, using bagasse, a waste from its own process, as sole source of heat.

The next step was the self-generation of all energy required, both thermal and electric, by developing co-generation systems adequate to the plants' needs, using exclusively bagasse for fuel.

In parallel, the thermal energy consumed in the process began to be better exploited, introducing the use of vegetal steam from evaporators.

A third challenge came up with public electricity deregulation, and hence the possibility of selling electric power to the distribution network at competitive prices.

Still, within the proposed utilization of Rankine cycles, the industry introduced new co-generation systems, with boilers and turbines working at higher temperatures and pressures.

However, new challenges are lurking around the corner, with the possibility of introducing BIG-CC cycles, as it's being planned in India, for different types of biomass (see RENEWABLE ENERGY FOCUS, 2009a), and also with the introduction of the so-called third-generation refineries (RENEWABLE ENERGY FOCUS, 2009b), in which bagasse is shifted from combustible waste into raw material.

In this chapter, the discussion will cover the shortest-range challenges, dealing with co-generation systems improvement, boiler exhaust gases exploitation system, as well as a better thermal integration of the process.

CO-GENERATION SYSTEMS

The co-generation concept has several definitions found in the literature, many of them being close to the one adopted by LIZZARAGA (1994), defining this term as the "joint generation of electricity (or mechanical energy) and usable thermal energy in a sequential process".

Anyway, it is evident that the co-generation option allows for more efficient energy generation, if compared to the independent generation of one sole form of energy, such as in a thermoelectric power generating station. The use of thermal energy enables high performance in the global use of energy, and consequently, savings in primary energy.

The growing worldwide interest in the rational use of energy, combined with minimum use of natural resources, finds in co-generation technology a very compelling technological option, which has conquered space in many industrial and utility applications.

In Brazil, sugar-alcohol industry mills have co-generation systems with the simultaneous production of heat and work for the sugar and ethanol production process, using sugarcane bagasse as fuel. The steam produced may be used to drive mills, pumps, blowers, as well as be converted into electricity, where it finds its noblest use.

Co-generation allows exploiting the energy in the bagasse, and generating electric power in a decentralized and independent manner at the various plants in this industry, that has its energy requirements fulfilled by these systems.

The need for disposal of bagasse, a residue biomass from the production process, was one of the reasons leading to the adoption of low-efficiency co-generation systems, thus making it possible to consume large quantities of residue, and locally generating the energy the process requires.

The restructuring of the Brazilian electrical power generation industry in the 1990s, following the worldwide trend towards distributed power generation, gave room to small-scale production of electricity, and fostered some keener interest in mills for more efficient co-generation systems. The possibility of non-utility generators selling their generated energy surplus contributed to increase the value of residual biomass as a source of energy for power generation.

Furthermore, increasing social demands for energy policies that value minimum environmental impact, alternative energy sources, and rationalization of energy inputs have shown the need for improved exploitation of sugarcane residues.

The structure of mills having low-efficiency co-generation systems and high power demand processes may be analyzed to improve energy usage in this industry, making it possible to generate surplus electric power that could be sold to electric utility companies. On top of using bagasse, the elimination of burning in sugarcane fields, the presence of mechanized harvest and recovering sugarcane tips and leaves, may also represent a significant increase in biomass availability for use as fuel in co-generation systems, further increasing surplus generation.

The decision on the optimum co-generation system for a mill depends on several factors to be observed, among them:

- process-required for mechanical, electric, and thermal energy;
- process-required for steam pressure and temperature levels;
- process energy intake dynamics; intermittent or continuous;
- system utilization factor;
- energy share in the final product cost;
- technical and economical feasibility of selling surplus electricity.

STEAM CYCLE SYSTEMS

Traditionally, topping-type steam cycle systems are adopted by mills, where bagasse is used to generate live steam to drive back-pressure turbines coupled to an electric generator. High pressure steam is taken to drive choppers, defiberers and mills, while the turbine low-pressure exhaust steam is used as a source of heat for various equipments in the plant.

Older systems, characterized by their low energy conversion efficiency are limited for generating electricity. Low-efficiency boilers, generating steam at around 22 bar pressure, overheated between 280 °C and 320 °C, and the process' high steam consumption, around 500 kg of steam per ton of sugarcane, are strong limiting factors to electricity generation, which makes surplus power virtually inexistent.

According to CAMARGO (1990), boilers used by the sugar-alcohol industry until the 1980s were conceived around eliminating bagasse, considered as an undesirable waste, therefore being low efficiency and low cost. Some alternatives available for increasing this equipment's efficiency in drawing energy from bagasse are described by NETO and RAMON (2002), among them the use of superheaters, thermal deaerators, savers, air preheaters, and bagasse dryers, in addition to efficiency-preserving actions, such as care in handling fuel, feed water treatment, and better control on combustion.

Systems with back-pressure turbines are limited to generation during the harvest period, as they need the process to condense the generated steam. Steam loss, or its condensation at turbine exhaust pressure is not economically justifiable, rendering off-harvest power generation unviable with such systems.

Increasing temperature and pressure levels of the steam generated by co-generation systems boilers makes it possible to increase the surplus electricity generated, which can be sold to utility companies. Furthermore, the use of extraction-condensation turbines makes it possible to generate electricity and sells it also during the off-harvest season.

Technological evolution of sugar-alcohol industry co-generation systems

In Brazil and all over the world, only steam systems are found in sugarcane mills. This is a widely known technology, using mostly locally-made equipment. There are many boiler, steam turbine, and electric generator manufacturers in Brazil, several of them also serving the international market.

It is observed that more efficient co-generation systems have been installed in the Brazilian sugar-alcohol industry, with boilers generating live steam above 60 bar and temperatures ranging between 480 °C and 520 °C.

The trend observed is towards using higher parameters in steam generation, to render more efficiency in electric power generation. The first boiler to operate at 90 bar pressure was installed in mid-2008 at Usina Equipav, located in Promissão, SP (STEFANO, 2009). DEDINI (2008) offers systems that operate at 100 bar pressure and 520 °C temperature. Internationally, KAMATE e GANGAVATI (2009) state that the highest pressure used industrially is 105 bar, in a sugar plant in Okeelanta, Florida, USA.

Inquires made to boiler and turbine manufacturers showed that there is an economic limitation to using higher temperatures to generate live steam, as steels currently produced in Brazil can only withstand temperatures up to 520 °C. Special steels, that can endure higher temperatures, would require importing the material, or ordering specific batches to Brazilian industries, which would lead to unaffordable costs (EQUIPALCOOL, 2006).

Another trend noticed was towards increasing the capacity of steam generation by boilers intended for the sugar-alcohol industry, shifting from the present systems that generate from 150 t/h to 250 t/h of steam to capacities between 300 t/h and 450 t/h.

The trend for larger capacity boilers is the monodrum type construction. The monodrum boilers technology is new to the sugar-alcohol industry; however it has been used for several years, both in and outside Brazil, in industries such as pulp & paper, petrochemical, and thermal electricity generation. According to the manufacturers, the technology used to build monodrum boilers allows adopting high steam flow rates, and pressures in excess of 100 bar (CALDEMA, 2006).

Regarding steam turbines, it is observed that Brazilian industry has been supplying the domestic demand for turbines operating at the highest pressure an temperature levels adopted for steam generation, however according to some manufacturers, the maximum power of such equipment is limited to 50 MW for economical reasons, since domestic electricity generators can only work up to this power level, importation still being unaffordable from the investment viability standpoint (NG, 2006).

However, it is observed that Brazilian industry has the technology to produce steam reaction turbines with power up to 150 MW, operating with intake steam up to 120 bar and 530 °C, however for export only (NG, 2006).

Evolution of bagasse boilers efficiency

Old 20 bar/300 °C boilers did not provide any device of how to use the exhaust gases enthalpy. With the progressive increase of steam pressure and temperature parameters, and the change in boiler design (single-pass on the gas side, at the convection beam), the temperature of gases from the steam generator increased, and for this reason devices were progressively aggregated for using this energy.

SOSA-ARNAO and NEBRA (2009) present a correlation for calculating this temperature, as a function of the vapor saturation temperature:

$$T_g = 42.94T_{sat}^{0.3962} \quad (1)$$

Correlation valid for temperatures up to 67 bar.

Thus, for 20 bar boilers we would have a temperature of the gases of 359 °C, and for 65 bar, 401 °C (these values depend on boiler constructive features, and may vary). In any case, it is a significant amount of thermal energy, which should be exploited.

So, with the technical improvement air preheaters were initially introduced, to use the thermal energy from exhaust gases to heat the air blown into the boiler itself.

Though seldom used in the Brazilian industry, another proper piece of equipment for using the thermal energy from exhaust gases is the bagasse dryer (SOSA-ARNAO *et al.*, 2006a).

The efficiency of 20 bar boilers with air preheaters and pneumatic type bagasse dryers was determined by SANCHEZ PRIETO *et al.* (2001). The schematics of the system studied by those authors is shown on Figure 1. Gases exiting the steam generator were split, part of them being sent to an air preheater, and the remainder to a bagasse dryer.

The Tables 1 and 2 show the boiler features and the data obtained.

The boiler's overall efficiency was calculated based on the low heat capacity of bagasse; this definition particularly fails to consider the energy spent in evaporating the water it contains. Calculating the efficiency according to the high heating value, such effect is taken into account, and efficiency is decreased by around 25%, as discussed by SOSA-ARNAO *et al.* (2006b).

Due to the high particle content of exhaust gases, the most popular heat exchanger is the shell and tubes type, which, as it requires a large area to transfer heat between two gaseous flows, takes up considerable space, its size being limited by the cost/benefit ratio.

Hence, it may be observed that the exhaust gas temperature at the air preheater is relatively high, causing significant heat loss. This effect is detected by the effectiveness parameter of the

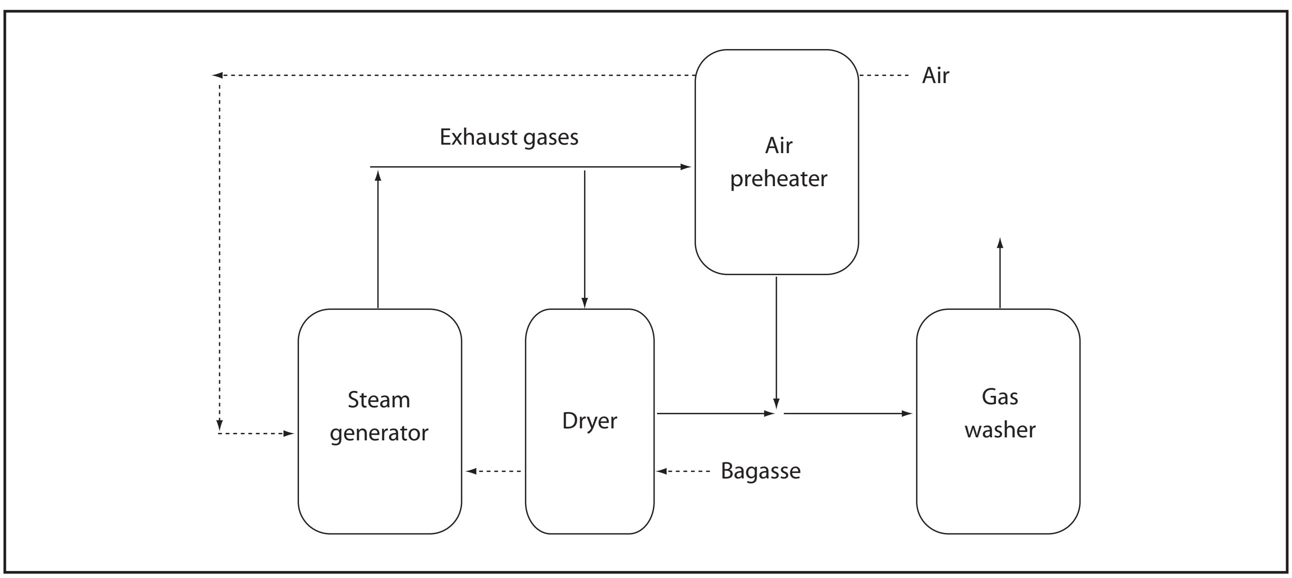


FIGURE 1 Schematics of the system studied by SANCHEZ PRIETO *et al.* (2001).

TABLE 1 Characteristics of boilers.

	Manufacturer	Temperature (°C)	Abs. pressure (bar)	Capacity (t/h)
1	Dedini S.A.	310	21.61	68
2	Dedini S.A.	315	21.61	74
3	Caldema	320	21.61	83

Source: SÁNCHEZ PRIETO *et al*., 2001.

air preheater (HOLMAN, 1983), which shows relatively low figures.

In terms of exploiting the available energy, the direct type dryer has better performance. Gas temperatures at its outlet are lower, and its efficiency shows good values for the first two boilers. It is smaller and cheaper equipment, however it must be carefully designed to offer good results.

Another important issue is the evolution in the way of burning bagasse. At the outset, bagasse was burnt in a stockpile, which resulted in unstable and deficient burning. In these cases, only primary air was used in combustion. Over time, boiler design was changed increasing the height of bagasse feed from 1 m to 4 m, and secondary air was introduced. The result was an increase in suspended bagasse burning, less superficial burning, and increased combustion efficiency.

The Sugar Research Institute – SRI developed the vortex bagasse burning system, where the bagasse enters the boiler immersed in the spiraling air flow, which gives it more drying and burning time in suspension than the traditional spraying system (DIXON *et al*., 2003).

TABLE 2 Systems parameters.

	Boiler 1	Boiler 2	Boiler 3
Produced steam flow rate (kg/s)	18.89	20.56	23.06
Total mass of exhaust gases (kg/s)	43.33	41.05	57.32
Air pre-heating gas intake (kg/s)	11.77	15.08	11.78
Dryer gas intake (kg/s)	31.56	25.96	45.54
Temp. gases input to air preheater/dryer (°C)	259	239	257
Temperature of gases at air preheater outlet (°C)	175	198	169
Temperature of gases at dryer outlet (°C)	91	83	83
Preheated air flow rate (kg/s)	14.52	11.93	20.87
Preheated air temperature (°C)	125	124	124
Bagasse flow rate after dryer (kg/s)	6.82	7.48	9.70
Bagasse moisture after dryer (% b.u.)	40	42	45
Overall boiler efficiency (%)	75.56	78.75	72.48
Air preheating efficiency (%)	46.77	32.47	60.34
Dryer efficiency (%)	78.96	89.14	39.41

Source: SÁNCHES PRIETO *et al*., 2001.

In Brazil, there is equipment using the same vortex principle, however, it only mixes the bagasse with the spiraling air at the sprayer outlet. This system, developed from burning rice husk, was introduced in the Branco Perez mill by the company Equipalcool Sistemas Ltda., in August 2008.

Bagasse dryers

In a comprehensive review, SOSA-ARNAO *et al*. (2006a) present a series of data on different dryer types used for bagasse, both industrial and experimental. So this comprises the classic rotating dryers, the descending flow ones, and the pneumatic ones, among others.

The pneumatic type dryers were tested by the Brazilian sugar-alcohol industry, using a model developed by the former Copersucar Technology Center, today Centro de Tecnologia Canavieira (Piracicaba). Experimental results obtained on the field compared to data simulations are reported by NEBRA and MACEDO (1989).

The design of any dryer should start from a careful analysis of material shapes and sizes (NEBRA and MACEDO, 1988; SOSA-ARNAO, 2007).

One important consideration is related to the source of energy to be used. Previously, an example of use of boiler exhaust gases was given. In the case of sugar-alcohol mills, this seems to be the best option. In any case, the process integration concept explained next requires that for the drying operation – which does not demand high temperatures – thermal waste be used, at 200 ºC or lower temperatures.

On top of the consideration regarding thermal waste, in the case of bagasse, care must be taken with its easy ignition. RAMAJO-ESCALERA *et al*. (2006), SOSA-ARNAO (2007), and SOSA-ARNAO and NEBRA (2009) present data relative to the combustion of this material, where it is possible to identify the point where carbon dioxide emissions (step) begins, around 200 ºC. Being part of the material composed by small-particles material, which will dry quickly (NEBRA DE MACEDO, 1989), it is advisable that drying gases in direct contact do not exceed much that temperature.

Regarding the type of dryer, considering the material size diversity and its light weight, the previously tested pneumatic types seem adequate. Cyclone dryers were also tested in laboratories, with promising results (CORRÊA, 2003; CORRÊA *et al*. 2004), as they are smaller units.

SOSA-ARNAO (2007) and SOSA-ARNAO and NEBRA (2009), discussed the efficiency and the economics of an arrangement using a pneumatic dryer with a separator cyclone at its end, considered to be the best option found. Some of the results from these works are shown next.

The system concept was guided by the idea of exploiting the boiler exhaust gases thermal energy, considering the use of air preheaters, feed water preheaters (savers), and dryers. The system was designed using optimization tools, in a way to obtain a dimensioning that led to the minimum costs for the overall system.

Three possible arrangements were analyzed (Figures 2 to 4), comparing them in terms of their energy efficiency and cost. In case III, the saver is placed before the air preheater. This was done because the return water from the plant being at a higher temperature that the surrounding air, so this way the saver increases its effectiveness.

The dryer type selected was the pneumatic type, with a cyclone at its end to separate bagasse and gas. Four pneumatic ducts were considered, each of them connected to a pair of cyclones, being each of the boiler burners fed by a cyclone. In this matter, dryers surrounded the boiler, in a proper layout, with the same maximum height.

In terms of system design, the same boiler was considered for all three arrangements, with a steam production capacity of 200 t/h, at 65 bar, and 500 ºC.

The calculation procedure for each type of equipment is reported on the mentioned works (SOSA-ARNAO, 2007 and SOSA-ARNAO and NEBRA, 2009).

Table 3 shows the thermodynamic data of the main system flows, in terms of their initial, pre-optimization values. Figures indicated correspond to those shown on Figures 2 to 4.

First-law efficiency, *based on the high heating value*, is 64.1% for case I, and 70.4% for cases II and III. Higher efficiencies in cases II and III is owed to the lower temperature of gases leaving the system, which contributes to reduced heat losses.

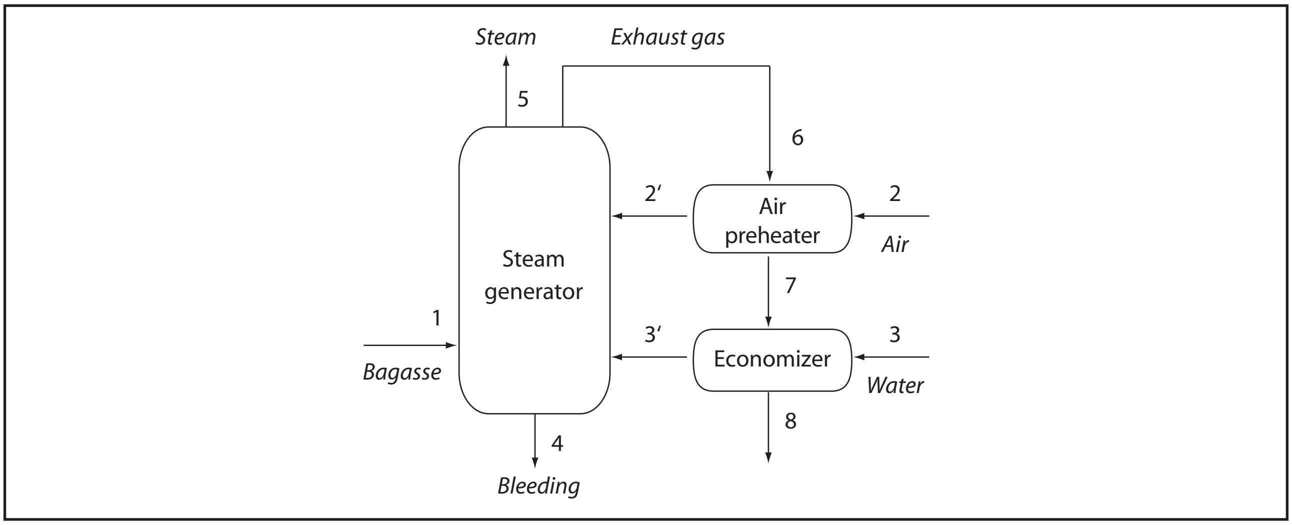


FIGURE 2 Tandem arrangement, air preheater and saver – case I.

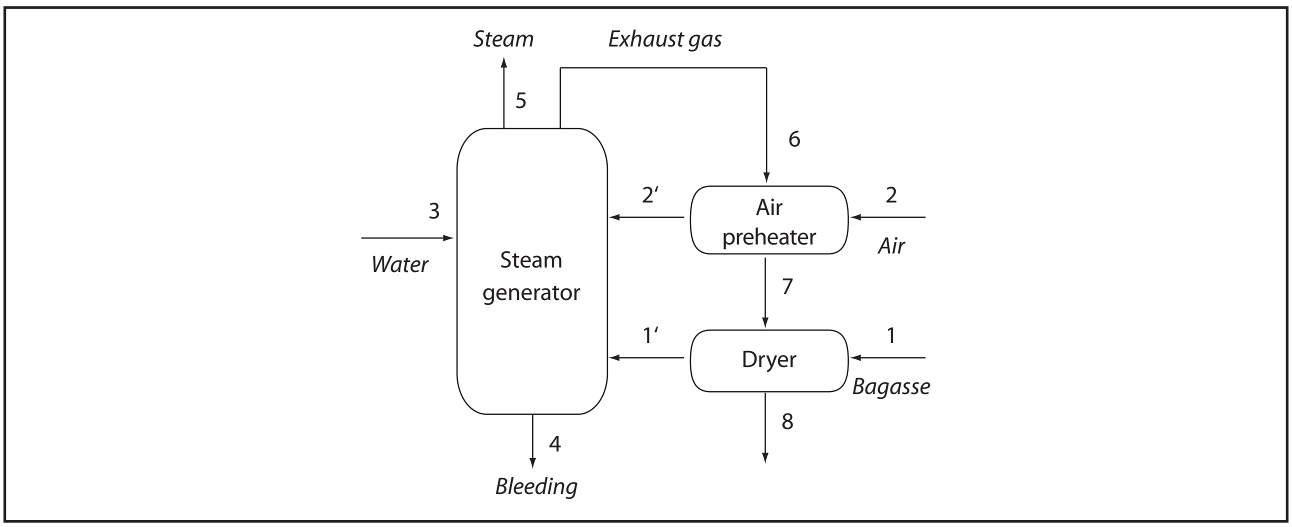


FIGURE 3 Tandem arrangement, air preheater and dryer – case II.

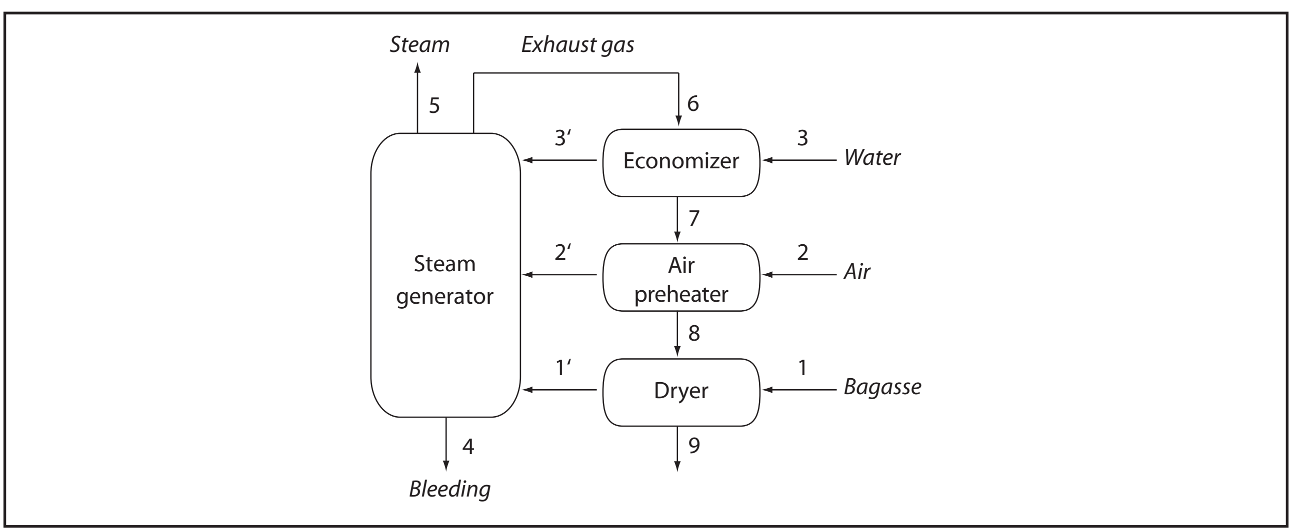


FIGURE 4 Sequential arrangement, saver, air preheater, and dryer – case III.

Costs corresponding to the initially dimensioned system are shown on Table 4. In the case of the saver and air preheater, costs were calculated based on the area of heat exchange, considering respectively values of 161.58 R$/m^2 (80.79 USD/m^2) and 138.62 R$/m^2 (69.31 USD/m^2). In the case of the dryer, the cost adopted was 9.70 R$/kg (4.85 USD/kg). Construction of this equipment was simulated using a 4 mm thick steel plate.

In case I, it is necessary to make a trade-off between the costs of the economizer an the air preheater, varying the temperature of air preheater outlet gases; the saver cost increases with this temperature (T7), as more energy is transferred to the water in the saver, and less to air in the preheater. This calculation may be observed in Figure 5.

The system was optimized in terms of equipment dimensioning, which led to variations in their intake and outlet temperatures, as well as their heat exchange areas and external dimensions. For optimum conditions, the temperatures shown on Table 5 and the costs shown on Table 6 were obtained.

From these results, it is possible to notice that the optimum system dimensioning corresponded to a smaller air preheater, a larger saver, always with a dryer, working with the highest input temperature allowed in the calculations: 215 °C. Under these conditions, it is possible to obtain a final moisture content in bagasse of 34.5% (h.b.).

From the results obtained in successive studies, bagasse dryers are an economical and functional option, which allows improving boiler efficiency.

PROCESS ENERGY INTEGRATION

The process integration (PI) concept came up in the early 1980s, and has been used ever since for analyzing energy usage and to reduce the environmental impact of industrial processes. This research area was initiated with research on heat recovery via the *Pinch Point* concept, however currently PI encompasses a wider universe of integration possibilities that goes beyond the use of energy in processes.

PI application in industry became a fundamental tool for planning and designing its activities, providing investment and operational costs reduction. Minimum consumption of natural resources in integrated industrial processes derives not

TABLE 3 Thermodynamic data of the main flows in the systems shown in Figures 2, 3, and 4.

Flow	Temperature [ºC]			Pressure [MPa]			Output		
	I	II	III	I	II	III	I	II	III
1	35	35	35	1	1	1	24.8	22.9	22.9
1*	–	74	74	–	1	1	–	17.5	17.5
2	30	30	30	1	1	1	95.0	75.0	75.0
2*	240	288	147	1	1	1	95.0	75.0	75.0
3	120	120	120	72	69	72	60.6	60.3	60.3
3*	171	–	165	69	–	69	60.6	–	60.3
4	281	281	281	65	65	65	5.08	4.74	4.74
5	500	500	500	65	65	65	55.6	55.6	55.56
6	401	401	401	1	1	1	119.8	97.9	97.9
7	260	215	300	1	1	1	119.8	97.9	97.9
8	165	74	215	1	1	1	119.8	97.9	97.9
9	–	–	74	–	–	1	–	–	97.9

TABLE 4 Costs of energy recovery systems before optimization.

Cases	Economizer	Air preheater	Dryer	Total cost
	[US$]	[US$]	[US$]	[US$]
I	285,013	429,032	–	714,045
II	–	547,930	149,020	696,950
III	81,618	201,594	149,020	432,232

only from optimized energy usage, but also from the consumption of raw materials and water, with analyses that include thermal and mass integration, on top of industrial waste management.

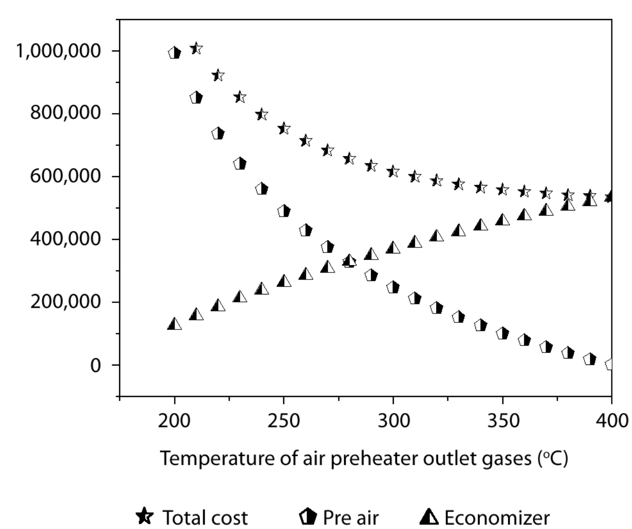
Process integration techniques application areas may be understood, at first, as those cases where less energy intake and lower environmental impact are sought; however their applications go beyond these objectives.

As a more immediate example, it may be mentioned the case of reducing energy consumption, which is usually associated to an increased investment in energy recovery equipment. The goal, in this case, is the search for a minimum total cost comprising both operation and investment. In other cases, the analysis can be made aiming at equipment cost reduction for a certain energy consumption level.

The major areas for process integration application in industry may be described as:

- new processes or retrofit design, including batch, continuous and semi-continuous operation modes;
- process operations planning;
- to increase efficiency in raw materials and energy intake, and to improve productivity (debottlenecking);
- equipment design, such as reactors, separators, and heat exchanger networks;
- integration of processes and utilities system;
- integration between industrial complexes, power plants and public HVAC systems;
- minimizing the generation of water-based effluents and process water consumption;
- minimizing residue and emissions generation.

It is important to point out that the use of process integration techniques, even in similar processes, may require different designs to fulfill the minimum desired demand goals. Each process should be studied separately, considering local investment operating costs, as well as operating conditions.



Source: SOSA-ARNAO, 2007.

FIGURE 5 Behavior of saver and air preheater cost as a function of air preheater outlet gases temperature.

TABLE 5 Temperature distribution corresponding to the optimized dimensioning of energy recovering systems.

Cases	$T_{g,6}$ [ºC]	$T_{g,7}$ [ºC]	$T_{g,8}$ [ºC]	$T_{g,9}$ [ºC]
I	401	368	–	165
II	401	215	74.5	–
III	401	252	215	74.9

The *Pinch* method

The *Pinch Point* concept for heat recovery was the most important contribution to the research area related to process integration, having been developed from works by HOHMANN (1971), UMEDA *et al.* (1978-1979), and LINNHOFF and FLOWER (1978a-b). The concept was later developed for technological application in industry, in the 1980s, by the LINNHOFF group in the University of Manchester (UMIST) in England.

Application of the *Pinch* analysis was presented in various works found in the literature, especially LINNHOFF *et al.* (1982), which describes the method in detail, being complemented by later works, such as LINNHOFF and HINDMARSH (1983), and LINNHOFF and AHMAD (1990).

Applying this method for improving usage of energy in industrial processes is the most explored alternative in studies carried out so far, though many advances have been made in other applications.

Based on analogies to the same concept, the methodology was expanded, relating transfer of heat by temperature difference to transfer of mass by difference of concentration of a certain component. This is how *Mass Pinch* (EL-HALWAGI, 1989-1990) started being used, with application in industrial processes where there are mass transfer units, such as absorbers, extractors, evaporators, distillation columns etc.

One specific application of the *Mass Pinch* concept was developed for industrial effluents treatment and waster intake reduction, evaluating possibilities for reusing, recovering, and recycling this resource. This methodology, named *Water Pinch* (WANG, 1994a-b), can also be applied to the distributed effluents treatment.

According to GUNDERSEN (2000), more recently the *Pinch* concept was applied to the so-called *Hydrogen Pinch*, developed by TOWLER *et al.* (1996), and ALVES (1999). This methodology is applied to the analysis of the distribution of hydrogen in petroleum refineries, optimizing its use, and evaluating the introduction of purification units, membranes, and cryogenic units.

Thermal process integration analysis

Pinch analysis applied to thermal integration is basically carried out in four separate phases:

- data collection on the process energy requirements and available utility systems;
- goal-setting, involving the definition of optimum performance relative to various project aspects;
- initial heat exchangers network design;
- project optimization with layout streamlining and analysis of issues such as operation ability, control, safety, and search for the minimum overall cost.

Data gathered should include the following information on existing flows in the process and utility system:

- mass flow rate;
- specific heat at constant pressure;
- initial temperature;
- final temperature;
- specific vaporization enthalpy for flows changing state;
- hot and cold utility operation temperatures available;
- heat transfer coefficient for each flow.

Having defined the problem and the data gathered of the process flows and utility systems, it is possible to move on to a preliminary analysis of the potential for thermal process integration, by determining consumption targets.

In the heat recovery area, the concept of goals is used in determining the minimum energy consumption, quantity of heat exchange equipments, total heat exchange area, and total cost.

TABLE 6 Optimized costs of the energy recovery system for the different cases.

Cases	Economizer [US$]	Air preheater [US$]	Dryer [US$]	Total cost [US$]
I	486,047	60,861	–	546,908
II	–	547,930	149,020	696,950
III	144,608	79,883	149,020	373,511

Some goals, such as energy consumption, are based on thermodynamic concepts, while others, such as quantity of heat exchange equipment, are based on heuristic rules.

In addition to the aforementioned goals, some others, like minimum generation of effluents and emissions and maximum power generation are applied; however, in all cases, under the assumption that no actual project can surpass the optimum performance obtained in such analysis, being it, in most cases, a guide to the most appropriate design.

Utility consumption goals – Table Method (Heat Cascade)

Definition of the minimum utilities intake goal may be calculated from the Table Method construction introduced by LINNHOFF and FLOWER (1978), which determines the so-called heat cascade.

This method starts by defining temperature ranges in which hot and cold flows involved in the process may exchange heat. In order to maintain the minimum temperature gap (t_{min}), preset for implementing the analysis method, temperatures in each range are determined, adding a $t_{min}/2$ value for cold flow temperatures, and subtracting a $t_{min}/2$ value for hot flow temperatures.

Temperatures are sorted in descending order, creating ranges where process flows may be ranked according to their initial and final temperatures, as shown on Figure 6.

Hot and cold flows fitting into the same temperature range have their thermal capacities (mcp) added, providing a sum for each range, considering a positive value for cold flows, and a negative one for hot flows.

This enables to build the thermal cascade, considering that the heat in each temperature range is transferred to the adjoining lower range. If there is a negative result for the energy balance at a certain range, the use of hot utilities should be prescribed. Likewise, if the result is negative, this quantity of heat may be transferred to the lower range, and so on, creating the heat cascade.

By implementing this procedure, it is possible to calculate the minimum hot and cold utilities demand in the system. The *Pinch Point* location can be so identified in the temperature range where there is no heat transfer to the next range, and where there is no demand for hot utilities.

Composite Curve

Visualization of results in graphic format by plotting Composite Curves – CCs is one of the major tools in this method, making it possible to ascertain, in a practical and simple way, the possibility of thermal integration, and the need for hot and cold utilities.

Like in the Table Method calculations, CC plotting for hot and cold flows is based on the distribution of process flows over temperature ranges. One curve for hot flows and another for cold ones may be drawn adding the enthalpy variation of the flows within each range, as shown on Figure 7, which also indicates areas where a possible thermal integration may be implemented, as well as the needs for hot and cold utilities, located on the graph extremities.

The value adopted for t_{min} defines the smallest distance between the two Composite Curves drawn, identifying the energy bottleneck, or *Pinch* that will divide the system in two parts, one below, and another above this point. This point limits the process thermal integration, representing the bottleneck from the energy recovery standpoint.

			Interval		1		2		3		4		5	
										Pinch Point				
Current	**Enthalpy (k-W)**	**mcp (kW/°C)**	**Temp. (°C)**	**165**		**145**		**140**		**85**		**55**		**25**
F1	700	6.09	Fria					◂	–	–	–	–	–	•
F2	500	8.33	Fria			◂	–	–	–	•				
Q1	700	5.83	Quente			•	–	–	–	–	–	–	–	▸
Q2	300	2.73	Quente	•	–	–	–	–	–	–	–	▸		

Source: ENSINAS, 2008.

FIGURE 6 Example of temperature ranges, indicating process flows.

The area above the *Pinch* will act as a heat absorber, consuming hot utilities. On the other hand, the region below this point will act as a heat source, requiring only cold utilities.

The separation of these two regions is important, as if cold utilities are consumed above the *Pinch*, it will be necessary to add even more hot utilities to supply the additional intake, increasing its energy demand, and consequently the energy consumption by the system as a whole.

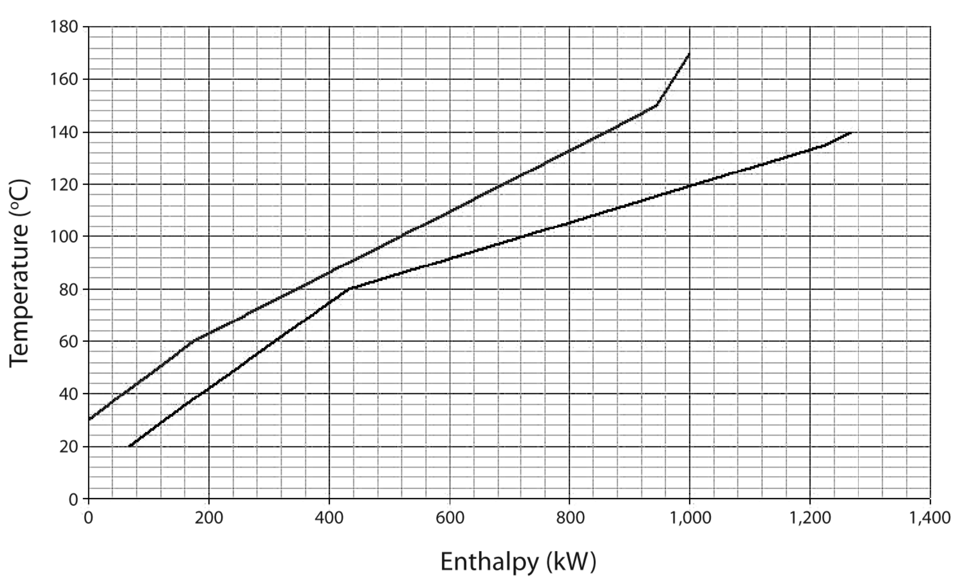
The same occurs at the region below the *Pinch*, where the addition of hot utilities implies in using cold utilities to supply the additional cooling requirement.

Thus, some basic application principles were set for the method, in order to avoid unnecessary use of hot and cold utilities:

- Do not use cold utilities above the *Pinch*.
- Do not use hot utilities below the *Pinch*.
- Do not transfer heat through the *Pinch*.

Great Composite Curve

The Great Composite Curve – GCC is yet another graphic tool for visualizing the minimum



Source: ENSINAS, 2008.

FIGURE 7 Composite Curve example

utility intake issue. This graphic representation combines the Hot and Cold Composite Curves into one, being also plotted by summing up their heat capacities at each temperature level.

Like CCs, the GCC representation is plotted on a temperature-enthalpy diagram, displacing the Hot Composite Curve to a value $\Delta t_{mín}/2$ below and the Cold Composite Curve to a value $\Delta t_{mín}/2$ above its original position, so that the two curves intercept at the *Pinch Point*.

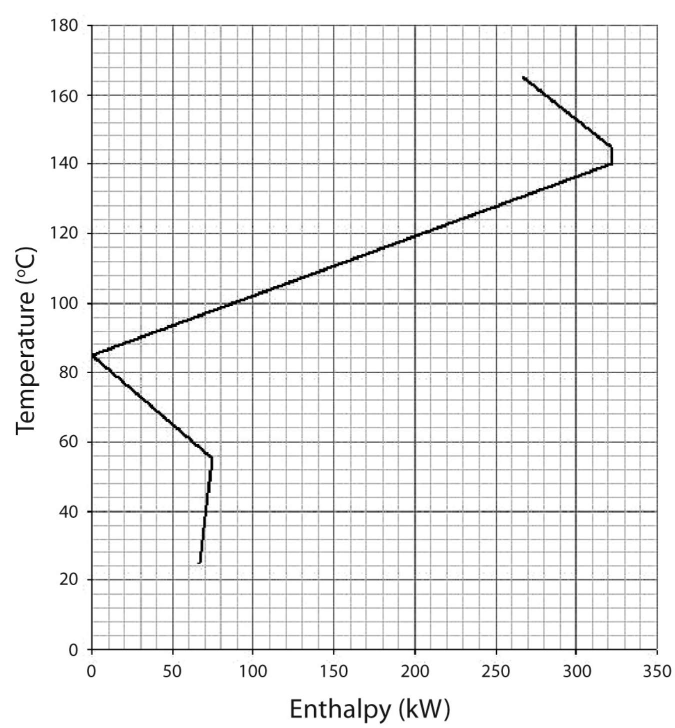
The GCC is obtained with the difference of enthalpies on Hot and Cold Composite Curves for each temperature level. *Pinch Point* is located at the point where the difference in enthalpies between the CCs is zero, as shown on Figure 8.

Hot utility requirements above the *Pinch Point*, and cold ones below it may be seen more clearly on the GCC, just as the regions where thermal integration is possible.

Furthermore, one of the main advantages of the GCC is the identification of the proper temperature level of utilities to be used, minimizing process irreversibility in the heat exchange process, and allowing the evaluation of using lower cost utilities.

By using the GCC, viability of equipment integration, such as evaporators, distillation columns, heat pumps, and steam turbines with the remainder of the process can be analyzed in detail, identifying the best applications from the energy savings standpoint. GUNDERSEN (2000) presents some basic conditions for integrating such equipments to the remainder of the process:

- ***Distillation columns:*** only if the reboiler operates at a temperature below the *Pinch Point*, or if the condenser works at a temperature above it.
- ***Heat pumps:*** only if they transfer heat through the *Pinch*, from the region below it to the region above. They should be integrated to distillation columns only if there is no possibility of integrating the columns into the process, since the implementation cost of a heat pump is usually higher than the other option.



Source: ENSINAS, 2008.

FIGURE 8 Composite Curve and Great Composite Curve example.

- *Steam turbines (back-pressure or extraction):* only if the exhaust or extraction steam has a sufficiently high condensation temperature to be used above the *Pinch*, or in the reboiler of a distillation column. Otherwise the steam should be expanded to its maximum in the condensation turbine for better energy use.

Initial heat exchangers network design

The strategy for the initial design of a heat exchangers network should have its origin close to the *Pinch Point*, where the most critical heat exchange between process flows takes place. Then the design proceeds towards the regions more distant from the *Pinch*, always ensuring that hot flows be used above it, and the same happens to cold flows in the lower region.

According to GUNDERSEN (2000), as a rule for heat exchangers located above the *Pinch*, it should be ensured that the "mcp" for cold flows be equal or higher than the "mcp" for hot flows with which they exchange heat, and that the number of cold flows be equal or larger than the number of hot flows.

Likewise, below the *Pinch Point*, the hot flows "mcp" should be higher or equal to that of cold flows with which t exchanges heat, and the total number of hot flows should be higher or equal to the number of cold flows.

If the rules above are not followed, flows should be split to achieve maximum heat recovery. Though the application of the *Pinch* method eliminates some clearly disadvantageous alternatives from the energy standpoint, there are usually several possibilities for the initial heat exchangers network design. Flow splitting usually allows more heat recovery between them; however, in some cases, there is a reduction of the total area required for heat exchange, or yet a reduction in the quantity of heat exchangers.

Advances of energy integration in sugar and ethanol production

The sugar production process presents, over its history, important technological advances relative to the use of energy. According to CHRISTODOULOU (1996), a first breakthrough was achieved by Antony Smith in 1692, upon ascertaining the possibility of using steam for evaporation instead of direct fire, as it was used until then. In 1813, Howard introduced evaporation at lower pressures, and in 1828, the tubular cooker.

However, the innovation actually considered as a milestone in world energy savings in the sugar and chemical industries was the multiple-effect evaporation system conceived by Norbert Rilleaux in 1832, which only obtained its patents in 1843, for the double-effect system, and in 1846 for triple-effect. In 1850, Robert introduced evaporators with vertical tubes that carry his name and are still used nowadays in the sugar industry

With the introduction of diffusion systems for making sugar from beets in 1870, a demand for more efficient evaporation systems appeared, as the further dilution of the juice required by this process required a higher energy consumption to concentrate it.

Technological innovations continued with the evolution of evaporators. New systems with more effects and different operating principles were developed. Descending plates and film evaporators are increasingly seen as alternatives for a more efficient concentration process. "Recompression" techniques applied to evaporation has also been explored since 1945 (VERNOIS, 1975 apud CHRISTODOULOU, 1996).

The integration of such equipments with the remainder of the process has also been studied, applying process integration techniques, which allows improving the use of primary energy. Analyses based on energy, exergy, or thermoeconomy concepts are tools that make it possible to evaluate improvements achieved with process integration, possibly complementing the integration study.

Some works are found in literature, pointing the best process integration options in sugar production by using the *Pinch* method.

The sugar from beets study was carried out in some works, like TWAITE *et al.* (1986) which analyzed the design of a British sugar mill using the *Pinch* analysis as assessment tool for the possibility of reducing the energy consumption in the plant. The introduction of six evaporation effects, replacing the five-effect system, with mechanical vapor recompression (MVR) on the first effect, was one of the proposed modifications, as the existing system was less effective in terms of reduced vapor intake. *Pinch* analysis made it possible to identify the process deficiency, especially the improper use of MVR.

CHRISTODOULOU (1996) analyzed, using the *Pinch* method, modification proposals on

works related to thermal integration in sugar from beets mills. The use of six and seven evaporation effects with falling film evaporators and plate heat exchangers were prescribed as viable and promising alternatives to reduce steam consumption in these processes.

Other studies are found in literature evaluating sugar production from sugarcane. FRANCO (2001) evaluated the integration of the evaporation system integration to the remainder of the process using the *Pinch* method, analyzing evaporators located above and below the *Pinch Point*.

REIN (2007) presents some opportunities for reducing process steam consumption in sugarcane mills, making it possible the generation of surplus bagasse in the co-generation system. From the issues raised, the following may be pointed out: the increase of the syrup Brix, leading to a higher steam intake in evaporation, however, reducing the consumption in the cooking stage; the use of vegetal steam of 1^{st}, 2^{nd}, or even 3^{rd} effect to supply the demand from cookers; the reduction of the use of water added to cookers and centrifuges; the increase in the number of evaporation effects; the use of condensates and vegetal steams to heat up mixed juice at the treatment stage, and the increase in the operation temperature in evaporators, allowing better use of steam bleeds in the process.

UPADHIAYA (1992) also presents some suggestions for steam saving, aiming to increase the production of electricity generated in sugarcane mills, including the maximization of vegetal steam bleeds and the use of continuous cookers.

WESTPHALEN (1999) developed a mathematical model for static and dynamic simulation of evaporation systems, evaluating the number and setting of the effects, feed temperature, condensate utilization and thermal “recompression”, however without including system integration to the remainder of the process.

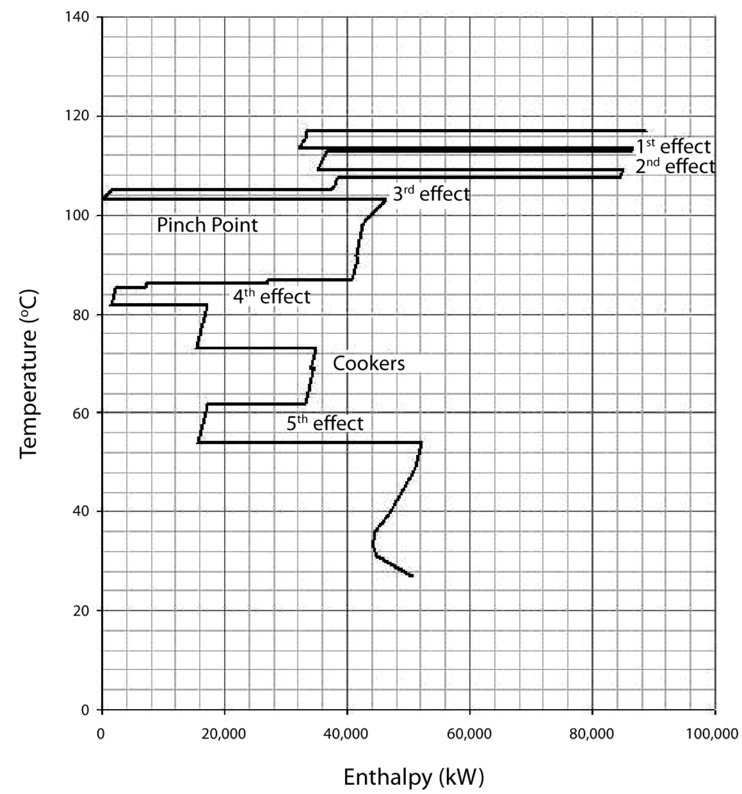
Energy integration of sugar and ethanol mills from sugarcane was studied in detail by ENSINAS *et al*. (2007a-b, 2008). The authors developed a mill energy integration procedure through the *Pinch* Method and thermoeconomic optimization that allows to determine which is the best use for the thermal energy available in the process flows, including vegetal steam bleeds, juice, mash, wine and stillage flows, on top of the energy from distillation and rectification columns. Studies show that important steam consumption reductions may be achieved without jeopardizing final costs, as economic criteria are considered, such as equipment costs for deciding upon integration options.

Figure 9 shows the profile of the Great Composite Curve for a thermally integrated mill with processing capacity of 500 tons of sugarcane per hour, directing 50% of the sugars for sugar in lump, and 50% for ethanol production. The analysis of this curve points out the major sources of heat available in the process, as well as the most interesting thermal integration regions from the energy standpoint.

HIGA (1999) also applied *Pinch* analysis and optimization techniques in the design of evaporators for sugar and ethanol mills, verifying the effect of reduced steam consumption upon shifting the bleeds to the last evaporation effects. In a later study, HIGA (2003) applied the *Pinch* analysis to the same process, aiming to increase the electricity surplus generated in the co-generation system.

Other works focused on ethanol distillation and dehydration stages, such as GUIMARÃES *et al*. (1996), who used thermal integration concepts to minimize utilities consumption in synthesizing a water-ethanol separation system through azeotropic distillation. MELO *et al*. (1998) also researched to reduce the energy intake of the extractive distillation process to obtain anhydrous ethanol.

Thermal integration of distillation columns is also analyzed by SEEMANN (2003), showing that the operation of distillation and rectification columns at different pressures, and the use of the condenser in the second column as reboiler for the first provide a significant reduction in steam intake.



Source: ENSINAS, 2008.

FIGURE 9 GCC of a thermally integrated mill.

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