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Energy and exergy analysis at the la joya sugar mill in Champotón, Campeche, Mexico

Análisis energético y exergético en el ingenio azucarero de la joya en Champotón, Campeche, México

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Abstract

An energy and exergistic analysis was carried out on the bagacera boiler of the sugar mill "La Joya" located in Champotón, Campeche, making the following assumptions: the process develops in a permanent state, the mass that flows through the control volume does not suffer variations with respect to time, there are no work interactions of the system with the environment, changes in kinetic energy and potential energy are considered negligible, thermodynamic data were provided by the mill's operation and control center. It was found that by increasing the mass flow of feed water (m_{water}) and decreasing the temperature of the dead state (T0) there was the least destruction of exergy. Simulations were carried out to determine the energy and exegetical efficiencies of the mill as a whole with the help of the Software Engineering Equation Solver (EES). When modifying m ̇_water, with T0 at 25 °C, and inlet water (T_{water}) 90 °C, an increase was observed both efficiencies; the energetic reached a maximum of 88, and the exergetic of 31; It was also observed that the maximum energy efficiency is obtained with the Twater 45°C. On the contrary, the exergetic efficiency at 15.3. It was concluded that it is more important to increase the mass flow of inlet water to increase global efficiencies in mill facilities than its temperature.

Energy and exergetic analysis, energy and exergetic efficiencies, bagasse-based cogeneration plant, sugarmill

Resumen

Se realizó un análisis energético y exergético sobre la caldera bagacera del ingenio azucarero “La Joya” situado en Champotón, Campeche, haciendo las siguientes suposiciones: el proceso se desarrolla en estado permanente, la masa que fluye por el volumen de control no sufre variaciones con respecto al tiempo, no hay interacciones de trabajo del sistema con el medio ambiente, los cambios en la energía cinética y la energía potencial son considerados como despreciables, los datos termodinámicos fueron proporcionados por el centro de operación y control del ingenio. Se encontró que aumentando el flujo másico del agua de alimentación ((m_{agua}) ̇) y disminuyendo la temperatura del estado muerto (T0) se tuvo la menor destrucción de exergía. Las menores temperaturas del estado muerto sólo se tienen para la época de otoño-invierno. Con la disminución del flujo másico del agua de alimentación, el precalentamiento de la misma antes del ingreso a la caldera y la T0 más baja posible se logró la menor destrucción de exergía. Se realizaron simulaciones para determinar las eficiencias energéticas y exegéticas del ingenio en su conjunto con la ayuda del Software Engineering Equation Solver (EES). Al modificar m ̇_agua, con T0 en 25 °C, y agua de entrada (T_{agua}) 90 °C, se observó un aumento ambas eficiencias; la energética alcanzó un máximo de 88, y la exergética de 31; también se observó que la máxima eficiencia energética se obtiene con la Tagua 45 °C. Por el contrario, la eficiencia exergética a 15.3. Se concluyó que es más importante aumentar el flujo másico del agua de entrada para aumentar las eficiencias globales en las instalaciones de un ingenio, que la temperatura de la misma.

Análisis energético y exergético, eficiencias energética y exergética, cogeneración en caldera bagacera, ingenio azucarero

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Introduction

In the context of Mexico's energy development, the "La Joya" sugar mill located in the municipality of Champotón, Campeche, Mexico, acquired a 20 MW turbo mega generator (TMG). Mexico, acquired a turbo mega generator (TMG) with a capacity of 20 MW. To date, it is fully installed. The purpose of this generator was to increase the company's own production of electricity and minimize the consumption of energy from the Federal Electricity Commission (CFE) network. The start-up of the TMG revealed a reality different from what was foreseen; the parameters of the steam produced by the baghouse boiler were not able to sustain the efficiency and production of the TMG. This implied making improvements in the steam production; therefore, an analysis of the boiler was proposed to determine if its production was sufficient and of the required quality. Most baghouse boilers in the world operate with technology from the beginning of the last century. Sugar production requires high-temperature processes obtained with steam or hot water; they are used for cleaning, evaporation and cooking of the sugarcane juice. In the early days of sugar production, firewood was used for the cooking processes; this fuel was a concern for landowners and administrators because the costs were onerous. Some time later (1647), sugarcane bagasse began to be used as fuel (Rivero, R. and Anaya, 1986). The introduction of steam in this industry occurred for the first time in Jamaica in 1768 in the Greenwich plantation, and was due to a John Stewart patent on the design of transmission of the energy produced by a steam engine to a sugar cane mill (Hugot, 2011). The first successful application of steam in mill and transmission processes was made in Cuba in 1797 at the estate of the Count of San Juan de Jaruco in Seibado; by 1808 there were already 25 mills operating with this type of energy (Molina Lóp ez, 2015). The old boilers were manufactured in three levels. Only the lower one was made of a single piece of metal, while the others were made of plates bolted or riveted together. This facilitated the replacement of the bottoms, the parts that wore out the most when exposed to the heat of the direct fire applied to them. The material used in their manufacture was copper; by 1880 some boilers were made of copper and bronze alloy, which made them lighter (Ruiz Labourdette, 2012).

It was not until the end of the 19th century that cast iron began to become widespread (Thomasset, 2011) for the manufacture of boilers. Innovations in boilers were subject to the conditions of the economic and social environment of the time. As new proposals were made, these boilers were used to generate electric power by coupling a turbine to an electric generator (Vallejo, 1982). The first electric power generators driven by steam generation were built, converting thermal energy into motion and motion into electric power generation (Molina López, 2015).

The bagasse boiler

This type of boiler is called bagasse due to the characteristic of its combustion, which uses bagasse (which is considered waste or garbage) as its raw material and converts it into fuel, Figure 1. The bagasse is transported by long belts and inserted into a furnace where combustion takes place, which heats the water supplied, until the necessary steam is obtained, which drives the turbine and propitiates the generation of electric energy through the electric generator coupled to the turbine. The furnaces of these boilers have adjustments in the arrangement of the bagasse supply, and a special ash removal system, as well as burners suitable for this fuel (Pistore, 2012).

Figure 1 La Joya sugar mill baghouse boiler
Source: Own elaboration.

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The first bagasse boilers were used to obtain sugar in haciendas that followed a traditional process. Sugar production was carried out with traditional implements in three distinct stages:

1. The sugar mill, where the milling process was carried out.

2. The boiler house, where there was a battery of kettles, pots, pots and cauldrons, which produced the heat necessary to carry out the processes of cleaning, evaporation and cooking of the sugar cane juice; these utensils could be said to be the first bagasse boilers. Later on, the essential equipment in this sector of the sugar mill was the set of vessels and cauldrons where the successive boiling heats of the guarapo were carried out, complemented by some scarce instruments for the manipulation.

3. The purging, where the crystallized sugar was separated from the honeys (Shield, 1975).

Nowadays, boilers are built with a high technological level, Figure 2, which achieve high yield results, all this added to the knowledge we have about the properties of water and steam.

Figure 2 Top view of the dome of a modern bagasse boiler
Source: Own elaboration

It is also noteworthy the great progress achieved in metallurgy; it has allowed the use of steels and alloys that withstand both, higher pressures and high temperatures; materials that also resist corrosion significantly (Manso, W. and Castillo, 2015).

Currently, the standards (NFPA 85-2019 and NOM-122-STPS-1996) that regulate the design and construction of steam boilers must be complied with, allowing control over the critical parts of these, which also helps to have better safety levels (Tornero, 2011). However, although the development of boilers is much and their manufacturing has been improved, sugar mills are characterized for being highly energy consuming and wasteful; largely due to low efficiency technology, as well as to the neglect of their facilities. Specifically, in sugar mills; steam generators are little attended as carriers of improvement in the production and performance of the same despite the fact that their operation involves the conversion of the energy potential of bagasse into thermal energy which in turn performs the transmission of this energy to a medium (steam), which can be used in useful work both in the industrial manufacturing process and for mechanical work of turbogenerators and mills (Ramos et al., 2019). While modern boilers are becoming more prevalent in new projects, there remains a large majority of older equipment that needs to be repowered (Singh, 2019). A boiler is itself an assembly, containing different elements (Ruiz Labourdette, 2012). Figure 3 shows a scheme that visualizes the points where bagasse, air and water involved in steam production are injected:

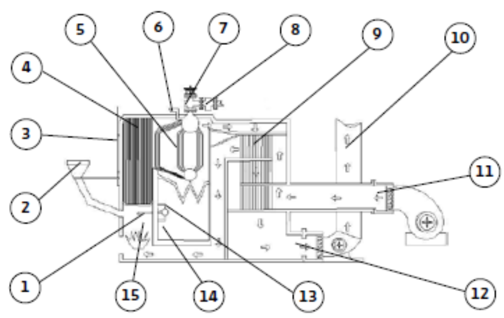
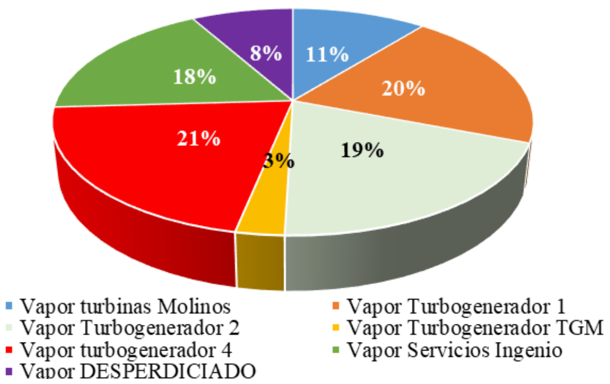


Figure 3 Main components of bagasse boiler
Source: Tornero et al., 2011

1 Burner	9 Air preheating
2 Bagasse Feeder	10 Chimney
3 Water level	11 Forced air duct
4 Fluxeria	12 Induced air duct
5 Steam overheating	13 Fuel oil spraying pipe (auxiliary)
6 Water inlet	14 Fuel oil pipe (auxiliary)
7 Steam outlet valve	15 Home
8 Steam non-return valve	

Justification

This work consisted of applying the exergetic method in the processes or stages developed at "La Joya" sugar mill, particularly in the bagasse boiler, to achieve maximum steam production under optimum operating conditions, according to the technical sheet of a 20 MW Turbo Mega Generator (TMG). With data provided by the Mill's Production Department, the production and management of operating steam in a month for the industrial process and electric power generation was determined, as shown in the monthly summary in Graph 1.



Graphic 1 Percentage of steam consumption at sugar mill Joya, Champotón, Campeche, Mexico
Source: Own elaboration.

Steam production in the boiler was 24.33 kg/s, of which 21.81 kg/s were used throughout the industrial process (auxiliary services steam) and for electricity generation. The mill estimated an approximate loss of 2.52 kg/s (this steam may have escaped at joints, pipes and valves). Although it appeared that they had excess steam, the reality is that it was not injected to the TMG in the quantity and quality necessary for the proper operation of the turbogenerator. It was necessary to increase the quantity and check the conditions of the steam to the TMG. With the steam in the initial conditions, it was impossible to sustain the production of electrical energy from the TMG (tripping). The conditions required by the TMG datasheet are as follows: Steam injection temperature 350 °C. Operating pressure 3.5 MPa (superheated steam conditions). Graph 1 shows that only 29% (Molinos turbines 11% and Ingenio Services 18%) of the steam was used directly in the industrial process, and 63% was used in electricity generation in 4 different types of generators. In addition, 8% of steam (purple tone) was not used in any part of the process.

It is possible to present different proposals to increase steam injection to the TMG:

– Change of equipment and auxiliary devices that are obsolete and decrease the steam production capacity.

– Change in pipes, fittings and valves in bad conditions or improve their quality.

– Exergetic and energetic analysis and redesign of the thermodynamic cycle used.

The boiler is the place of maximum energy loss (by the amount of heat lost), but also the place of thermal energy creation, the focus of this work was to demonstrate that, by enhancing the efficiency of the heart of the plant, the operating efficiency of the system as a whole is increased.

Objective

To achieve the maximum steam production in a steam generator (baghouse boiler) of a sugar mill, at the optimum operating conditions, according to the technical sheet, of the TMG of 20 MW, determined through the application of energy and energy analysis to the industrial process and electric power generation of the sugar mill in operation. As well as to contribute with low investment energy strategies,

Hypothesis

A fundamental parameter for the steam production of the boiler is the nominal power of the Turbo mega Generator. This power is ideal, it is not attached to the real power of the system. The manufacturer does not consider losses and irreversibilities; in specific climatic and geological situations there are important variations with the values according to the working place of the equipment. With the application of the exergy method, the optimal operating conditions of the baghouse boiler and the losses in strategic points, which cause its low efficiency and poor steam quality in the system, will be determined.

Problem Statement

The mill is operated with a steam generator, fed with sugarcane bagasse (bagasse boiler). The generator produces superheated steam which is injected into the turbine of the 20 MW electric generator (TMG). However, during the operation of the TMG the plant was experiencing failures or tripping of the steam line feeder valves, leaving the turbine out of service; after reviewing the system and its operation, it was determined that the steam did not meet the specifications (quality) demanded by the technical sheet of the TMG electric generator. Therefore, the problem to be solved was to obtain and improve the quality of the steam required for the optimal operation of the TMG. According to the TMG data sheet, the required steam conditions (parameters to be met) were determined for this purpose. The analysis of the baghouse boiler was proposed to improve its production and efficiency. We pointed out that, even limiting the analysis to the boiler, there were problems in the equipment or processes. It was proposed to solve these problems with:

– Replacement of obsolete equipment that reduces the capacity and quality of steam production.

– Change in current piping, accessories and valves to others of higher quality.

– Analysis and redesign of the thermodynamic cycle used. In first and second law.

This project proposed to increase the efficiency of the baghouse boiler to supply optimum steam to the 20 MW turbogenerator. Also, it was proposed the energetic and energetic analysis applied to the steam generator, to identify which are and how the maximum losses occur in it. In this way to avoid costly investments, which have little impact on the good performance of the system (Ma *et al.*, 2023).

Methodology proposed for the analysis of the baghouse boiler

An energetic and energetic analysis was carried out on the steam generator (baghouse boiler). According to the literature review, several authors highlight that, within a traditional sugar mill, the steam generation area presents the main energy losses with 53.3% (Molina López, 2015). However, all these designs are based on technical-economic criteria from the point of view of the first law of thermodynamics and although the determining factor of efficiency is the fuel converted to energy, it is advisable to perform the energetic balance. Therefore, the energetic analysis of the baghouse boiler and its relationship with the whole cycle as a whole was developed in order to establish the best conditions under which it can operate more efficiently (Ma et al., 2023). We start for this analysis, the current operating conditions. The steam generator analysis was performed under the following thermodynamic assumptions:

– The process runs in steady state.

– The mass flows through the control volume; it does not undergo variations with respect to time, therefore, the variation of this is equal to zero.

– By balance, the Enthalpy and Entropy difference must be equal to zero.

– There are no work interactions of the system with the environment (no arrow work).

– Changes in kinetic energy and potential energy are considered negligible.

– The thermodynamic data for each point were obtained from the La Joya mill's operation and control center during normal operation.

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Theoretical framework

Under the above assumptions, the mass and energy balances for this system can be expressed as a ratio as follows: steam generator (baghouse boiler): mass, energy and exergy balances for the control volume. For a steady state control volume with negligible changes in kinetic and potential energies, the mass, energy and exergy balances are as follows (Cengel, 2015),(Cengel, 2011):

$$\sum\left(1-\frac{T_0}{T}\right)\dot{Q}-\dot{W}+\sum c\psi_{output}-\sum\dot{m}_{input}\,\psi_{input}-\dot{X}_{ddestroyed}= \quad (1)$$

$$\left(1-\frac{T_0}{T}\right)\dot{Q}-\dot{W}+\dot{m}_{\dot{m}_{output}}(\psi_{input}-\psi_{einput})-\dot{X}_{destroyed}=0 \quad (2)$$

Being:
$\dot{m}$ mass flow rate of the process water or steam.
$\dot{Q}$ process heat
$\dot{W}$ arrow work
h enthalpy of a specific point
$\dot{X}_{destroyed}$ exergy destroyed.
ψ *exergy of a specific point.*

The thermal exergy transfer flux due to heat transfer from the boiler to the environment, at temperature T (expressed in K) is given by: : $\sum\left(1-\frac{T_0}{T}\right)\dot{Q}$. Where T_0 is the dead state temperature (room temperature expressed in K). The exergy of water and steam are given by the following equation:

$$\dot{m}_{fluid}(\psi_{output}-\psi_{input})=\dot{m}\left[(h_{output}-h_{input})\right]$$

$$-T_0\left(s_{output}-s_{input}\right) \quad (3)$$

Substituting Equation 3 into 2, the relationship for a steady flow device and a single current (one input and one output), is as follows:

$$\left(1-\frac{T_0}{T}\right)\dot{Q}-\dot{W}+m[\,(h_{output}-h_{input})$$

$$-T_0\left(s_{output}-s_{input}\right)]-\dot{X}_{destruida}=0 \quad (4)$$

For our case there is no arrow work so $\dot{W}$ is equal to zero. The energy efficiency of the plant is given by (Singh, 2019).

$$\sum\left(\frac{1-T_0}{T}\right)\dot{Q}-\dot{W}=\sum\dot{m}_{output}\psi_{output}$$

$$-\sum\dot{m}_{input}\psi_{input}+\dot{X} \quad (5)$$

The total heat used in the sugar production process is given by:

$$\dot{Q}_{process}=\dot{Q}_{\text{boiler house}}+\dot{Q}_{miscellaneus} \quad (6)$$
$$\dot{Q}_{miscellaneus}=negligible$$

The energy efficiency of the plant is given by (Singh, 2019):

$$\eta_{energy\ plant}=\frac{\dot{W}_{net}+\dot{Q}_{process}}{\dot{E}_{combustión}} \quad (7)$$

$$\eta_{energy\ plant}=\frac{\dot{W}_{net}+(\dot{H}_{input}-\dot{H}_{output})}{10{,}276\frac{kJ}{kg}*\dot{m}_{combustible}} \quad (8)$$

The total exergy used during the sugar production process is (Kanoglu & Dincer, 2009):

$$\eta_{energy\ plant}=\frac{\dot{W}_{net}+\dot{X}_{process}}{\dot{X}_{fuel}} \quad (9)$$

The fuel exergy is given by:(Singh, 2019).

$$\psi_{fuel}=\psi_{fuel\ chemistry}=12{,}459\ \frac{kJ}{kg}$$

$$\eta_{energy\ plant}=\frac{\dot{W}_{neto}+(\dot{X}_{output}-\dot{X}_{input})}{12{,}459\frac{kJ}{kg}*\dot{m}_{fuel}\frac{kg}{s}} \quad (10)$$

$$\dot{X}_{output}=\dot{m}_{fluid}\psi_{input}=\dot{m}_{fluid}\left[\left(h_{input}-h_0\right)-T_0\left(s_{input}-s_0\right)\right] \quad (11)$$

$$\dot{X}_{output}=\dot{m}_{fluido}\psi_{input}=\dot{m}_{fluid}\left[\left(h_{output}-h_0\right)-T_0\left(s_{output}-s_0\right)\right] \quad (12)$$

$$\dot{W}_{net}=\dot{m}_{vapor}\frac{kg}{s}\left(h_{steam\ turbine\ output}-h_{steam\ turbine\ inlet}\right)\frac{kJ}{kg} \quad (13)$$

The related properties in the specified states are determined by steam tables (Cengel, 2015) and EES own libraries. The "La Joya" sugar mill has an automated monitoring and control system (Computerized Command Center). It monitors in real time the main operating parameters, Figure 4.

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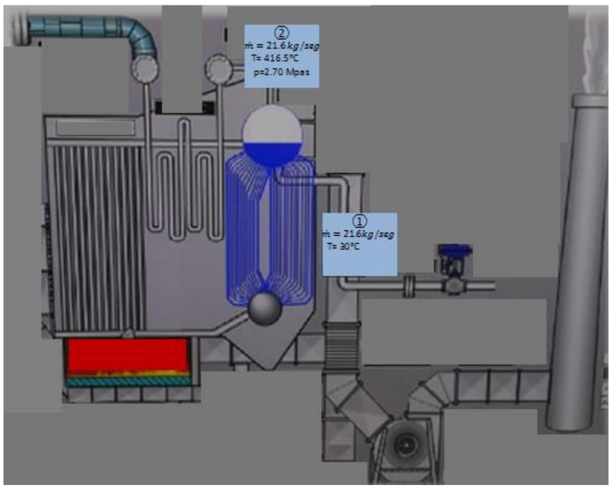


Figure 4 Diagram of the steam generator with its operating parameters
Source: La Joya mill computerized command center.

System operating data

The sugar mill's control system provided us with its operating data recorded and compiled during the harvest process, specifically for the steam generator (baghouse boiler). Figures 4 and 5, and Table 1. We used the Engineering Equation Solver (EES) software to determine the thermodynamic properties of these points, Table 1. A schematic diagram of the boiler was made as a control volume for analysis.

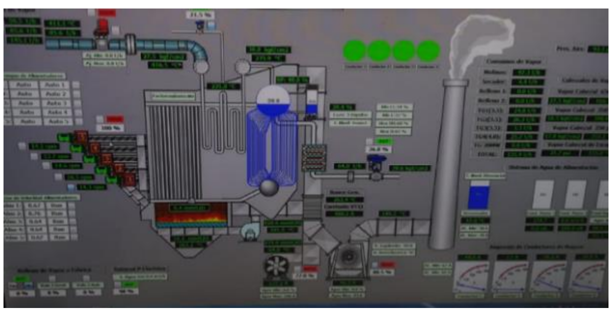


Figure 5 Diagram of the system analyzed in the steam generator
Source: Ingenio la Joya control system. Own elaboration

Figure 6 is the schematic diagram of the control volume of our analysis; the steam generator presented in a simplified form. It shows the mass flow of the feed water and the hearth. Steam production at 416 °C and 2.70 MPa is considered. The assumptions of the problem are the same as those stated above.

State	ṁ [kg/s]	T [ºC]	P [MPa]	h [kJ/kg]	s [kJ/(kg K)]
1	21.6	30	0.00424	125.74	0.4368
2	21.6	416	2.7	3272.64	7.0310

Table 1 Thermodynamic properties of selected points to perform the analysis
Source: La Joya Control Center.

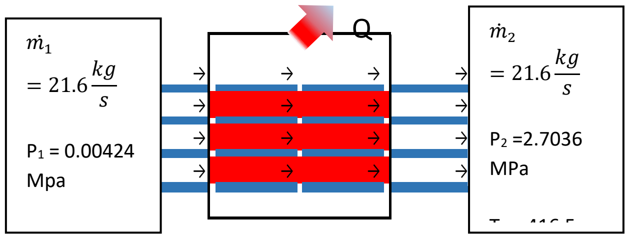


Figure 6 Schematic diagram of the control volume. Simplified shape of the steam generator
Source: own elaboration.

The assumptions of the problem are the same as those pointed out in previous paragraphs. The diagram allowed us to visualize that there was a problem in the quality of the steam obtained, since the requirements according to the technical specifications of the turbogenerator are: temperature and outlet pressure of the superheated steam 350 oC and 3.5 MPa respectively. The exergy destroyed is given by equations 1, 2 and 3 (Cengel, 2015):

$$\dot{X} = T_0\, S_{generated} \quad (14) \qquad (1)$$

$$\dot{S}_{generated} = \dot{m}_1 * (\dot{S}_1 - \dot{S}_2) \quad (15) \qquad (2)$$

$$\dot{X}_{destroyed} = \left(1 - \frac{T_0}{T}\right) Q + \dot{m}[(h_1 - h_2) - T_0\, S_{generated}] \quad (16) \qquad (3)$$

Energy balance

For the proper operation of the integral system of the La Joya sugar mill, a steam mass flow was required at a temperature of 350 °C and a pressure of 3.5 MPa. On the other hand, the total steam produced by the mill before our analysis was 24.3 kg/s and wasted 2.6kg/s. It was proposed to increase the mass flow and steam quality to reach the required and adequate output conditions. Figure.3 represents the conditions required by the TMG data sheet. When comparing the diagrams in Figures 3 and 2, a difference in the outlet pressure (P_2) of 0.7 MPa is observed with respect to the condition in Figure 2. There is also a difference in the steam mass flow rate by 10 kg/s.

Exergetic balance

Taking into account the above, it is proposed:

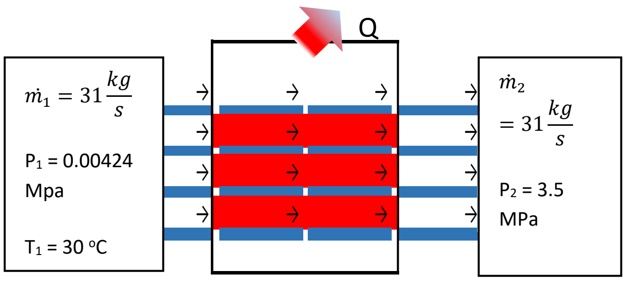


Figure 7 Schematic diagram of the control volume with the required values. Simplified shape of the steam generator
Source: own elaboration.

1. To produce steam to what is strictly necessary for the needs of the mill.

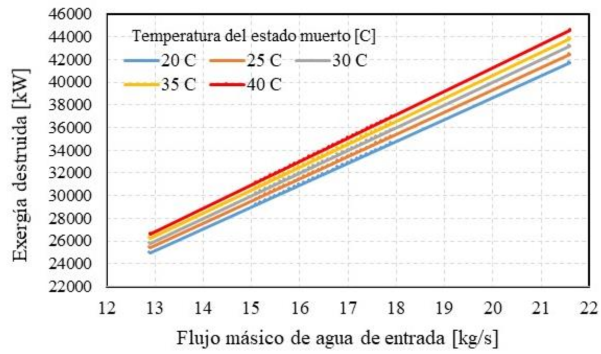
2. To consume the strictly necessary amount of steam. Fuel for the steam generator (sugarcane bagasse) is not a problem, it is in excess. There is a problem in the use of water needed for steam production. It requires extraction and subsequent treatment (softening it to convert it to steam). Therefore, it was proposed to focus on the efficient use and consequent saving of water in two ways:

   – Adjust the water temperature at the inlet to the steam generator and thus increase the efficiency of the system.

   – Adjusting the mass flow of the feed water to achieve greater system efficiency.

According to what was described in the previous paragraph, several simulations were carried out applying the equations previously described. We note that the inlet temperature of the feed water is a preponderant factor for the generation of entropy and the consequent destruction of exergy. Therefore, it is recommended that the boiler supply water be preheated before entering the boiler. This can be achieved if a water preheater is installed in the cycle; it will be necessary to check if this proposal is economically feasible. At different inlet temperatures, the behavior of the steam in entropy generated and exergy lost were calculated. Another way to save energy is to limit the mass flow of water.

Remembering that this is a necessity since it reduces water treatment costs (softening); for this analysis we used a mass flow rate of 16.6 kg/s. To complement this, a comparison is proposed at different possible dead state temperatures for Champotón, Campeche. The corresponding calculations were performed and the following results were obtained.



Graphic 2 Parametric analysis of the exergy destroyed as a function of the dead state temperature (T_0) and the feed water temperature in the baghouse boiler at a constant mass flow rate
Source: own elaboration

The exergy destroyed as a function of the dead state temperature (T_0) and feed water temperature in the baghouse boiler is observed. We note that the lower the dead state temperature (ambient temperature) and the higher the feed water inlet temperature, the lower the exergy destruction. However, the lower dead state temperatures are only for the fall-winter season and it is a parameter that we cannot control. On the other hand, the controllable parameter is the inlet water temperature. Parametric analysis of the variation of destroyed exergy as a function of the dead state temperature (T_0) and the mass flow rate of the feed water in the baghouse boiler was also performed. The results are presented in Graph 2. The variation of exergy destroyed as a function of the dead state temperature (T_0) and the mass flow rate of the feed water in the baghouse boiler is observed. It can be seen that the higher the mass flow rate of the feed water and the lower the dead state temperature (ambient temperature), the lower the exergy destruction. However, the lowest dead state temperatures are only available for the autumn-winter season and it is a parameter that we cannot control. The controllable parameter is the mass flow rate of the feed water to the baghouse boiler.

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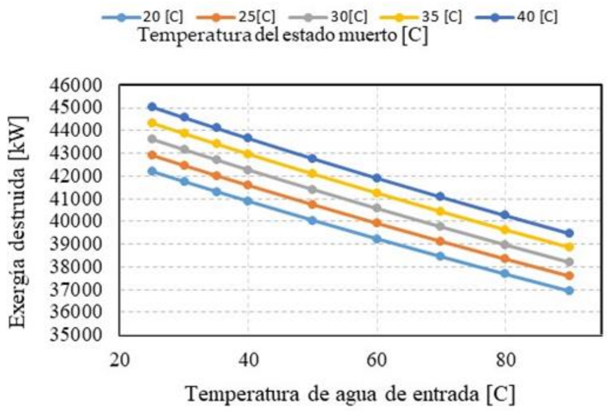
From the previous graphs, 1 and 2, it is concluded: with the decrease of the mass flow of the feed water, and the preheating of the feed water before it enters the boiler and with the dead state temperature conditions as low as possible, the lowest exergy destruction is achieved. However, this exergy analysis is only performed for the steam generator or baghouse boiler. It is necessary to know the behavior of the sugar mill as a whole, to establish whether it is feasible or not to control the mass flows of the feed water, as well as its inlet temperature.



Graphic 3 Parametric analysis of the variation of exergy destroyed as a function of the dead state temperature (T_0) and the mass flow of the feed water in the baghouse boiler
Source: own elaboration

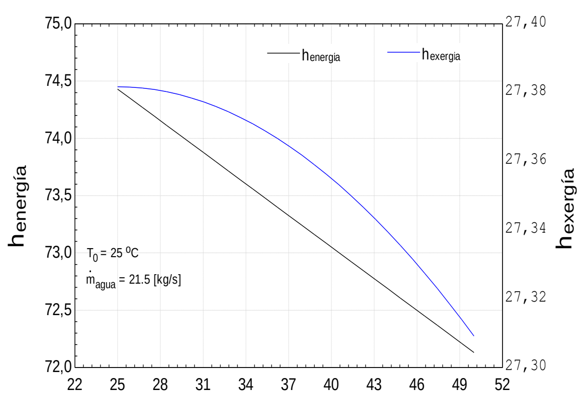
In addition, simulations were carried out by applying equations 1 to 13, to determine the energy and exergy efficiencies of the mill as a whole. The values provided by the mill's control center were used as input data. The Engineering Equation Solver (EES) software was used to perform the calculations. The programming done in EES is presented (report format) as well as the results obtained according to the proposed variations.

Algorithm written in EES, report format.

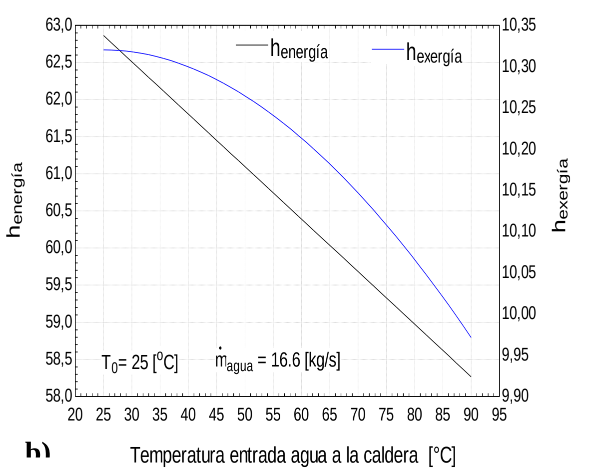
$$\eta_{energía} = \left[\frac{\dot{W}_{turbina} + \dot{m}_{agua} \cdot \left(h_{vapor} - h_{agua}\right)}{10276 \cdot \dot{m}_{bagazo}}\right] \cdot 100$$

The results obtained are shown in Graphs 4a) and 4b). It is observed that the temperature of the water entering the steam generator is an important factor in the variation of the efficiencies (energetic and exergetic), however, its influence on the energetic efficiency is more important. When going from 25 to 50 ^{o}C, the energy efficiency changes by 2.5 units, while the exergy efficiency changes only 0.08 units.

In Figure 4a), a mass flow rate of 21.5 kg/s was maintained and the dead state temperature was kept fixed at 25 ^{o}C. For Graph 4b), a mass flow rate of 16.6 kg/s was maintained and the dead state temperature was kept fixed at 25 ^{o}C. We also note that the energy and exergy efficiencies decrease considerably as the mass flow rate of the supply water decreases. Both show that the energy efficiency decreases linearly as the boiler inlet water temperature increases; the exergy efficiency also shows a decrease, in a parabolic form, as the boiler inlet water temperature increases. Figure 5 shows the variation of the mass flow rate of the boiler feed water, keeping the dead state temperature (T_0) fixed at 25 ^{o}C, and the inlet water temperature (W_{ater}) at 30 ^{o}C, and the change of the energy and exergy efficiencies as it changes. We note that, in both cases, the efficiencies increase with increasing mass flow rate. The increase in energy efficiency is more noticeable when increasing the mass flow from 10 to 25 kg/s, there is an increase of 49 units with a maximum of 85, while in the exergy efficiency the change was only 15 units from 16 to 31.



a)



b)

Graphic 4 Parametric analysis. Variation of the energy and exergy efficiencies of a sugar mill as a function of the temperature of the water entering the boiler and the mass flow of the feed water to the baghouse boiler
Source: Own elaboration

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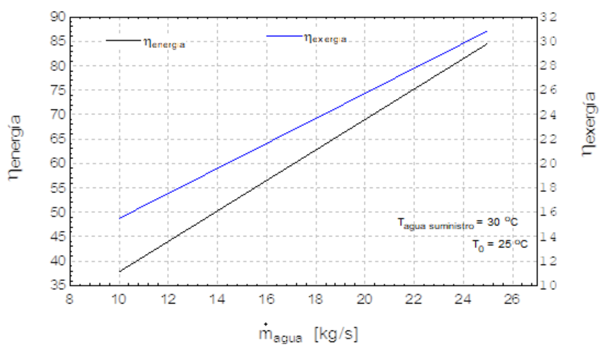
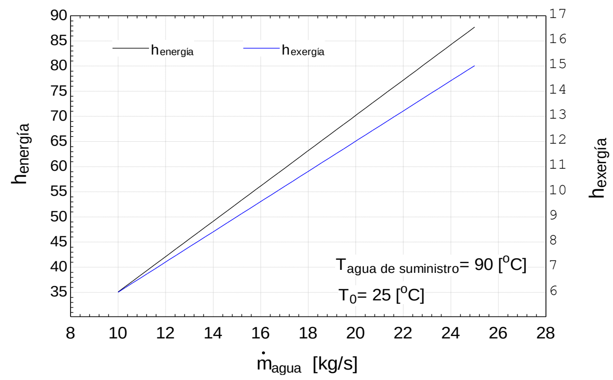
In Graph 5 we observe the variation of energy and exergy efficiencies when the mass flow of the baghouse boiler feed water is modified, keeping the dead state temperature (T_0) fixed at 25 °C, and the inlet water temperature (T_{water}) at 30 °C. We note that, in both cases, the efficiencies increase as the mass flow rate increases. The increase in energy efficiency is more noticeable when increasing the mass flow from 10 to 25 kg/s, there is an increase of 49 units with a maximum of 85, while in the exergy efficiency the change was only 15 units from 16 to 31.



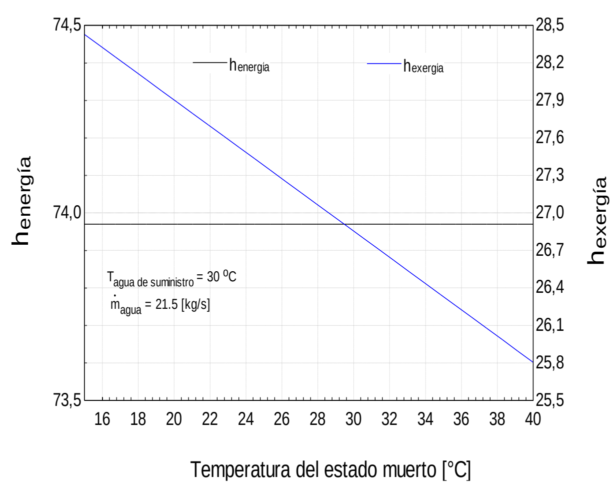
Graphic 5 Variation of energy and exergy efficiencies by varying the mass flow of feed water, in a mill with baghouse boiler, T_0 25 °C, T_{water} 30 °C
Source: Own elaboration

Graph 6 shows the variation of the energy and exergy efficiencies when the mass flow of the feed water is modified, keeping the dead state temperature (T_0) fixed at 25 °C, and the inlet water temperature (T_{water}) at 90 °C. We observe that the efficiencies increase as the mass flow rate increases, but the values achieved are lower with respect to the case of T_{water} at 30 °C. The increase in energy efficiency is more noticeable with an increase of 49 units. However, as a point of comparison we take the mass flow of 21.5 kg/s, where it does not reach 74 units; on the other hand, the exergy efficiency, for 21.5 kg/s the change was negligible. It is more convenient to keep the supply water temperature at 30 °C. It is clear that the mass flow rate of the inlet water is more important as a parameter to increase the overall efficiencies in the complete cycle of a plant than the temperature of the water.



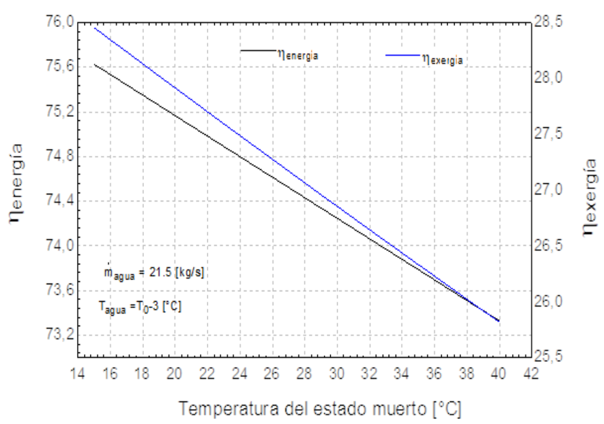
Graphic 6 Variation of energy and exergy efficiencies when varying the mass flow of feed water, in a mill with baghouse boiler, T_0 25 °C, T_{water} 90 °C
Source: Own elaboration

Graph 7 shows the variations of the energy and exergy efficiencies when the dead state temperatures are modified, keeping the feed water mass flow rate fixed at 21.5 kg/s and the inlet water temperature (T_{water}) at 30 °C to compare how the efficiencies change when the dead state temperature is modified. For this case it is observed that the exergy efficiency increases as the dead state temperature decreases, going from 25.8 units (at 40 °C) to 28.5 (at 16 °C). The gain is small, but it increases. It is concluded that the process is more efficient in the autumn-winter season (when the ambient temperature is between 20 to 23 °C) in Campeche. It is observed that the energy efficiency remains constant at a value just below 74 units. This efficiency is not affected by the ambient temperature. It can be understood because in the corresponding equation the temperature variable of the dead state is not involved. Unlike the exergy efficiency equation where it is present in the entropy generation term; equations 1 to 16.



Graphic 7 Variation of the energy and exergy efficiencies by modifying the dead state temperatures and keeping fixed the generator water inlet temperature (T_{water}) 30°C, and the mass flow of feed water at 21.5 kg/s.
Source: Own elaboration

In Figure 8, to compensate a little for the null effect of the dead state temperature variation on the exergy efficiency (Figure 6), the variation of the energy and exergy efficiencies was made by including a variable called water temperature (T_{water}) obtained by subtracting a constant of 3 °C from the dead state temperature (T_{water} = [Dead test -3] °C) to reach the wet bulb temperature of the water, in such a way that it affects the thermodynamic temperatures involved in the energy efficiency equation. Keeping the feedwater mass flow rate and inlet water temperature fixed. For this case it is observed that the exergy efficiency increases as the dead state temperature decreases, going from 25.6 units at 40 °C, to 28.5 units at 15 °C. On the other hand, the energy efficiency also increases from 73.3 units at 40 °C to 75.6 units at 15 °C. As in Graph 5, it is concluded that the process is more efficient in the autumn-winter season, when the ambient temperature decreases in Campeche. Equations 1 to 16 were also used, but the thermodynamic changes that occur when the inlet water temperatures are modified are taken into account; this is a more realistic situation due to the relationship of water temperature with the environment.



Graphic 8 Variation of energy and exergy efficiencies by modifying the dead state temperatures while maintaining the generator water inlet temperature, $T_{water} = T_{0-3}$ °C, and the feed water mass flow rate at 21.5 kg/s
Source: Own elaboration

Conclusions

A baghouse boiler was modeled in 1st and 2nd law of thermodynamics, as well as the complete cycle of the sugar mill "La Joya" in the state of Campeche, Mexico. For the mathematical modeling, the equations reported in the literature were used. The combustion chamber is the area where the greatest exergy loss is concentrated.

In this area, losses of 68% of the fuel input exergy are considered (Singh, 2019). It should be noted, that for the operation of this boiler the fuel (bagasse) is not necessary to save it. It is more necessary is to decrease the consumption of feed water because of the cost associated with the extraction, water treatment, as well as the care of the quality of the steam produced by the boiler. From the behavior of the model, it is clear that a lower ambient temperature results in a lower exergy destruction and therefore in a higher second law efficiency. From the boiler analysis, the following conclusions can be drawn:

– Energetic Analysis; the optimum values for the operation of the electric generation system were determined.

– Energetic analysis; the parametric analysis of the exergy destroyed in the boiler was carried out, observing the factors that have the greatest influence on the generation of entropy.

The variables considered were:

- Inlet water temperature.

- Mass flow rate.

- Dead state temperature.

– Simulations were carried out to determine the energy and exegetic efficiencies of the steam generator with the Engineering Equation Solver Software (EES).

– According to Graphs 5 and 6, the efficiency of the boiler is affected according to the time of the year; that is, at the beginning of the harvest, when the dead state temperature is (T_0) 20°C, there is a maximum efficiency with respect to the dead state temperature in the hottest seasons.

- The steam mass flow required for the boiler was determined to be 16.6 kg/s, which is equivalent to a saving of 5 kg/s with respect to the mass flow with which the plant was operating (21.5 kg/s). The boiler was more efficient in controlling the mass flow of water, saving treated water consumption and meeting the goal of obtaining the steam necessary for the process with the least destruction of exergy. In addition, there is a smaller amount of softened water, which reduces operating costs.

- In the separate exergy analysis of the boiler, an increase in the feed water temperature produces a lower exergy destruction in the boiler; but when considering this same parameter in the overall exergy efficiency of the cycle, it results in a lower efficiency.

- The behavior of the sugar mill as a whole was determined to establish the feasibility of controlling or not, the mass flows of the feed water, as well as its inlet temperature.

- By modifying the mass flow of the feed water and keeping the dead state temperature (T_0) fixed at 25 ºC, and the inlet water temperature (T_{water}) at 90 ºC, to compare how the efficiencies change, it was observed that they increase as the mass flow increases; by increasing the mass flow from 10 to 25 kg/s and with T_{water} at 90 ºC, there was an increase of 53 units in the energy efficiency, reaching a maximum of 88 units.

- For T_{water} at 90 ºC, the energy efficiency changed by 9 units from 6 to 15 units. It was concluded that, it is much more important to increase the mass flow of the inlet water to increase the overall efficiencies in the installations of a mill, than the temperature of the same.

- Variations in energy and exergy efficiencies were determined by varying the dead state temperatures, keeping the feedwater mass flow rate and inlet water temperature fixed. It was observed that the exergy efficiency increases with decreasing dead state temperature. It is concluded that the process is more efficient in the autumn-winter season, when the ambient temperature decreases in Campeche. On the other hand, it is observed that the energy efficiency remains constant at a value slightly lower than 74 units. This efficiency is not affected by the ambient temperature. It is understood because in the corresponding equation the temperature variable of the dead state is not involved. Unlike the exergy efficiency equation where it is present in the entropy generation term.

- To compensate for the null effect of the T0 variation in the exergy efficiency, the water temperature variable (Tagua) was included with a constant of 3 ºC (Twater = [Dead Tested -3] ºC to simulate the wet bulb temperature; in such a way that it affects the temperatures involved in the energy efficiency equation. Feedwater mass flow rate and inlet water temperature were kept fixed. It was observed that the exergy efficiency increased as the dead state temperature decreased from 25.6 units at 40 ºC to 28.5 units at 15 ºC. The energy efficiency also increased from 73.3 units at 40 ºC to 75.6 units at 15 ºC.

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