



## Performance of Plate Heat Exchangers compared to Shell and Tube Heat Exchangers

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**Abstract.** *In this article we seek to demonstrate the advantages of using the plate heat exchanger opposed to the shell and tube heat exchanger in a sugarcane mill. It was a comparative study regarding the balance of mass and energy in the thermal treatment of sugarcane juice for fermentation systems using this type of equipment. The methodology is based on the calculation of the overall coefficient of heat exchange for each device, as well as the thermal balance. Due to the constant pursuit of improvement in industrial productivity, companies have sought to increase the performance of their equipment to achieve these goals. Thus, the balance of mass and energy in high energy consuming components such as evaporators and condensers has attracted the attention of industrial managers, since it is known that a small gain in efficiency implies high sum of funds. In this plant, which recently installed a new heat exchange system and now two plate heat regenerators instead of a multi-jet system, there was a gain providing significant savings in the consumption of bagasse, which generates income for the company. Given the current global concerns with environmental preservation and sustainability, in addition to economic gains, we are confident that this work will have a major contribution to the academic, industrial and environmental sector.*

**Keywords:** *plate heat exchanger, shell and tube heat exchanger; thermal efficiency; sugarcane mill; sustainability.*

### 1. INTRODUCTION

This work was developed with a company engaged in the biofuel industry, being one of its units sugar and alcohol producer. The unit is responsible for processing annually 4.1 million tons of sugar cane, producing 420,000 tons of crystal sugar, 160,000 cubic meters of alcohol, 2,270 tons of yeast for animal consumption and cogeneration of 1.5 Million MWh of electricity.

Among the various stages of the manufacturing of ethanol from the point of view of energy, the thermal treatment of the fermentation juice is one of the most important bearing in mind that the more complete the heat treatment, the greater the tendency to increase the efficiency of fermentation, and thus higher production of alcohol per ton of sugar.

The juice for the production of ethanol is heated at 105 °C to 108 °C to promote the fermentation by making a sterilization of bacteria and wild yeasts that compete with the yeast fermentation process. Once heated, the juice is cooled to a temperature of 32 °C and sent to fermentation tanks. To heat the juice it is used steam from the boilers, consuming large amounts of water, bagasse and financial resources.

Given that there is currently a major concern in preserving the environment, particularly natural resources, there is a responsibility to deploy solutions that seek sustainability and continuous improvement of processes, providing business profitability. According to this policy of sustainability, this study sought to conduct a balance in the thermal treatment of the juice for fermentation, presenting the results obtained with a plate heat exchanger, compared with the previous project, showing the energy savings and demonstrating how the new project was profitable for the company.

### 2. HEAT EXCHANGERS

According Incropera & Dewitt (2002), heat exchangers are devices used to transfer heat from a liquid or gaseous substance into another kind of substance, which may or may not be in direct contact. These machines are widely used in thermal industries in general, for example, in heating and cooling of environments, cooling towers, heat recovery, etc.. The heat exchangers are classified according to the nature of the transfer and type of construction.

About the nature of the transfer, the heat exchangers can have direct or indirect contact. Regarding exchangers in direct contact, the fluids come in direct contact with each other; thus, making the hot fluid yield heat to the cold fluid ,

transferring each other a lot of mass and energy. The construction of such a heat exchanger compared to the indirect contact heat exchangers is generally less expensive; therefore, their use is very limited due to the majority of cases where the mixing of the fluids involved in heat exchange is not permitted.

When using heat exchangers in indirect contact there is always a solid surface which prevents direct contact between the fluids. These surfaces are usually made of metal, for they allow better heat exchange. In this type of heat exchanger, there is a constant exchange of heat energy, where the hot fluid transfers heat to the cold fluid through a wall which prevents contact between both. As for construction, heat exchangers may be classified into two types: tubular and plates (Duarte, 2012).

## 2.1 Tubular Heat Exchangers

The tubular exchangers can be subdivided into: double pipe, shell and tube and coil, (Stoecker and Jones, 1985).

➤ Double tube: This exchanger comprises two concentric tubes of different diameters. Inside the inner tube passes one of the fluids and in the space between the inner tube and the outer tube passes the other fluid. The use of this heat exchanger is very limited due to the small area of heat transfer, Fig. 1.

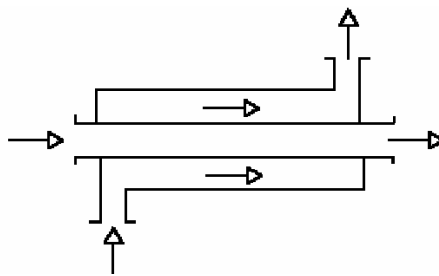


Figure 1: Representation of a double tube heat exchanger.

➤ Coil: it is formed by a tube "wrapped" in the form of a spiral. These heat exchangers enable a larger heat exchange area than the double tube heat exchangers, Figure 2.

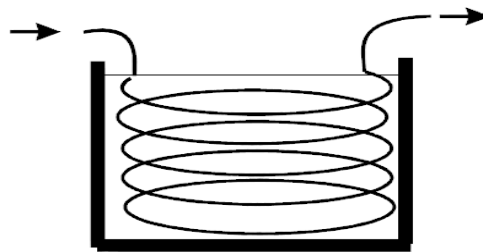


Figure 2: Representation of a type exchanger coil.

➤ Multi-tubular: equipment are basically composed of a bundle of tubes surrounded by a shell, called the hull. Basically, the principle of operation is simple: one fluid bathes the outside tube and the other fluid flows inside the tubes, Figure 3.

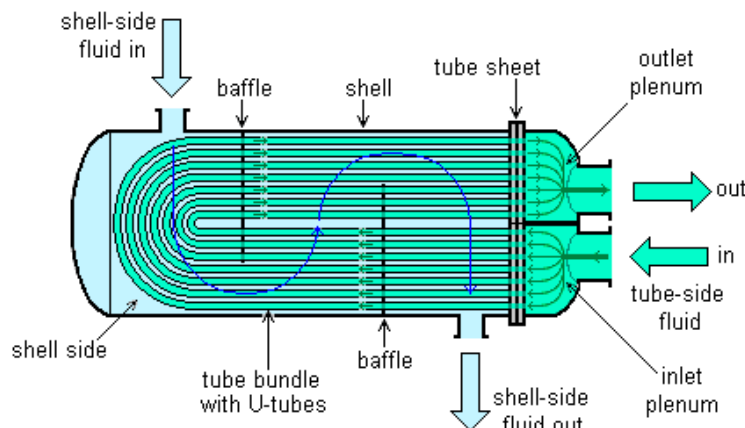


Figure 3: Representation of a multi-tubular exchanger.

## 2.2 Plates Heat Exchangers Type

The plate heat exchanger is a device formed by stacking plates, smooth or corrugated sheets of the same size, compressed by tie rods on a pedestal with port holes for the passage of the two fluids between which the heat transfer will occur. The sealing of the plates is made by gaskets, that are glued or attached to each pair of plates. The advantage of using plate exchangers is the space saving, flexibility to increase or decrease the area of heat transfer, high thermal efficiency and ease to perform cleaning and maintenance. Due to the extensive use of gaskets there is a limitation of pressure and temperature. There are three other different types of plate heat exchangers: spiral, slide and PCB. This work will consider only the heat exchanger plates with gasket, Fig 4.

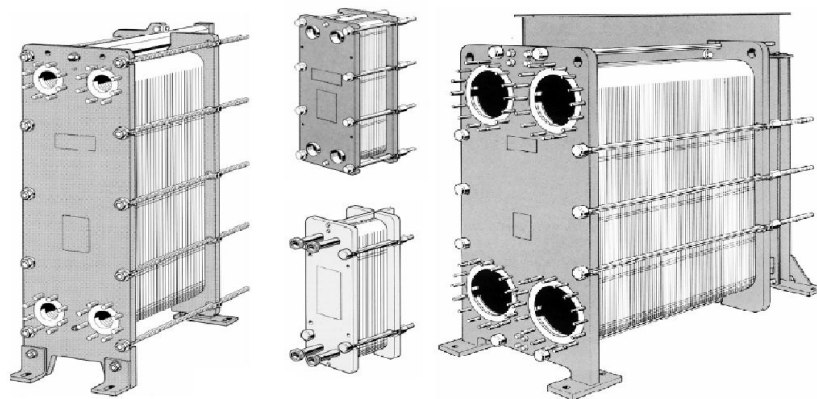
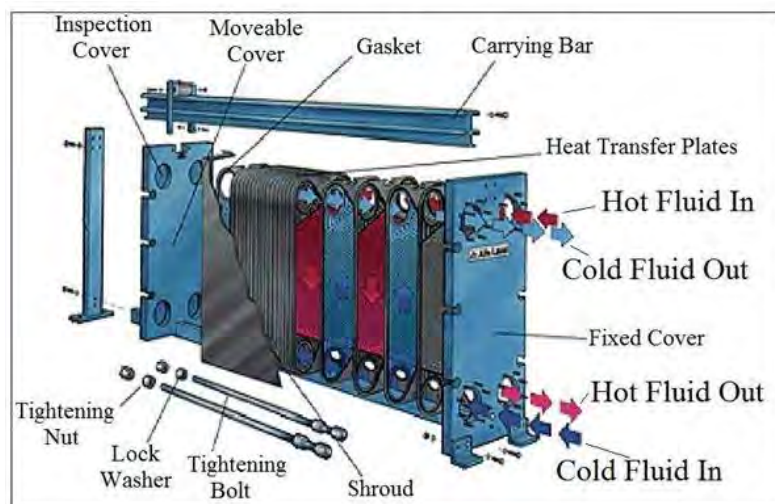


Figure 4: Representation of different models of the exchanger plates (Gut, 2003)

The plate heat exchangers are constructed with a certain amount of corrugated metal plates, which form channels for the flow of the fluid, with a thin depth, grouped in sets mounted on a pedestal of carbon steel and sealed at each end by seals, called gaskets. Due to the strategic position of the gaskets, the fluid flows alternately between the plates. In the plate heat exchangers, heat exchange occurs through the thin plate heat exchanger, Figure 5.



### Plate and Frame Heat Exchanger Parts

Figure 5: Main parts of the heat exchanger plates and gaskets (Gut, 2003).

The main components of a plate heat exchanger are:

➤ **Pedestal:** comprising a structure plate (fixed), pressure plate (mobile), top and bottom bus, clamping screws, connections and support column. The structure plate serves as a support for abutting heat transfer plates. On the other hand, the pressure plate is movable and slides over the top bus during the opening or closing of the exchanger. The clamping screws have the function of compressing the heat exchange plates together. The connections are holes in the

frame plate or pressure plate, allowing access of the fluid to the heat exchanger. The top bus houses the heat exchange plates and the pressure plate; the bottom bus maintains the extremities of the heat exchange plates supported and aligned.

➤ plates: the plates are generally rolled metal, usually stainless steel AISI-316, but other ductile metals such as titanium may be employed, Hastelloy C-276TM, Incoloy 825TM, Nickel 200, Copper / Nickel, Monel 400TM, Inconel 600TM, aluminum -Brass or Tantalum (Gut, 2003). The plates are corrugated and profiled through the forming and pressing process. The plates have grooves that give them great dimensional rigidity, and even a small flow causes high turbulence, providing high values of heat transfer. The outer edges of the plates have a channel, where the gaskets are fixed or bonded. The plates of the exchanger have two types of corrugation: herringbone or chevron and interlocking (washboard). The type of corrugation and the inclination angle of the grooves have great influence on the thermal and hydraulic performance of the equipment (Gut, 2003). The chevron type plates are the most used. The chevron type plates are aligned alternating the direction of the grooves, so that it permits the formation of several points of contact between the compression plates, Fig. 6 (Gut, 2003).

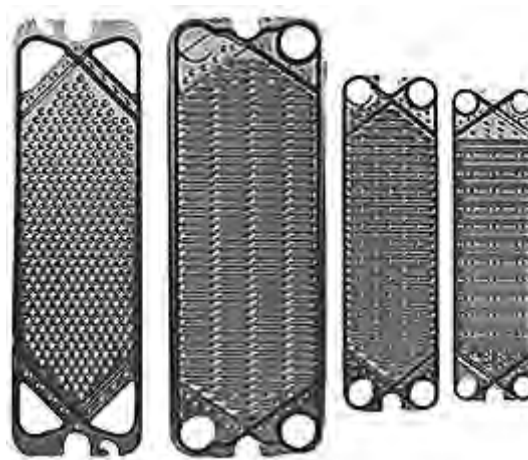


Figure 6: Diagram of a plate showing the flow channel formed by the gasket (Gut, 2003).

Gaskets: are joints, glued or embedded, to perform the sealing of fluids that circulate between the plates. The gasket materials are generally nitrile or butyl rubber and elastomer. The gaskets are placed in positions with the nozzles sealing switched to allow the passage of fluids between the plates, alternating hot fluid and cold fluid. The restrictions on the use of plate heat exchangers are due to the limitations of temperature and pressure that the gasket can withstand. Generally, the maximum temperature permitted is 150 ° C, but with the use of special gaskets it can operate up to 250 ° C (Gut, 2003). The heat exchangers have some typical characteristics of use and, despite its versatility as to the use, they have operating limits. In table 1 are presented the corresponding characteristics and operating limits.

Table 1: Typical characteristics and limitations of operations for plate heat exchangers (Gut, 2003).

|  | Shah and Focke (1988) | Usher (1992b) | Hewitt et al. (1994) | Kakaçu and Liu (2002) |
|--|-----------------------|---------------|----------------------|-----------------------|
| Pressure (bar)                                   | 1 to 25               | until 20      | until 25             | until 25              |
| Temperature (°C)                                 | -40 to 260            | until 250     | -25 to 175           | until 160             |
| Flow (m <sup>3</sup> /h)                         | until 2500            | until 2500    | until 2700           | until 3600            |
| Surface (m <sup>2</sup> )                        | until 2500            | until 1500    | 1 to 1200            | 0.1 to 2200           |
| Number of plates                                 | 3 to 700              | -             | until 700            | until 700             |
| Thermal change coefficient (W/m <sup>2</sup> .K) | 3000 to 7000 (water)  | -             | 171 to 4171          | 3500 to 7500          |

There are two types of possible configurations for a plate heat exchanger regarding the number of passes: single pass, and multi-pass Fig. 7, Fig 8. As for the type of flow the exchangers are classified into parallel streams and crossed streams.

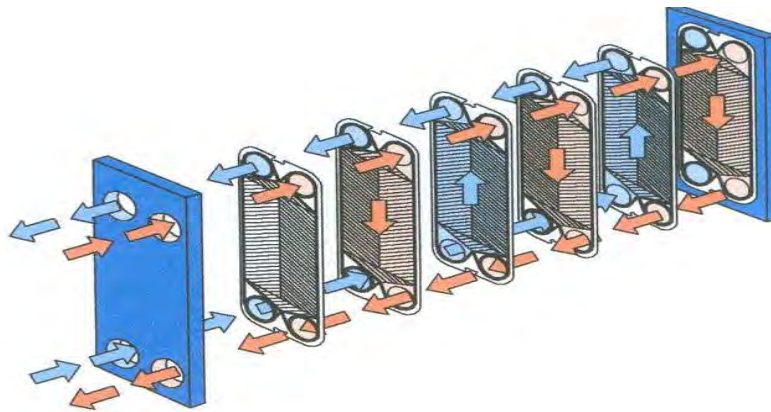


Figure 7: Arrangement of the single pass plate exchanger with crossed streams.

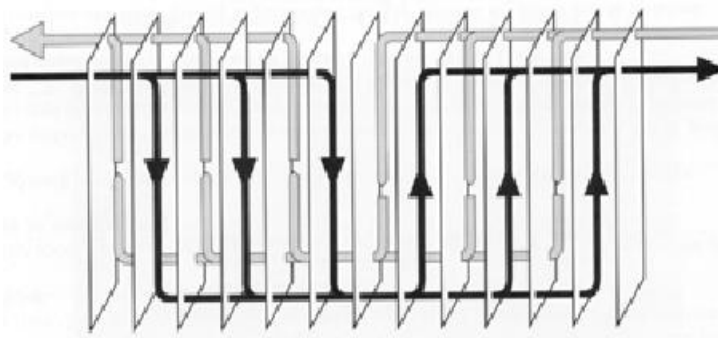


Figure 8: Arrangement of the multi-pass plate exchanger with crossed streams.

The exchanger studied in this work has the following settings: multi-pass and operates on the principle of countercurrent. In this configuration, the mixed juice from the mill (cold fluid) is pumped through the pipe to the heat exchanger (ZOCCA, 2011).

The juice to be heated enters the exchanger plates through the mobile column, through the connection. The output of the liquid, in this case of multi-passe arrangement, is by the fixed column. The preheated mixed juice, after being directed to a tank, is pumped to the heater to be heated to a temperature of  $108\text{ }^{\circ}\text{C}$ . After heating, the juice goes to the settling tank equipment responsible for the separation of impurities from the juice. After the juice is clarified, it is sent back to the plate heat exchanger where it will exchange heat with the mixed juice. The hot juice comes in counter-currently through the front of the heat exchanger, flows through the plates exits from the mobile column and goes to the distillery, where it will again be cooled to a temperature of  $32\text{ }^{\circ}\text{C}$ . The operating pressure is generally 3 to  $6.5\text{ kg/cm}^2$ . The flow of cold fluid is generally equal to the warm fluid.

Regenerators are heat exchangers that take energy from a hot fluid that would be cooled anyway to heat a cold fluid that should be heated. The regenerative heat exchanger in this study is a plate heat exchanger. It has 90 corrugated plates, manufactured using Alloy 316. The thickness of the plates is 0.60 mm. The gaskets are made of EPDM Glued. The pressure during operating and testing (performed by the manufacturer) is 10.0 bar and 13 bar, respectively. The dimensions of the heat exchanger plates are  $2160 \times 1154 \times 3210\text{ mm}$  (length, height and width), comprising a heat exchange surface of  $166\text{ m}^2$ . The configuration of the plate heat exchanger regarding the number of passes is multi-pass, as to the fluid flow, counter-current.

When the distilling process is in operation only one heat exchanger is in use, allowing the other exchanger to be cleaned on the site, called CIP (Clean-In-Place). The cleaning of the heat exchanger, which occurs every eight hours, is performed with clarified water heated to  $90\text{ }^{\circ}\text{C}$  re-circulating in a closed circuit in a tank through a pump.

The mixed juice (cold fluid) from the mill is pumped to the plate heat exchanger, being preheated from  $55\text{ }^{\circ}\text{C}$  to  $80\text{ }^{\circ}\text{C}$  and sent to the juice heaters. This heating is given by the clarified juice (hot fluid) which, after being heated to a temperature of  $108\text{ }^{\circ}\text{C}$ , passed by decantation and screening process, is pumped back to the regenerator at approximately  $96\text{ }^{\circ}\text{C}$  exchanging heat with the mixed juice. After the heat exchange, the juice will exit the exchanger with a temperature of  $70\text{ }^{\circ}\text{C}$ . The reduction in temperature of the clarified juice of  $108\text{ }^{\circ}\text{C}$  to  $96\text{ }^{\circ}\text{C}$  is due to the passage of the heated juice through the decanting and screening processes, thereby losing  $12\text{ }^{\circ}\text{C}$  to the environment.

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The plate heat exchangers of the must are responsible for the final cooling of the juice that comes from the regenerator. The clarified juice enters the heat exchanger at a temperature of 70 °C and is cooled to a temperature of 32 °C, the ideal temperature for the fermentation process. The must heat exchanger has 186 plates made of AISI 316 stainless steel with a thickness of 0.50 mm, and the thermal exchange area of 99.2 m<sup>2</sup>. Operates on the principle of counter-current and single-pass.

The cooling fluid in this heat exchanger is water from a cooling tower, which is constantly replenished by the water abstracted from a dam. The cooling tower, which operates in closed circuit has three sections, in each one there is an extractor responsible for removing heat from the water. The must cooling system consists of six plate exchangers, and during the process only three exchangers are in operation, while the other three are undergoing CIP, which is the sanitizing process responsible for eliminating part of bacteria and microorganisms that would compete with the yeast, or the exchangers are kept for manual cleaning.

The operating exchangers work in parallel, in which the juice coming from the regenerator is evenly distributed by a feed ring, and with the aid of an automatic valve, the juice is distributed into the three plate exchangers. After the thermal exchange, the juice is sent to fermentation tanks, which are already with the "tub foot", thus beginning the fermentation process.

### 2.3 overall coefficient of heat transfer

The overall coefficient of heat exchanges, based on the external area,  $U_e$ , is given by Equation (1), (ASHRAE, 2004):

$$\frac{1}{U_e \cdot A_e} = \frac{1}{h_i \cdot A_i} + R_{cond} + \frac{1}{h_e \cdot A_e} + R_{inc\_1} + R_{inc\_2} \quad (1)$$

For the laminar flow of fluids inside tubes, the formulations listed below, as Singh and Heldman (2009), are applied to the calculation of the overall coefficient of heat exchanges by convection. For Graetz number less than 100, we have Eq (2):

$$Nu = 3,66 + \frac{0,085 \cdot Gz}{1 + 0,045 \cdot Gz} \left( \frac{\mu}{\mu_w} \right)^{0,14} \quad \text{para } Gz < 100 \quad (2)$$

For Graetz number greater than 100, we have Eq (3):

$$Nu = 1,86 \cdot Gz^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0,14} \quad \text{para } Gz > 100 \quad (3)$$

The Graetz number is given by equation (4):

$$Gz = Re \cdot Pr \cdot \frac{D}{L} \quad (4)$$

The fluid properties must be taken in the average temperature of the mixture. The formulas can be used for non-circular section ducts, with the application of the equivalent hydraulic diameter. The generic formula applied to the turbulent flow of fluids inside the tubes, taking into account the actual conditions on the resistance layer (ASHRAE, 2004), is the equation (5):

$$Nu = 0,023 \cdot Re^{0,8} \cdot Pr^{1/3} \left( \frac{\mu}{\mu_w} \right)^{0,14} \quad (5)$$

### 3. MASS BALANCE IN MILLING

According Hugot (1977), PCI sugarcane bagasse is given by Eq (6):

$$PCI = 4,1868(4250 - 12Pb - 48,5Ub) \quad (6)$$

The necessary amount of pulp to feed the boiler and generate the steam required for the process, which relates specific consumption of bagasse into a high pressure boiler and the steam flow rate is given by the following equation (7):

$$Wb = \frac{Wv.(hv-ha)}{PCI} \quad (7)$$

The juice used in the fermentation is the mixed juice, i.e. the broth to which is added water during the extraction. For a good discussion of the presented work the balance of the mass in the mill is performed, in order to show the composition of the juice that will undergo heat treatment. Thus, it is calculated the amount of mixed juice extracted per ton of sugarcane, the amount of mulch and moisture bagasse obtained at the output of the mill and the calorific value of bagasse.

The amount of residue generated in the extraction of the juice is expressed by the following equation (8):

$$Wb = \frac{Wc.Fc}{100-(Ub+Polb)} \quad (8)$$

The final bagasse obtained in the last grinding process is very useful during the process of steam generation. The same serves as boiler fuel, thus generating steam that, in a work chain, which will produce steam to heat the mixed juice. Therefore, it is possible to obtain the mass balance in the mill, this balance will indicate the amount of juice that is available to manufacture the sugar and ethanol, whereas for the manufacture of ethanol is used a small volume of juice due to the use of final molasses which has a high content of sucrose (FERNANDES, 2003). The heat treatment of the juice is of utmost importance for the production of alcohol, whereas if the heat treatment is good, there will be a smaller amount of impurities in the juice, and the fermentation will be best conducted. Usually in the sugarcane plants the heat treatment of the juice for the production of alcohol is almost the same thermal treatment of the juice for the manufacturing of sugar. The difference between the two processes is by not having the addition of lime and sulfur in the juice, because these chemicals are harmful to fermentation. The function of the juice heat treatment sector is basically to pasteurize the juice by heating it at 108 °C and rapidly cooling it to 32 °C (TDI et al. 1990). Temperatures above 108 °C can cause emulsification of the waxes present in the juice, thus hindering the separation of impurities. Temperatures below 105 °C would not cause complete sterilization of the juice.

#### 4. DISCUSSION OF THE RESULTS OBTAINED

To obtain the results of the thermal balance, we used some variables contained in the company's industrial bulletins and laboratory tests that are performed periodically. In some cases the variables are collected using instant measurers that are available in the field or in supervisory equipment. Some variables that were not identified in the industrial bulletins or laboratory analysis were obtained through periodic samples collected at strategic points in order to get results closer to the reality, ensuring the accuracy of the calculations presented in the work. The present calculations are based on flow measurers, temperature transmitters found in the equipment and the equipment manuals. The incrustations in the pipes and in the heat exchange plates won't be considered, whereas the values of the calculations presented are regarding the equipment after cleaning. The temperature of the mixed juice after leaving the mill and that enters the regenerator is 55 °C. The juice has this temperature due to the fact that the water used in the soaking is condensed water with temperature of 95 °C. This juice is also called secondary juice. To validate the gains from the change of equipments, we calculated the overall coefficient of two heat exchangers with the same thermal capacity, obtaining a significant difference compared to the plate heat exchanger.

##### 4.1 Analysis of the old system and of the gains from the current system

The heat treatment of the juice was formerly composed of the following equipment: heater, multi-jet and must heat exchangers. The old system had some deficiencies such as:

- all the heaters were in operation to raise the temperature of the juice from 55 °C to 105 °C, hindering the cleaning.
- The multi-jet cooling system performed by high vacuum generated extremely high sucrose drags, reducing the efficiency of the process.
- high consumption of steam to heat the juice, whereas after heating the juice, its energy was not used.

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Due to the high costs in the generation of heat energy, we designed a project to reuse the heat that would be lost by the process fluids. With the fluids passing through the exchanger alternately, the hot fluid gives off heat, and the cold fluid gains the amount of heat transferred and is heated to a point where it will require a small amount of power to achieve the desired temperature. The project evaluated by the board of the company with the highest heat gain was the regenerator plate exchanger, being implemented in the process phase. The feasibility of the retrofit process is shown in the efficiency gains of the proposed system, since there was a monthly saving of R \$ 56,376.00, with payment of the capital in 16 months. Considering the operation time of one month, running 24 hours a day, the cost of the bagasse would be R \$ 18,00 / ton.

Thus, during the harvest month, the plant saves R\$ 56,376.00 in bagasse that would be used in boilers for heating the juice from 55 ° C to 108 ° C. With regenerator plate exchanger, it is possible to obtain a gain providing great capital savings. Therefore, there was a considerable economy of bagasse, without taking into account the water used in boilers for steam generation, the inputs used in water treatment and depreciation of equipment.

#### 4.2 Comparative analysis of the heat exchanger shell and tube and plate type

This comparison was made by taking two heat exchangers from the same thermal exchange area, same water flow, same flow and the same steam inlet temperatures of steam and water. In the shell and tube heat exchanger, water flows inside the tubes and the steam from the side of the hull. The heat exchanger has the following characteristics:

- Plate heat exchanger : containing three sets of plates made of stainless steel of a thickness of 0.65 mm, height of 245.6 mm and a width of 84.15 mm.
- Shell and tube heat exchanger: containing six carbon steel pipe outside diameter 19 mm, internal diameter 17 mm and length 400 mm.

In the theoretical simulation, made using the software EES (Engineering Equation Solver), there was a significant difference in calculating the global coefficient of heat exchange (U), obtaining the following values:

- plate heat exchanger:  $U = 3104 \text{ W/m}^2\text{K}$
- shell and tube heat exchanger:  $U = 2031 \text{ W/m}^2\text{K}$

The simulation in an experimental laboratory, for the second part of this work, should be presented on another occasion.

#### 5. CONCLUSION

In an increasingly globalized world that is concerned about the sustainability of business, the companies have been trying at all costs to they fall within the patterns and environmental standards, which every day become more stringent. This is due to the shortage of vital raw materials for economic development and material, such as minerals, water, food, oil, which have been decreasing every day due to man's exaggerated and non-conscious consumption.

Concerned with meeting the current needs of man and without compromising future generations, the organizations that are responsible for the environment are forcing companies that want to stay in the market to have in its scope certifications, such as ISO 14000 environmental standard, ensuring that the company is committed to significantly reduce damage to the environment.

And, to meet environmental standards, professionals from various industries have continuously sought to develop solutions that reduce emissions and reduce water consumption used by companies and others.

Contributing to the preservation of natural resources and emissions, some measures have been adopted by the sugarcane sector, such as the reduction of water in the sugarcane washing, use of vinasse in irrigation, cooling towers which use water in a closed circuit and others.

Analyzing the sugar and alcohol mills that produce them through the industrialization of sugarcane, especially the juice heat treatment industry for the fermentation, it appears that this area accounts for a significant share in respect to energy savings, therefore the water consumption.

Even if the steam produced and consumed in a sugarcane plant operates in closed system, or if all of the steam generated by the boiler returned condensate to the same, there is still much loss of steam, and therefore water vapor during the journey, requiring replacement of water to supply the amount lost, thus consuming resources.

To generate the steam used in the process, the company has purchased large quantities of bagasse, because the demand of the boiler is greater than the bagasse extracted on grinding. And with the high demand for bagasse, its price rose rapidly, from R \$ 18,000 per ton in 2009 to R \$ 100.00 in 2012.

Proposing a reduction in the consumption of bagasse, the present study sought to make a mass and energy balance in the thermal treatment of the juice for fermentation sector, achieving results of steam consumption and energy on the new project and making a comparison between the old project and the new project, obtaining a significant amount of bagasse saved. We conclude that, with the installation of regenerative plate heat exchanger, we obtained a saving of R \$ 56,376.00 on monthly consumption of bagasse, without taking into account the consumption of water and inputs.

In times of financial crisis, global warming and dwindling natural resources, companies have sought every day the strategic sustainability of its business which includes reducing costs, reducing emissions and responsible use of natural



resources. Thinking about it, the company made the implementation of this heat exchanger project, making sure it can implement improvements in order to achieve the objectives, of the environmental agencies, which are environmental preservation and sustainability, enabling the continuity of the cycle of life on the planet.

## 6. NOMENCLATURE

A = area of heat exchange (always perpendicular to the heat flow Q) m<sup>2</sup>;  
 A<sub>i</sub>, A<sub>e</sub> and A<sub>m</sub> are the areas of internal, external and middle heat exchange respectively m<sup>2</sup>.  
 D is the pipe diameter, m;  
 Δ TML is the logarithmic mean temperature difference, K  
 Gz is the Graetz number, (-);  
 h<sub>i</sub> is the coefficient of heat exchanges by convection of the fluid inside; W/m<sup>2</sup>.K;  
 h is the coefficient of convective heat exchange fluid outside W/m<sup>2</sup>.K;  
 L is the tube length, m;  
 μ is the fluid viscosity, Pa · s;  
 μ<sub>w</sub> is the fluid viscosity measured the wall temperature of the tube Pa.s;  
 Nu is the Nusselt number, (-)  
 PR is the Prandtl number, (-);  
 Q = flow through the heat exchanger, W;  
 R<sub>cond</sub> is the thermal conduction resistance of the wall material of the tube, K / W;  
 Re is the Reynolds number, (-).  
 R<sub>inc\_1</sub> fouling resistance is on the internal wall of the tube, K / W;  
 R<sub>inc\_2</sub> is the resistance to fouling on the outside wall of the tube, K / W;  
 R<sub>T</sub> is the overall resistance will heat transfer, K / W  
 ρ is the fluid density, kg/m<sup>3</sup>;  
 U is the overall coefficient of heat exchanges, W/m<sup>2</sup>.K;  
 V is the fluid velocity, m / s;  
 PCI is the lower heating value, kJ / kg  
 P<sub>b</sub> is the bagasse pol (sucrose contained in bagasse)  
 W<sub>b</sub> is the amount of bagasse, kg / s  
 W<sub>v</sub> is the amount of steam produced in the boiler kg / s  
 h<sub>v</sub> is the enthalpy of the steam at the boiler outlet  
 h is the enthalpy of the water in the boiler input  
 η is the efficiency of the boiler  
 W<sub>b</sub> is the mass flow rate of bagasse generated in juice extraction (t / h)  
 W<sub>c</sub> is the flow rate at the entrance of sugarcane milling (t / h)  
 F<sub>c</sub> is the fiber content in cane (%)  
 U<sub>b</sub> is the moisture generated from bagasse (%)  
 Pol<sub>b</sub> pol is the amount present in the residue (%)

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