Energy use in the production of unrefined sugar in Colombia (exergy analysis)

Uso de energía en la producción de panela en Colombia (análisis exergético)

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(Recibido el 4 de mayo de 2010. Aceptado el 25 de noviembre de 2010)

Abstract

The aim of this study is to determine how energy resources are used in the production of unrefined sugar in Colombia. To do this, measurements were carried out in eight sugar mills that represent the typical production processes for unrefined sugar. These data were used to obtain first and second law balances, which were then used to calculate efficiencies and some energy use indicators. By comparing the mills it was found that technological improvements enable energy efficiency to be increased to acceptable levels due to better combustion processes and reductions in energy losses from exhaust gases and heat transfer to the walls. The effect of these improvements in second law efficiency is not significant, which suggests that cogeneration systems should be implemented in large-scale production processes in order to make a better use of the energy resources.

----- *Keywords:* Unrefined sugar production, sugar mills, energy efficiency, exergy analysis

Resumen

El objetivo de este estudio es determinar cómo se usan los recursos energéticos en la producción de panela en Colombia. Para este fin, se realizaron mediciones en ocho trapiches que representan los procesos productivos típicos de la panela. Con los datos experimentales se obtuvieron los balances de primera

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y segunda ley de la termodinámica, a partir de los cuales se calcularon las eficiencias y algunos indicadores del uso de la energía. La comparación de los trapiches mostró que las mejoras tecnológicas permiten aumentar la eficiencia energética a niveles aceptables debido a un mejor proceso de combustión y a la reducción de las pérdidas energéticas asociadas con los gases de escape y la transferencia de calor a través de las paredes. El efecto de dichas mejoras sobre la eficiencia de segunda ley no es significativo, lo cual sugiere que se deberían implementar sistemas de cogeneración en los procesos de producción a gran escala con el fin de hacer un uso más racional de los recursos energéticos.

----- *Palabras clave:* Producción de panela, trapiches, eficiencia energética, análisis energético

Introduction

Unrefined sugar is known as *panela* in Colombia, *gur* in India and Pakistan, *rapadura* in Brazil and Ecuador, *chancaca* in Peru and Chile, and *papelón* in Mexico, Guatemala and other countries of Central America. This product is the result of evaporating sugarcane juice produced by milling. For centuries it has been produced in a traditional fashion, although current production processes include several technological improvements. India is the most important of the 25 countries producing unrefined sugar with about 86% of production, followed by Colombia with 13.9% of world production in the period of 1998-2002. Colombia consumes more unrefined sugar per capita than any other country, with a consumption of 38.6 kg/person/year [1, 2].

Sugar cane is the raw material for unrefined sugar production. The cane is crushed in a mill which extracts the juice with efficiencies ranging between 55 and 70%. The milling residue, called bagasse, has moisture content between 45 and 60%. For this reason, many producers dry the bagasse in atmospheric conditions before using it as fuel. The juice extracted is passed through a purification and concentration process in order to obtain unrefined sugar [2]. In Colombia there are about 23,000 mills for unrefined sugar production. Sugar cane production takes the second place after coffee, with nearly 308,238 farmed hectares [1]. Unrefined sugar is produced in 402 of the 1098 municipalities of the country, and the industry generates more than 350,000 jobs per year, which represents 12% of the economically active rural population [3].

Several studies on the energy diagnostics of unrefined sugar production processes have shown that chimney losses are near 30%, exhaust gas temperatures are near 700 ºC, losses through walls are near 7%, energy efficiency is between 20 and 25%, and CO emissions may reach values of up to 10% by volume [4, 5]. In many mills the bagasse produced is not sufficient as fuel due to the low energy efficiency of the mill, which leads to the use of wood or used tires to supply the energy for the process [5]. The studies that use exergy analysis are dedicated to refined sugar production and to the use of bagasse in power generation systems [6, 7]. There is a lack of studies that use second law analysis of unrefined sugar production. This paper presents an energy and exergy evaluation of unrefined sugar production processes in Colombia using experimental data from the different processes. A traditional furnace-type mill designed by one of the authors is included in the evaluation [8]. First and second law efficiencies were determined for the different processes and some indices were calculated, which allowed a characterization of production units.

Production processes of unrefined sugar

Unrefined sugar is obtained using processes with different degrees of technological development. The simplest process is the furnace-type, used in traditional mills. This is composed of two main parts: the combustion chamber and the juice evaporation zone, or process zone. The gases generated by the combustion of bagasse are used in the evaporation of sugar cane juice. Evaporation is carried out in large containers or pans exposed to the atmosphere. The bottom of these pans is exposed to combustion gases (see figure 1). The furnace-type mills use natural draught.

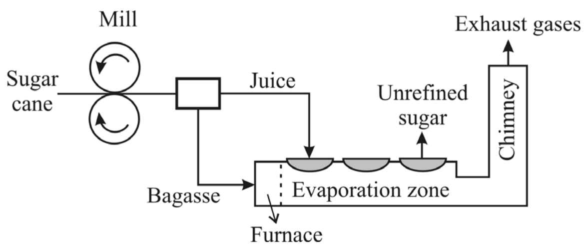

Figure 1 Sketch of a furnace-type sugar mill

Furnace-type sugar mills are classified according to the flow direction of the production process with respect to the combustion gases. When both process and gases are flowing in the same direction, the mill is said to be a parallel flow furnace-type mill. In this kind of mill the product is obtained at the end nearest to the chimney. Modifications to this configuration include the counter flow and combined flow furnace-type mills, where the product is obtained at the furnace end and in the centre, respectively (see figure 2).

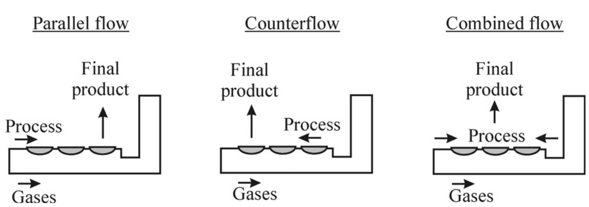

Figure 2 Classification of furnace-type sugar mills

In more advanced processes the combustion chamber is replaced by a boiler that produces steam. This steam is used for the evaporation process by means of heat exchangers submerged in the containers, or in a vacuum process (see figure 3).

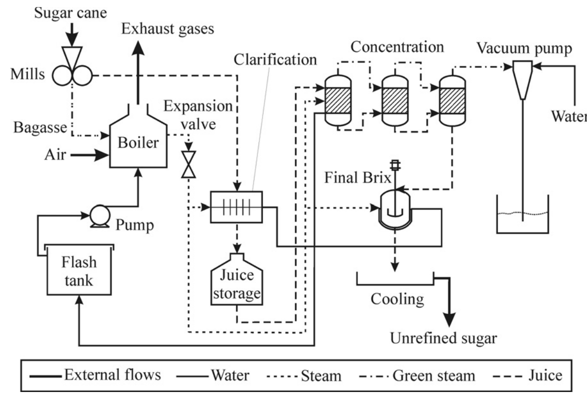

Figure 3 Sketch of an industrial process for unrefined sugar production

These industrial processes allow increased production levels with more control, resulting in a higher quality product.

Methodology

Concerns about depletion of natural resources and environmental pollution have lead to new designs for production processes, aimed at achieving higher energy efficiency. In this study we use a group of sugar mills that represent production processes for unrefined sugar in Colombia: traditional furnace-type (FT) mills, some furnace-type mills with technological improvements, and industrial processes. The facilities are located in different regions of the country. The main characteristics of the mills studied are presented in table 1. The mills are listed in an approximate order of technological development. The abreviature CIMPA in table 1 stands for Centro de Investigaciones para el Mejoramiento de la Agroindustria Panelera (Research Centre for the Improvement of Unrefined Sugar Agro-Industry). GIPUN stands for Grupo de Investigación en Panela (Research Group in Unrefined Sugar), Universidad Nacional de Colombia.

The nearly 23,000 mills for unrefined sugar production in the country have a production capacity between 50 and 300 kg/h. About 83% of the mills are small units that produce less than 100 kg/h, 15% are mid-capacity units producing 150-250 kg/h, and only 2% of the mills are classified as "large" units, with a production higher than 250 kg/h [1]. According to the knowledge of the authors most of mills are of types M1, M2 , M3, and M5. Also, there are no more than ten mills of type M4 and M7, only one mill of type M6, and less than five mills of type M8.

Table 1 Sugar mills studied

Designation	*Mill type*	*Characteristics*
M1	FT in parallel flow	Built at the beginning of the 20th century, typical of small-scale production in Colombia
M2	FT in parallel flow	Similar to the previous one, but built in 1998
M3	FT in counter flow	Designed by CIMPA in 1996
M4	FT in counter flow	With two feeding ports, designed by CORPOICA in 2000
M5	FT in parallel flow	Forced draught mill with a blower at the furnace inlet
M6	FT in combined flow	Designed by GIPUN in 2004
M7	Vapour process	Industrial process. Evaporation is carried out by means of heat exchangers submerged in containers exposed to the atmosphere
M8	Vacuum process	Industrial process. It uses vacuum evaporation in the juice concentration stage.

Atmospheric pressure, temperature and relative humidity were measured in order to calculate the balances. Process variables were also measured, such as temperature at each stage, juice temperature and purity, and mass flows of sugarcane, bagasse, and unrefined sugar. These data was used to determine the enthalpy, entropy, and exergy of the streams. The chemical exergy and activity coefficient of the juice were determined according to Nebra and Fernandez-Parra [9].

Combustion was characterized by measuring the composition (in dry basis), temperature and mass flow of flue gases, as well as the temperature in the combustion chamber. The elemental composition, heating value and moisture content of bagasse were determined at the Laboratorio de Carbones (Coal Laboratory) of the Universidad Nacional de Colombia. The values measured were verified by comparison with those reported in the technical literature [10, 11]. Table 2 presents representative values of the temperature of combustion gases (T_{cg}), temperature of chimney gases (T_{gch}), mass flow of chimney gases ($\dot{m}_{gch}$), dry bagasse mass flow ($\dot{m}_{db}$), and unrefined sugar production ($\dot{m}_{US}$) for the studied mills.

Table 2 Relevant operating data for the mills

Mill	T_{cg} [ºC]	T_{gch} [ºC]	$\dot{m}_{gch}$ [kg/h]	$\dot{m}_{db}$ [kg/h]	$\dot{m}_{US}$ [kg/h]
M1	927	540	3032	193	108
M2	967	637	2126	193	150
M3	809	457	6534	387	260
M4	1087	481	2577	190	155
M5	1067	507	2511	174	120
M6	967	413	3192	274	260
M7	–	354	7042	610	330
M8	–	315	8186	752	600

There is no data of T_{cg} for the last two mills, since the energy source for evaporation in them comes from steam instead of coming from combustion gases. Steam temperature for mills M7 and M8 is of 449 ºC and 457 ºC, respectively. The values of T_{gch} are quite high, which means that chimney gases still have a significant energy potential.

Thermodynamic analysis

In order to carry out a first and second law evaluation of the sugar mills it is necessary to do mass, energy and exergy balances of the production processes. The energy balance, taking the mill as control volume, can be expressed according to equation 1.

$$\dot{m}_{db} \cdot LHV + \dot{m}_{bw} \cdot h_{fw} + \dot{m}_a . h_a = \dot{m}_{cg} . h_{cg} + \sum_i \dot{m}_i . h_i + \dot{E}_l \quad (1)$$

In equation 1 $\dot{m}$ stands for mass flow, *LHV* stands for lower heating value of dry bagasse, *h* stands for specific enthalpy, and $\dot{E}$ stands for energy flow. Subscript *db* stands for dry bagasse, *bw* stands for moisture in bagasse, *fw* stands for saturated liquid water, *a* stands for air, *cg* stands for combustion gases at furnace outlet, *i* stands for a generic sub process in the production of unrefined sugar, and *l* stands for energy losses through walls and with exhaust gases.

Differing from traditional first law analysis, exergy analysis includes a consumption term that quantifies the irreversibility of processes [12]. For this reason it is very useful in the study of energy conversion systems, since it allows the determination of location, type and true magnitude of losses [13-15].

The global exergy balance of processes, taking the whole mill as control volume, can be expressed as shown in equation 2.

$$\dot{B}_{db} + \dot{B}_j = \dot{B}_{gch} + \dot{B}_{US} + \dot{I} \quad (2)$$

In this equation $\dot{B}$ stands for exergy flow and $\dot{I}$ stands for irreversibility rate or flow of exergy destruction. Subscript *j* stands for sugarcane juice, *gch* stands for gases at the outlet of the chimney, and *US* stands for unrefined sugar. The physical exergy of bagasse, of the moisture in bagasse, of air, and of unrefined sugar are zero because all of these are at ambient conditions. The exergy flow of the wastes (which is considered as destroyed) is negligible due to its low thermal level and mass flow. The chemical exergy of dry bagasse is determined from its composition as expressed in equation 3 [16].

$$\frac{b_{db}^{ch}}{LHV} = \frac{1.0438 + 1.882\frac{X_H}{X_C} - 0.2509\left(1 + 0.7256\frac{X_H}{X_C}\right) + 0.0383\frac{X_N}{X_C}}{1 - 0.3035\frac{X_O}{X_C}} \quad (3)$$

where the superscript *ch* stands for chemical, *X* is the mass fraction of each component and the subscripts *H*, *C*, *N* and *O* stand for hydrogen, carbon, nitrogen, and oxygen, respectively.

The chemical exergies of sugarcane juice and unrefined sugar are calculated as those of a sucrose-water solution, following the model proposed by Nebra and Fernandez-Parra [9].

It was assumed that combustion was complete. This can be justified by the low levels of CO measured. As a consequence, the combustion products will consist of species present in the environment (O_2, CO_2, H_2O, N_2). The chemical exergy of this stream is calculated as indicated by Moran and Sciubba [14].

In order to analyse the processes used in the mills in a detailed fashion, the system is divided in two parts: heat generation zone and process zone.

Heat generation zone

The exergy balance in this zone for the furnace-type mills can be expressed according to equation 4.

$$\dot{B}_{db} = \dot{B}_{cg} + \dot{I}_c \quad (4)$$

The exergy supplied by bagasse is transformed into hot combustion gases with some exergy destruction. Subscript *c* stands for the combustion process. In the processes that use vapour, the boiler inputs are wet bagasse, air and water condensates, and its outputs are combustion gases, water vapour, and residues, with some exergy destruction. Recalling that the physical exergy of air and water are zero, and neglecting the exergy of residues, the exergy balance is as shown in equation 5.

$$\dot{B}_{db} + \dot{B}_{cond} = \dot{B}_{gch} + \dot{B}_{s} + \dot{I}_{c} \quad (5)$$

In equation 5 subscript *cond* stands for condensates and *s* stands for steam.

Process zone

The final product for both types of mills is the same, the only difference being the energy resource used. In the furnace-type mills, the energy of combustion gases is used to evaporate the sugarcane juice, while the energy resource in the other processes is the steam generated in a boiler. The input exergy is used for unrefined sugar production with the corresponding irreversibilities. For the furnace-type mills, the exhaust streams are chimney gases, while for the industrial processes the exhaust stream is the condensate. equations 6 and 7 show the exergy balance for furnace-type and for industrial mills is, respectively.

$$\dot{B}_{cg} + \dot{B}_{j} = \dot{B}_{gch} + \dot{B}_{US} + \dot{I}_{p} \quad (6)$$

$$\dot{B}_{s} + \dot{B}_{j} = \dot{B}_{US} + \dot{B}_{cond} + \dot{I}_{p} \quad (7)$$

The subscript *p* in these equations stands for process.

Results and discussion

Sugar mills aim to be self-sufficient by using bagasse as fuel. This allows the definition of an index that records excess or lack of bagasse, defined as remainder bagasse Φ_1 (see equation 8). The moisture content of the bagasse produced and consumed varies with the juice extraction and drying processes. For this reason, it is not possible to make a direct comparison of the mills when wet bagasse is used. Instead it is necessary to define this index based on the dry bagasse produced and consumed.

$$\Phi_1 = \frac{\dot{m}_{db,p} - \dot{m}_{db,c}}{\dot{m}_{db,p}} \quad (8)$$

In equation 8 subscript *p* stands for produced and *c* for consumed. The value of this index is shown in figure 4.

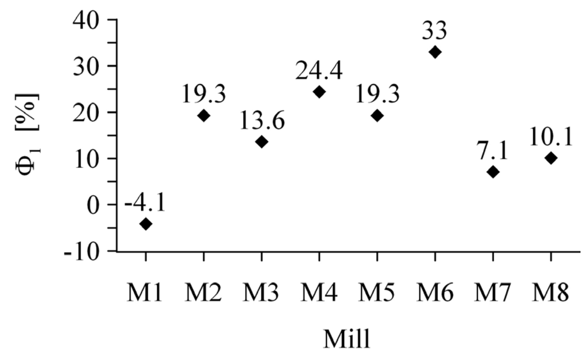

Figure 4 Index of remainder bagasse

It can be observed that technological improvements help in achieving the goal of energy self-sufficiency. It can also be observed that traditional mills need to use additional fuels. The first mill is the only one in which the energy of the bagasse is not enough for unrefined sugar production, showing a lack of 4.1% in the bagasse necessary for the mill to be self-sufficient. This is an alarming result, since most production units in the country have similar characteristics to this mill.

Energy efficiency is a very important index of a mill's performance (see equation 9). This is defined as the ratio of the energy used in the transformation of sugarcane juice into unrefined sugar, and the energy of the fuel.

$$\eta_I = \frac{\dot{E}_{ew} + \dot{E}_{sp} + \dot{E}_{US}}{\dot{m}_{db} \cdot LHV + \dot{m}_{bw} \cdot h_f} \quad (9)$$

In equation 9 η_I stands for first law or energy efficiency, subscript *ew* stands for evaporated water, *sp* stands for solid juice residue. The efficiency for the mills studied is shown in figure 5.

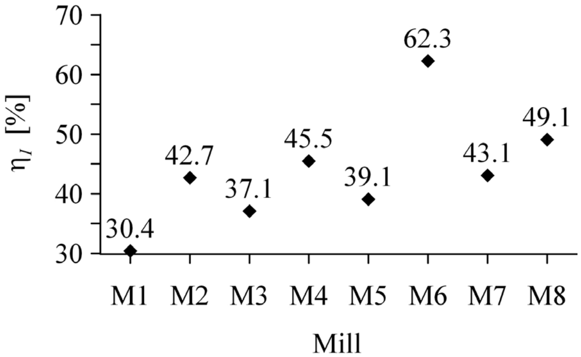

Figure 5 Energy efficiency

The low efficiency of the traditional furnace-type mill (M1) is evident. This result agrees with previous measurements [4, 5]. It can be seen that technological improvements allow energy efficiency to be increased. The fraction of the energy lost with exhaust gases is defined in equation 10.

$$\Phi_2 = \frac{\dot{E}_{gch}}{\dot{E}_{in}} \tag{10}$$

In equation 10 the subscript *in* stands for input. The energy flow of the exhaust stream is a function of its mass flow and specific enthalpy. For this reason, its value depends on excess air as well as on the temperature of chimney gases. Figure 6 shows the value of this index.

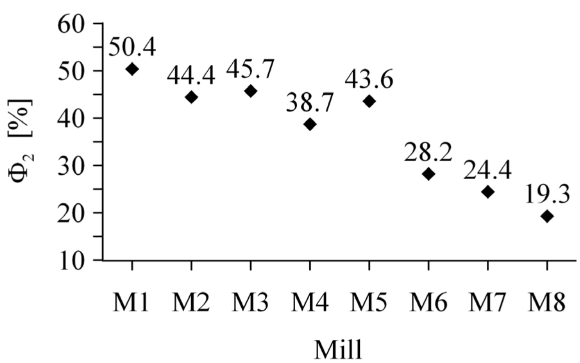

Figure 6 Index of losses with exhaust gases

This figure shows how losses with exhaust gases decrease as technological development increases. The results of the energy balance for the unmodified traditional mill (M1) and for the mill designed with engineering criteria (M6) are shown in figure 7. Mill M6 is superior in regard to the distribution of energy resources. This advantage results in higher productivity.

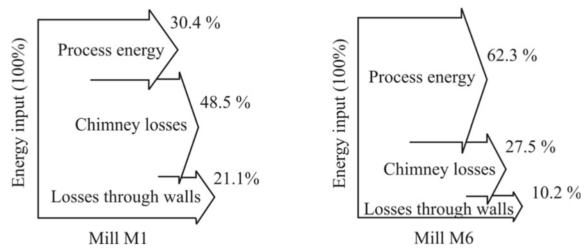

Figure 7 Energy balance

The exergy efficiency of the combustion chamber in the furnace-type mills is defined in equation 11 as the ratio of the exergy of hot combustion gases to that supplied with bagasse.

$$\eta_{II,c} = \frac{\dot{B}_{cg}}{\dot{B}_{db}} \tag{11}$$

In equation 11 η_{II} stands for second law efficiency and subscript *c* stands for combustion chamber. For the processes that use vapour, the exergy efficiency of the boiler (equation 12) is defined using the exergy of the produced steam and that of the input flows of bagasse and condensates.

$$\eta_{II,c} = \frac{\dot{B}_{s}}{\dot{B}_{db} + \dot{B}_{cond}} \tag{12}$$

The exergy efficiency of the heat generation process of the mills is shown in figure 8.

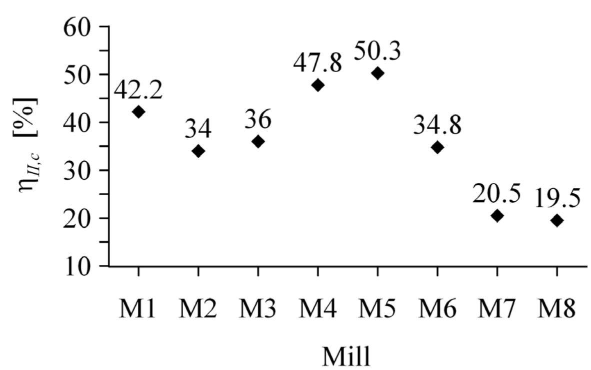

Figure 8 Exergy efficiency of heat generation zone

The behaviour of exergy efficiency in the combustion chamber is determined by the burning of the fuel, the mixing of air with fuel, the temperature of the combustion chamber, the flow of gases, and the moisture of the bagasse, among other factors. Consequently, it would be necessary to perform a detailed analysis in order to determine the effect of each factor.

The mills that use vapour for the process have low exergy efficiencies, due mainly to the fact that temperatures in the combustion chamber are lower because the bagasse burned is wet, and because the gases produced are used for steam production instead of being used directly for unrefined sugar production, which introduces an additional source of irreversibilities. The second law efficiency of the process in the furnace-type mills is defined in equation 13.

$$\eta_{II,p} = \frac{\dot{B}_{US}}{\dot{B}_{cg} + \dot{B}_j} \qquad (13)$$

For the processes with vapour, the efficiency will be as in equation 14.

$$\eta_{II,p} = \frac{\dot{B}_{US}}{\dot{B}_s + \dot{B}_j} \qquad (14)$$

Figure 9 shows the exergy efficiencies of the process for the different mills.

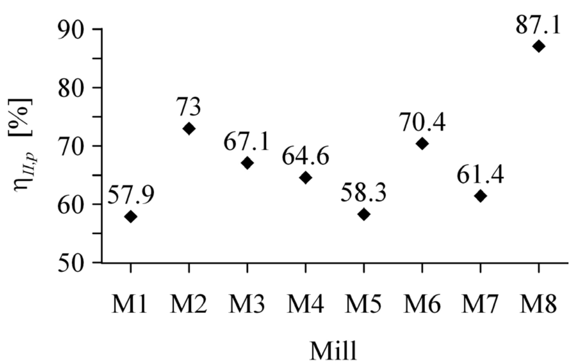

Figure 9 Exergy efficiency of the process

The nature of the evaporation process in the mills studied means that it is not possible to make a direct comparison between furnace-type mills and the ones that use vapour. There are many factors determining this behaviour: temperature of combustion products, heat transfer coefficient, flow of gases, etc. Mill M8 has the highest process exergy efficiency due to the use of vacuum evaporators in series for the concentration of the juice.

The global exergy efficiency of a mill is defined according to equation 15.

$$\eta_{II} = \frac{\dot{B}_{US}}{\dot{B}_{db} + \dot{B}_j} \qquad (15)$$

Figure 10 shows the value of the global exergy efficiency for the mills studied.

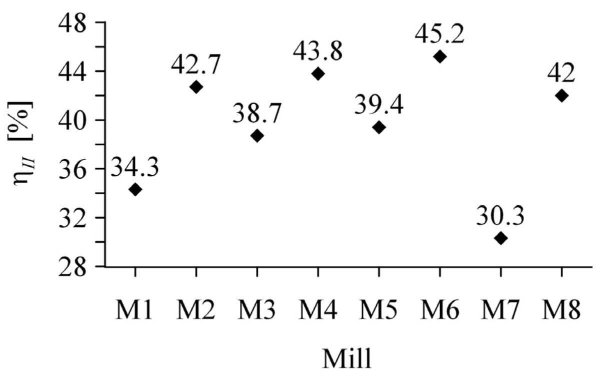

Figure 10 Global exergy efficiency of the mills

Mill M6, recently built and designed with the aim of improving the use of energy, is the one with the highest exergy efficiency. In the processes that use vapour, the energy of the fuel suffers an additional degradation step in the boiler. In mill M8, this is compensated by the high efficiency of the concentration process. In mill M7 the efficiency of the process is sacrificed in the interests of a higher quality product (ecological unrefined sugar). The sugar cane used in this mill is farmed without using chemical products, so its sucrose content is lower and it has higher moisture content. As a consequence, the evaporation of the juice requires a higher amount of bagasse.

It is interesting to define an index that quantifies exergy losses through chimney gases (equation 16).

$$\Phi_3 = \frac{\dot{B}_{gch}}{\dot{B}_{db}} \quad (16)$$

The behaviour of this index is similar to the energy losses with exhaust gases (see figure 11). The mills that use vapour have lower losses due to controlled combustion, which allows low temperature of the chimney gases and excess air.

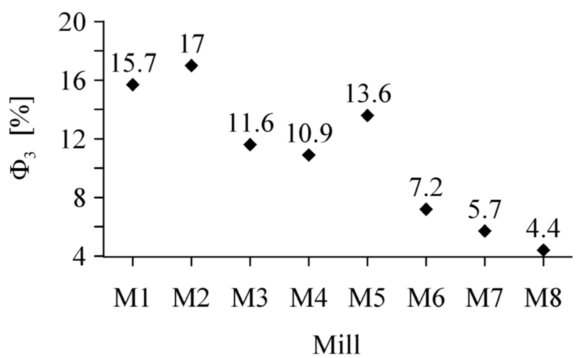

Figure 11 Exergy losses with exhaust gases

It is useful to define an index for characterizing the exergy use in the mills that takes into account the production level of each mill (see equation 17). This index is defined as the ratio of the exergy supplied with bagasse and the mass flow of unrefined sugar produced:

$$\Phi = \frac{\dot{B}_{db}}{\dot{m}_{US}} \quad (17)$$

A low value on this index indicates a good relationship between exergy use and productivity. This exergy production index is shown in figure 12. The value of this index for mill M1 is high due to major energy losses and low productivity. Mill M2 has reduced losses through walls and higher productivity, which partially compensates the high exergy losses through exhaust gases, resulting in a lower index. In mill M3 the bagasse is not dried, leading to significant energy consumption in the evaporation of its moisture, increasing the value of the index. In the mill with two feeding ports (M4), there are moderate losses and bagasse is effectively dried, resulting in a low value for the exergy production index. Although in mill M5 the bagasse is dried, there is a high amount of excess air, and consequently the index is relatively high. Mill M6 has been designed to improve the combustion process and heat transfer, and has moderate excess air and exhaust temperature. As a result, the exergy production index for this mill is the lowest. Mill M7 operates with "ecological production" criteria, sacrificing productivity in order to obtain a high quality final product. The term "ecological production" means that despite the high energy demand of the process, bagasse is the only energy source used with no additional consumption of fossil fuels. This explains why the highest index corresponds to this mill. This drawback is compensated by increasing the price of the product. The index corresponding to mill M8 is low because the efficiency of the process is very high.

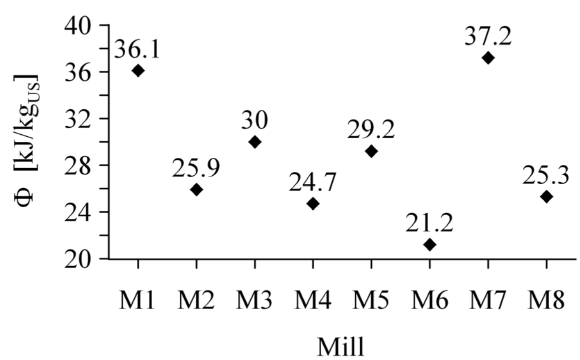

Figure 12 Exergy production index

The exergy balance for mills M1 and M6 is shown in figure 13. The improvements in design result in better use of energy resources. It is important to mention that construction and operation costs of mills M1 and M6 are similar.

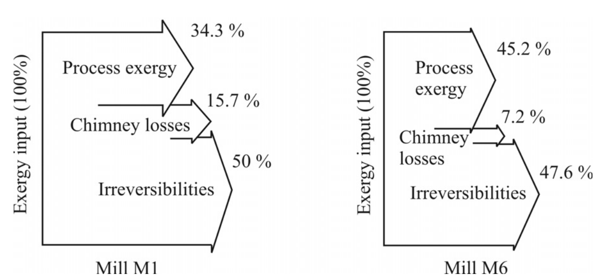

Figure 13 Exergy balance

Conclusions

In this study, first and second law analyses were applied to eight sugar mills that represent the different mill designs for unrefined sugar production in Colombia. The study is based on experimental data from the mills, and on laboratory tests to characterize bagasse fuel. The main findings of the research are the following:

- In spite of the technological improvements in furnace-type sugar mills, there is still a high energy potential in exhaust gases due to high mass flow and temperature in the chimney.
- Technological improvements of furnace-type mills result in an increase of energy efficiency, leading to self-sufficiency.
- The application of thermal engineering criteria to design of furnace-type mills allows energy and exergy efficiency to be increased, as well as improving self-sufficiency and productivity, as demonstrated by the results of mill M6.
- The results show that improvements have been conceived based on first law criteria and not on an exergy basis. Consequently, the exergy destruction remains high.

There is a high potential for improving second law performance in sugar mills by using cogeneration. In this way, the exergy of the fuel will be used for power generation, and the residual streams for evaporation of sugarcane juice. This alternative is more suitable for larger, industrial mills.

Acknowledgements

The authors wish to thank FEDEPANELA Antioquia, especially to engineer Francisco Cadavid; to the owners of the mills studied, and the members of GIPUN, especially to engineers Eugenia Gonzalez, Pedro Rivero, and Jorge Iván Álvarez.

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