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STEAM EJECTOR USED AS A SUBSTITUTE FOR COOLING TOWER IN THE ETHANOL PRODUCTION PROCESS

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ABSTRACT

Nowadays petroleum dependency in transportation is widely discussed all over the world. Atmospheric pollution and global warming are deleterious consequences of gasoline consumption. Ethanol is a natural substitute fuel that has been increasingly used. One of the most important raw materials used for ethanol production is the sugar cane. The exothermic fermentation reaction of the sugar cane juice in the ethanol production process requires a rigorous temperature control. This control is usually made by using cooling water from cooling towers. The heat released from cooling towers not only has an economical cost as well as it contributes to the global heating. Steam ejectors can substitute cooling towers thus improving the ethanol production plant efficiency and reducing world heating. Furthermore, steam ejectors are smaller, cheaper and are very simple equipment when compared with cooling towers. Furthermore, its use provides an improved thermal efficiency of the production plant resulting in the reduction of the global warming effects. In this work the use of steam ejector is proposed for the fermentation cooling of a typical Brazilian sugar and ethanol production plant. The steam which feeds the steam ejector is obtained from the plant utilities and the low temperature obtained from steam expansion within the ejector is used for sugar cane fermentation process cooling. The steam ejector discharge heat is recovered as it is used to sugar and ethanol production process heating. The sugar and ethanol production plant overall energy fluxes either using cooling towers as well as using steam ejectors are presented and the results are compared and discussed.

Keywords: steam ejector, cooling tower, ethanol production.

1. INTRODUCTION

There are several biomass sources for ethanol production. The ethanol can be obtained from cellulose, amylaceous or saccharin as raw materials. The most common source of cellulose that is used comes from wood or agricultural wastes such as sugar cane bagasse. Amylaceous are extracted from corn, manioc, sweet potato and several other types of grains. The saccharin plants such as saccharin sorghum, beet and sugar cane are used both for ethanol and sugar production. The use of cellulose and amylaceous for sugar production requires the conversion of glucose polymers of those plants to simple molecules of glucose.

The production of ethanol from sugar cane is the most efficient way for ethanol production. For the sake of comparison with the production of ethanol from corn [1], Table 1 presents some data regarding costs, energetic and pollution considerations.

The production cost and consequently the sale cost of the ethanol obtained from sugar is almost a half of that obtained from corn. If the productivities are compared, one hectare cultivated with sugar cane produces 2.5 times more than a hectare cultivated with corn. However, the low emission of GHG (Green House Gases) for producing ethanol from sugar cane is quite significant: while the production of ethanol from sugar cane generates 33.6 g of CO_2 per MJ, from corn the CO_2 discharged in the atmosphere is 2.5 times greater. By comparing with the GHG produced to obtain gasoline, the CO_2 emission from sugar cane is 1/3 of that.

Table 1 Ethanol from corn x sugar cane

	Ethanol from corn	Ethanol from sugar cane
Basic reaction	Starch → maltose + glucose	Saccharose → glucose + fructose
Production Cost	U$ 0.42 per liter	U$ 0.28 per liter
Productivity	3,000 liters / ha	7,500 liters / ha
Energetic Balance (I/O)	1:1.29	1:3.24
Sale cost	U$ 0.92 per liter	U$ 0.42 per liter
CO_2 emission	84.9 g of CO_2 / MJ	33.6 g of CO_2 / MJ

The production of gasoline has an important environmental impact duty when compared with the ethanol production. The emission of GHG to obtain gasoline is around 100 g of CO_2 per MJ while CHG from ethanol production is one third of that.

Nowadays, the world ethanol production is around 40 billion liters per year. For substituting only 10% of the gasoline burned in the world should be necessary more 150 billion liters of ethanol per year. In such world scenario, any efficiency improvement in the ethanol production process is welcome as it results in lower bagasse burning and consequently reducing CO_2 emission.

In this work a proposal for improving the thermal efficiency is made by using steam ejectors for substituting cooling tower.

The steam discharged from the steam ejector is reused in the ethanol and sugar production process which heat consumption are presented in the next item where the production process of ethanol and sugar is detailed.

2. ETHANOL PRODUCTION FROM SUGAR CANE

Sugar cane is the raw material used to the combined ethanol and sugar production in Brazil. The sugar cane is composed basically of solids, fibers and water. The solids (11 to 18%) are saccharose, glucose, fructose and salts [2].

The fibers are not water soluble. The quantity of fiber is an important characteristic because it quantifies the bagasse percentage and how difficult is to extract the sugar cane juice. The fibers correspond from 8% to 14% and water from 65% to 75%. There are also little quantities of organic and inorganic acids, proteins, wax, coloring, starch and grease.

As shown in Figure 1, sugar and ethanol have the same initial sugar cane juice generation process. The produced sugar cane juice is composed by soluble components such as sugars, ash, nitrogenized substances and others [3].

The sugar cane bagasse resulting from milling is burned into furnaces to produce steam in boilers. As a general rule there is an excess of bagasse. The steam is used in the sugar and ethanol production process and to move turbo-machinery and turbo-generators in the power plant. The energy is used in the production process and as a general rule the plant is also capable of delivery surplus energy.

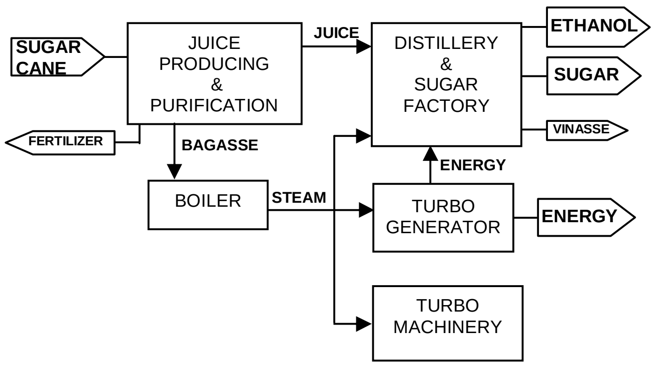

Fig. 1 Sugar and ethanol production general flowchart

The distillery discharges high quantities of vinasse, a pollutant and fetidness waste which is used partially as fertilizer [4]. Each liter of ethanol produced corresponds to approximately 13 liters of vinasse. The sugar cane juice sent to the sugar factory is transformed in sugar. The waste from sugar factory known as pie is used as fertilizer. The main stages presented in Figure 1 are detailed below focusing the heating necessities for each stage.

2.1 Sugar Cane Juice Production

The sugar cane is collected in the field, transported through trucks or trains, weighted, sampled and discharged into feed tables.

If the sugar cane is hand harvested, it is cleaned with water to obtain a better juice quality and to remove earth and sand which damage the plant equipment. When the sugar cane is mechanically harvested, it is not washed as the washing process reduces the saccharose level of the thole.

After washing, the sugar cane is transferred through conveyor belts to a knife set and pricking equipment for density increasing. After that the sugar cane is sent to the shredder which separates the sugar cane into fibres or threads. A magnet is also used to remove ferrous materials which could damage the equipment. At this stage, the sugar cane is prepared for milling [5].

The next step in the juice production is the milling which objective is to extract the juice through roll mills. As a result of milling, the bagasse is separated from the juice of sugar cane and saccharose is dissolved in the juice. After drying, the bagasse is used as a fuel in boilers for steam production.

Hot water is added in the mill on an inhibition process which objective is the increase in the sacharose extraction through sugar dilution resulting in higher milling efficiency. In this process, the inhibition water which reaches 30% is introduced at the top roll of the last mill and a sugar cane juice is obtained which content of sugar of cane reaches 96% . The cane juice returns from the last mill to the last but one mill and then on up to the first mill. The overall milling process can be increased through inhibition water heating up to 80^{o}C [6].

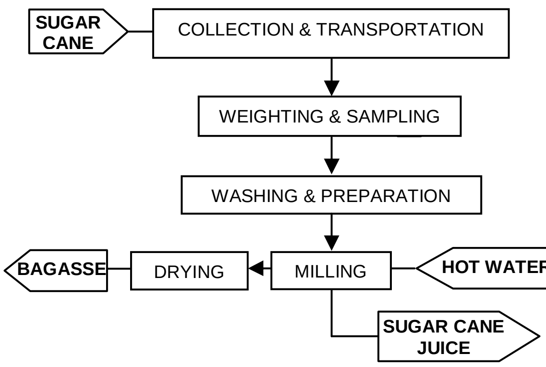

Fig. 2 Sugar Cane Juice Production

2.2 Sugar Cane Juice Impurities Removal

The sugar cane juice from milling contains impurities which shall be removed to improve the sugar and ethanol production efficiency. The rough impurities are well removed through straining, and they are coagulated allowing a later separation. The processes described below are used for an appropriate minor impurities removal except the sulfitation process which is not necessary in the ethanol production process. After purification, a portion of purified sugar cane juice is sent to the distillery where ethanol is produced. The remaining juice is sent to the sugar factory.

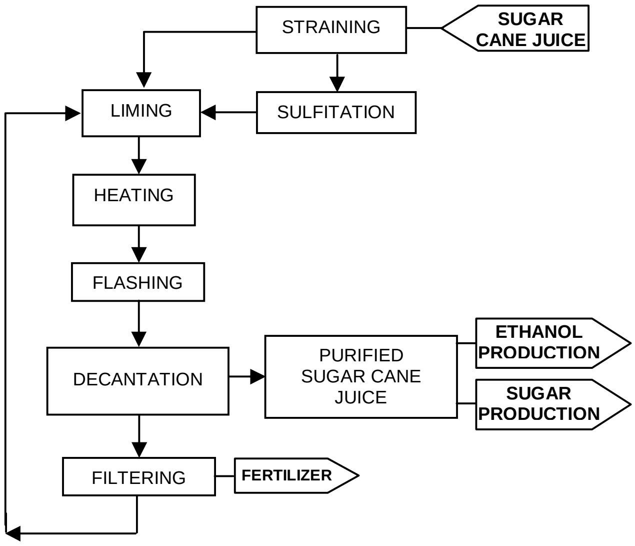

Fig. 3 Sugar cane juice impurities removal flowchart

In the sulfitation process, SO_2 is absorbed by the juice allowing for colloidal coagulation and further separation. Liming or whitewashing is the addition of lime milk which also coagulates colloidal materials and improve the drag of soluble and insoluble minor impurities. The sugar cane heating to around 105^{o}C is performed to accelerate and to make easier the coagulation reactions, grease and wax emulsification as well as colloids and all of non-sugar protein flaking. The flashing consists of a sudden pressure reduction which results in a juice boiling and air elimination. The decantation allows the flaked impurities removal and purified sugar cane juice production. The impurities are filtered and the bottom filter loam is collected and used as cake fertilizer. The remaining juice, with sacharose content is sent back for liming [7].

2.3 Ethanol and Sugar Production

After removing the sugar cane juice impurities, the purified juice is sent to the ethanol distillery and sugar factory. Those plants which are described below, with focus in the heat necessity, operate in parallel and are connected by molasses piping.

The sugar factory process starts with the juice evaporation at temperatures around 115^{o}C which objectives are bacterium and fungus elimination, and evaporation for water reduction from approximately 80% to 40%. The concentrated juice is known as sugar cane syrup.

After the evaporation, the juice is cooked for crystals formation. The temperature of cooking is around 60^{o}C. In the crystallization process, the juice is cooled for crystals growing.

The next step is the centrifugation where the sugar is mechanically separated from the sugar honey. Immediately, afterwards the sugar water content is reduced by drying and the sugar is ready for storage. The sugar honey obtained from centrifugation is sent to the ethanol production process.

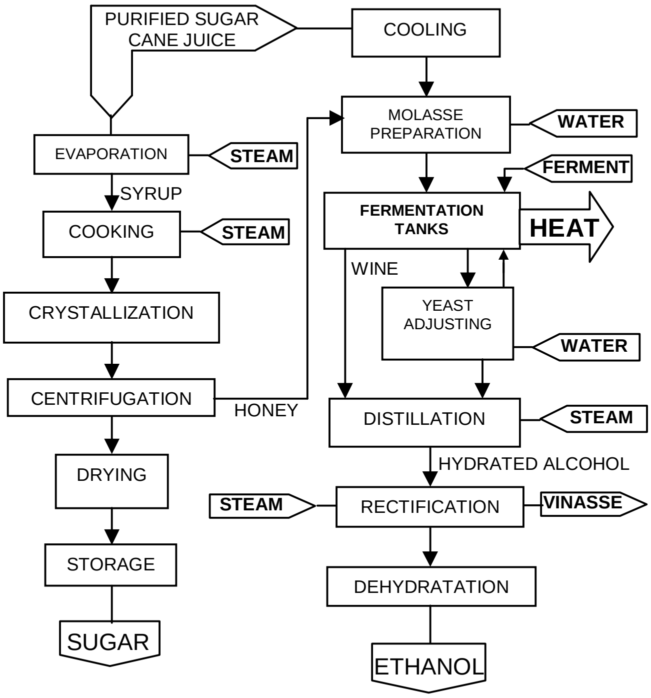

Fig. 4 Sugar and ethanol production flowchart

The first step of the ethanol production is the juice cooling due to process requirements. The cooling to approximately 30°C can be performed through heat exchanging between hot and cold juices or through hot juice and cooling water.

The molasses are a blend of sugar cane honey, purified sugar cane juice and water in such a way that the final concentration presents a concentration of around 20° Brix (relation between the number of grams of soluble solids under suspension and 100 grams of solution). Therefore, the molasses are a sugar solution properly adjusted to obtain an efficient fermentation.

Fermentation is a bio-chemical process and the most common distillery fermentation process is the Melle-Boinot in which the yeast is recuperated through wine centrifugation. Before being sent again to the process, the recuperated yeast is adjusted as it is blended with water to reduce the alcohol level and sulphuric acid to obtain an acidic pH level of around 3.

The fermentation process occurs inside closed fermentation tanks where ferment is added and on which a fermented mass composed of 2 parts of molasses are blended with 1 part of the recuperated yeast. In the Gay-Lussac fermentation reaction presented in Equation 1, the yeast composed by fungus like Saccharomyces Cerevisae hydrolyse the sacharose through the invertase enzyme. As a result, glucose and fructose ($C_6H_{12}O_6$) are produced.

$$C_{12}H_{22}O_{11} + H_2O \longrightarrow C_6H_{12}O_6 + C_6H_{12}O_6 \qquad (1)$$

After that, ethanol is produced through the zymase enzyme. The reaction, shown in Equation 2, also generates heat and carbon dioxide gas which carries evaporated ethanol. Afterwards a washing/condensing process separates the carried alcohol.

$$C_6H_{12}O_6 \longrightarrow 2\,CH_3\,CH_2OH + 2\,CO_2 + 24\text{ kcal} \qquad (2)$$

The fermentation process ends after approximately 8 hours. During that time, due to fermentation requirements, the temperature shall be maintained at 32°C by removing around 24 kcal per glucose/sacharose mol.

Nowadays, this heat is not recovered and it is lost through two main processes: wet cooling towers or aspersion over a lake. Dry cooling towers are costly and rarely used.

The cooling through aspersion is the cheapest one. It requires piping, pumps, valves, etc. between the plant and the lake, generally an artificial one, properly localized near the plant. The loss of water in this kind of cooling requires a constant supply of water from a river or well. If a well is used, the costs are increased. Furthermore, if a river is used, the thermal pollution makes this system more and more infeasible. The fouling due to the not treated (purified) water requires more maintenance attention.

The use of cooling tower is more expensive due to installation costs. As advantage, it can be installed near the plant, not requiring long piping. However it requires water treatment and maintenance of fans.

In this work, a steam ejector system is used as cooling equipment instead of cooling tower as presented below.

3. COOLING THROUGH STEAM EJECTOR

The steam ejector is an equipment that has no moving parts or a mechanical driver, it presents a simple operation and it can be used for fluid compressing or vacuum producing. The usual working fluids in an ejector are water, gases or steam. The heat removing capacity is obtained through vacuum produced in the ejector suction chamber which generates its corresponding low temperature.

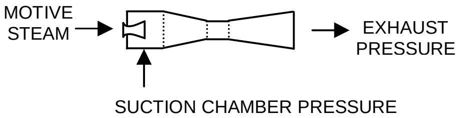

Fig. 5 Steam ejector

Steam ejectors can be used in single stage or multiple stages. The more the number of stages, higher is the vacuum obtained. The number of stages of a steam ejector cooling system depends on the relation between exhaust pressure and suction chamber pressure. If this relation is larger than 10, more than one stage shall be necessary. Suction chamber pressures as low as 0.007 kPa and temperatures below 0^oC can be achieved by using multiple stage steam ejector systems.

A steam ejector cooling system can be classified as direct or indirect. Figure 6 presents a fermentation tank using a direct cooling system.

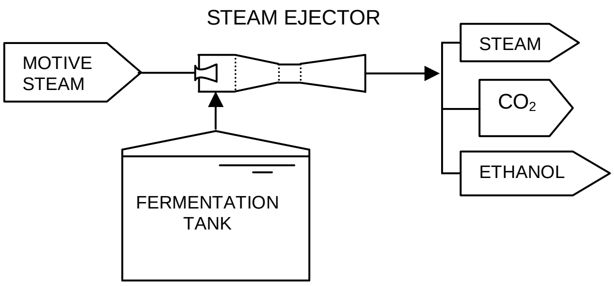

Fig. 6 Direct cooling steam ejector system

A steam ejector direct cooling system presents the advantage of higher temperature difference between fermented sugar cane juice and the suction chamber than the indirect. However, the CO_2 and ethanol vapour generated in the fermentation process shall be separated from steam in a distillation process to allow appropriate heat transfer and feed water pumping in the boiler as well as for the ethanol recovery. The high quantity of steam involved makes the direct cooling system not feasible for fermentation heat removal.

The indirect cooling system shown in Figure 7 do not mixes hot and cold fluids as it uses a sealed cooling water coil piping. However, it requires an evaporator, water sprays, pump and coil tubing. The water in the State (0) is saturated at low pressure and low temperature. Furthermore, the temperature difference between hot and cold fluids is lower than in the direct cooling system. Despite those disadvantages, the indirect cooling system is better than the direct one if one considers the distillery difficulties for the CO_2 and ethanol removal from the steam.

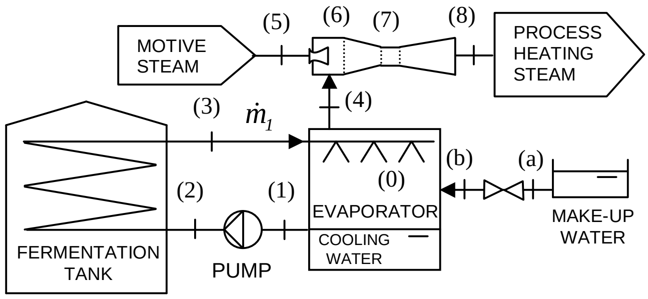

Fig. 7 Indirect cooling steam ejector system

The motive steam of the ejector can be obtained from the boiler live steam line. However, the high pressure and high temperature from live steam has a better use on turbo machinery feeding. The main turbo machines are: combustion and scavenging fans, shredder, pricker, rotative knifes, mills, turbo-generators and feed water pumps.

Typically, the turbo machines are exhaust counter pressure designed and discharge to a secondary steam header, as shown in Figure 8. This header operates under medium pressure and feeds steam to the producing plant and can feed steam to the ejector too. The exhaust steam from steam ejector can be used in all processes which need heat in the production of sugar and ethanol. The overall resulting condensed water is sent to a condensed steam tank. From this tank, the water is pumped back to the boiler through feed water pumps.

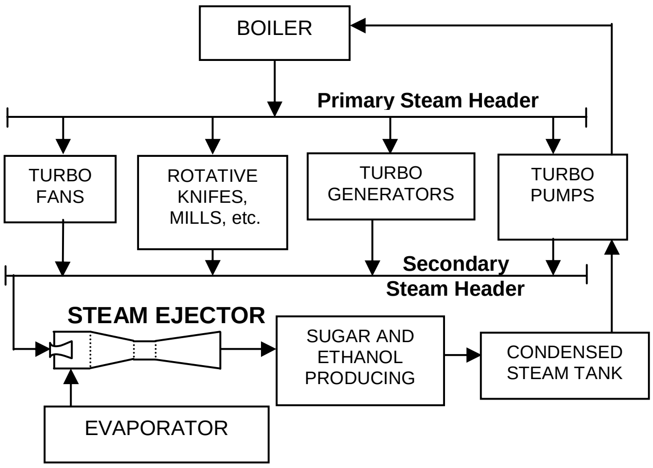

Fig. 8 Sugar and ethanol plant steam management

3.1 Steam Ejector Process Design

As presented in Figure 9, the steam ejector parts are the jet nozzle, the suction chamber, the mixer and the diffuser. The mixer is the low pressure region where the motive steam is mixed with the steam from the evaporator.

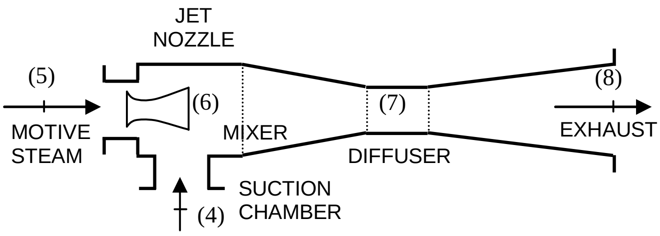

Fig. 9 Steam ejector main parts

The steam ejector suction chamber pressure is the saturation pressure of the water at the evaporator temperature. For the sake of an example, 1^oC is the steam saturated temperature at 0.7 kPa pressure. The mean fermentation temperature and TTD (Terminal Temperature Difference) [9] between hot and cold fluids determines the cooling water temperature and, consequently, the suction chamber pressure.

The jet nozzle is a converging and diverging device where the motive steam reaches high velocities. By applying the First Law of Thermodynamics [8] to the jet nozzle in steady state conditions result:

$$h_5 + \frac{\overline{V}_5^{\,2}}{2} = h_6 + \frac{\overline{V}_6^{\,2}}{2} \qquad (3)$$

where h is the specific enthalpy (kJ/kg) and $\overline{V}$ is the steam velocity.

The energy balance applied to the mixer neglecting any heat loss, results:

$$\dot{m}_6\,(h_6 + \frac{\overline{V}_6^{\,2}}{2}) + \dot{m}_4\,(h_4 + \frac{\overline{V}_4^{\,2}}{2}) = \dot{m}_7\,(h_7 + \frac{\overline{V}_7^{\,2}}{2}) \qquad (4)$$

where $\dot{m}$ is the mass flow (kg/s).

The momentum equation applied to the mixer results:

$$\dot{m}_6\,\overline{V}_6 + \dot{m}_4\,\overline{V}_4 = \dot{m}_7\,\overline{V}_7 \qquad (5)$$

The First Law applied to the diffuser results:

$$\int_{P7}^{P8} V\,dP + \frac{\overline{V}_8^{\,2} - \overline{V}_7^{\,2}}{2} = 0 \qquad (6)$$

where V is the volume (m^3) and P is the pressure (kPa).

The following equation can be used to the flow in the diffuser by considering that the steam behaves approximately as a perfect gas:

$$P\,V^n = P_7\,V_7^{\,n} = P_8\,V_8^{\,n} \qquad (7)$$

where n is the adiabatic constant for steam and assumes a medium value of 1.33. Equation (7) can be written as:

$$V = P^{-1/n}\,P_7^{1/n}\,V_7 = P^{-1/n}\,P_8^{1/n}\,V_8 \qquad (8)$$

By substituting Equation (8) in the first term of Equation (6), results:

$$\int_{P7}^{P8} V\,dP = V_7\,P_7^{1/n}\int_{P7}^{P8} P^{-1/n}\,dP = V_7\,P_7^{1/n}\left[\frac{P^{-1/n+1}}{\left(-1/n+1\right)}\right]_{P7}^{P8} =$$

$$= V_7\,P_7^{1/n}\left(\frac{n}{n-1}\right)\left[P_8^{\,n-1/n} - P_7^{\,n-1/n}\right] \qquad (9)$$

Finally, from Equations (6) and (9) result:

$$\frac{\overline{V}_8^{\,2} - \overline{V}_7^{\,2}}{2} = \left(\frac{n}{n-1}\right)P_7\,V_7\left[1 - \left(\frac{P_8}{P_7}\right)^{n-1/n}\right] \qquad (10)$$

The solution of the equations presented above allows for the steam ejector process design.

3.2 Make-Up Water

Through the suction chamber of the steam ejector, water vapour is lost in the evaporator. The make up water that shall be replaced in the evaporator $\dot{m}_{rep}$ can be determined through the following energy balance in the evaporator (refer to Figure 7):

$$\dot{m}_{rep}\,h_b + \dot{m}_3\,h_3 = \dot{m}_4\,h_4 + \dot{m}_1\,h_1 \qquad (11)$$

where, $\dot{m}_{rep} = \dot{m}_4$, for maintaining a constant evaporator water inventory, and $\dot{m}_1 = \dot{m}_3$. Therefore, Equation (11) reduces to:

$$\dot{m}_{rep} = \frac{\dot{m}_1\,(h_3 - h_1)}{(h_4 - h_a)} \qquad (12)$$

3.3 Cooling Water Mass Flow

The cooling water mass flow is determined through the following equation:

$$\dot{m}_1 = \frac{\dot{Q}_{fer}}{(h_3 - h_2)} \qquad (13)$$

where, $\dot{Q}_{fer}$ is the heat flow to be removed from fermentation tanks and $h_3 - h_2$ is the cooling water enthalpy difference. Figure 10 presents the processes, in a T-s diagram, which occur in the cooling water circuit and in the steam ejector.

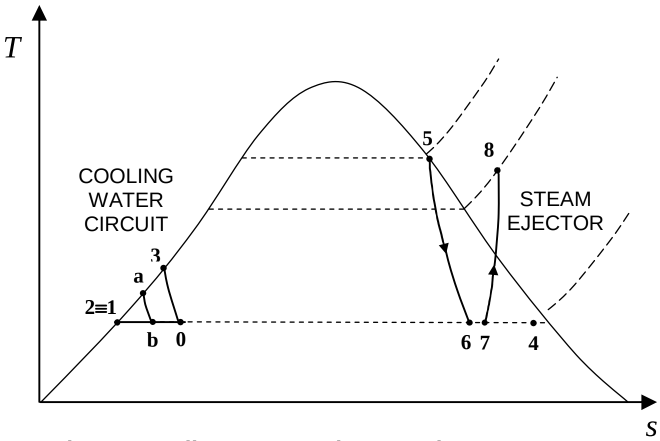

Fig. 10 Cooling water and steam ejector processes

4. ENERGY & DESIGN CONSIDERATIONS

The descriptive and theoretical background presented above is used here to compare a conventional sugar and ethanol production plant which uses cooling tower, with a steam ejector equipped plant.

The focus of this analysis is a typical Brazilian sugar and ethanol plant which processes 337 t/h of sugar cane. The imbibition process described in item 2.1 requires 0.25 m^3 of water per ton of sugar cane. The resulting bagasse mass is around 27% of the sugar cane milled and 5% is the fertilizer mass resulting from milling process. As a result, 312 t/h of purified sugar cane juice is produced. The mass flows of sugar cane, water, bagasse, fertilizer and purified sugar cane juice are presented in Figure 11.

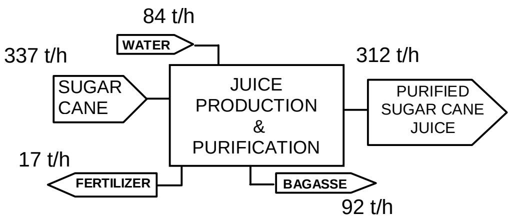

Fig. 11 Juice production and purification mass flows

The purified sugar cane juice mass flow is sent to the distillery and sugar factory. As described in item 2.3 and presented in Figure 4 (right), heat shall be removed from fermentation tanks in the distillery. Figure 12 presents a conventional plant (left) and a steam ejector equipped plant (right).

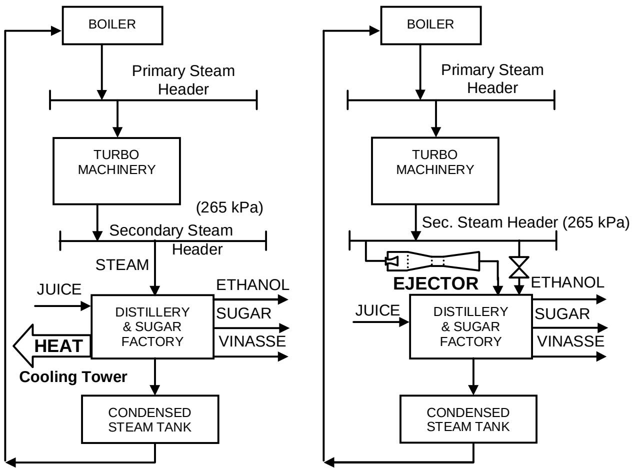

Fig. 12 Cooling tower x steam ejector

According to the fermentation reaction (Equations 1 and 2), each mole of fermented mass, composed by saccharose ($C_{12}H_{22}O_{11}$) and water, generates 24 kcal. Therefore, 312 t/h generates approximately 20 million kcal per hour or 23.5 MW.

The amount of cooling water ($\dot{m}_1$) (see Figure 7) for such a heat removal is 2016 t/h by applying Equation (13) and considering the following conditions:

Table 2 Cooling Water Circuit Parameters

Parameter	Value
Fermentation Tank temperature	32°C
Cooling water temperature from Evaporator	17°C
Terminal Temperature Difference	5°C
Temperature increase in the Fermentation Tank	10°C

The fermentation tanks temperature shall be around 32°C and a cooling water temperature of 17°C allows a reasonable log mean temperature difference for heat transfer. Consequently, the saturated state in the evaporator requires a pressure of 2 kPa that is also the pressure in the suction chamber of the steam ejector.

Figure 13 shows the cooling water process parameters, with the corresponding values, where x is the mass percentage of steam.

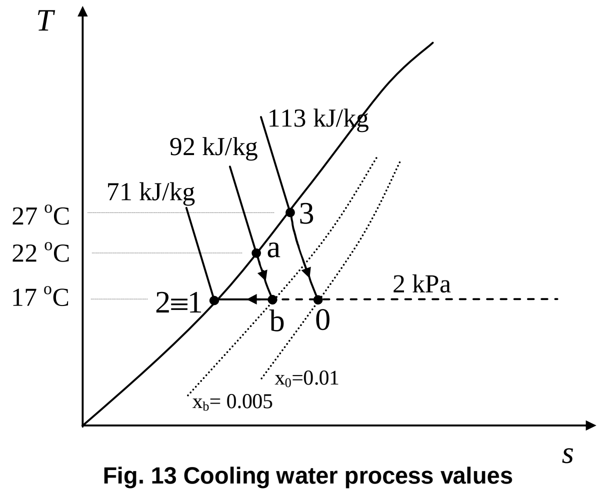

Fig. 13 Cooling water process values

A selected pressure of 120 kPa in the ejector exhaust and its corresponding temperature allows appropriate conditions for sugar/ethanol producing requirements. By considering the above selected exhaust and suction chamber pressures, a relation of 60 is achieved requiring the use of a two stage steam ejector. Typically the exhaust turbo machinery pressure is around 265 kPa which is the secondary steam header pressure as well as the steam ejector motive steam pressure. By applying Equation (3) to the jet nozzle and considering that the jet nozzle velocity exit is bigger than the velocity of the motive steam, the term corresponding to the entrance velocity is negligible. Adopting an exit steam velocity of 1100 m/s in the jet nozzle and a typical nozzle efficiency of 90%, the state (6) is determined (see Figure 14).

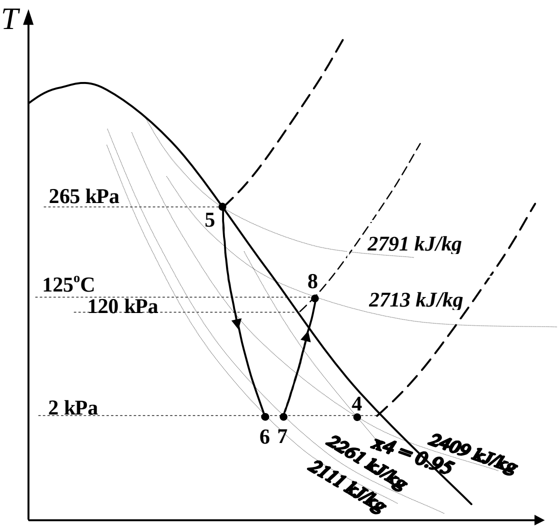

Fig. 14 Steam ejector process values

The make-up water to the evaporator is determined through Equation 12 and its value is 36 t/h. Finally, through Equations (4), (5) and (10), the states (7) and (8) are obtained by considering a typical moisture percentage of 5% to state (4) and a velocity of 10 m/s. As presented in Figure 14 the steam ejector exhaust steam enthalpy is 2,713 kJ/kg. As a final result, a mass flow of 162 t/h of steam ejector motive steam is obtained.

The typical values of steam mass flow required from secondary steam header for ethanol and sugar production are respectively 4.5 kg steam / kg ethanol and 3.6 kg steam / kg sugar. The steam from secondary steam header has an energy content of 2,791 kJ/kg. The typical plant under focus produces 18 t/h of ethanol and 60 t/h of sugar. Therefore, 297 t/h of steam are required, which corresponds to an energy flux of 230.3 MW_t. If 162 t/h of steam with 2,713 kJ/kg comes from steam ejector exhaust, only 139.5 t/h of steam shall be sent directly by secondary steam header and the total quantity of steam is 301.5 t/h. In both plants presented in Figure 12, the condensed steam tank conditions are the same.

5. CONCLUSIONS

In the study presented above the steam ejector cooling system can substitute cooling tower avoiding the loss of 23.5 MW_t of heat flux. By considering a turbo generator power plant thermal efficiency of 20% this thermal energy can be transformed in almost 5 MW_e of surplus energy. If this electrical energy be not necessary, the amount of bagasse burned in the boiler can be reduced with consequent reduction of green house gases.

The total amount of steam by using steam ejector (301.5 t/h) is almost the same of that required by a conventional sugar and ethanol production plant (297 t/h). Consequently, the secondary steam header, tubing, valves, etc. remain the same.

The use of steam ejector instead of cooling tower reduces to zero the consumption of water lost by evaporation in the open circuit cooling tower. The make-up water to the evaporator (36 t/h) is included in the overall water inventory and is not lost.

The indirect cooling steam ejector system requires the use of an evaporator which operates under vacuum and two stage steam ejector. On the other hands pumps, valves, tubing and maintenance required by cooling tower are not required by using steam ejector. Furthermore, steam ejector has no moving parts, its maintenance is simple and it is compact.

As presented in this work the use of steam ejector instead of cooling tower is feasible. As a future work are proposed an exergetic analysis of the overall steam system of the sugar and ethanol production plant, a cost analysis and a green house gases reduction evaluation.

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