Exergy Analysis applied to a Mexican flavor industry that uses liquefied petroleum gas as a primary energy source

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Abstract: An exergy analysis to a Mexican flavor industry, which uses liquefied petroleum gas as a primary energy fuel in their process equipment was carried out. .
The analysis used a proposed method that quantifies efficiency by means of exergetic indicators. To apply it to this case study equipment, the system or process was assumed to be a block that interacts with the surroundings in three ways: heat, work and mass transfer. The analyzed blocks were boilers, a thermal oxidizer, dryers, a distillation tower and extractors. Work and heat needs were covered by liquefied petroleum gas.
The exergy indicators quantify the degradation of energy by determinining the difference between the actual operation efficiency of the block and the maximum operation, both of them obtained from second law point of view. These indicators were exergy loss, efficiency, effectiveness, performance and potential of improvement.
Following the exergetic method application, it was found that the indicators of the effectiveness and performance in all blocks analyzed are near zero. This means that the process equipments are using a high exergy source to perform their function and also in large quantity. The results show that the oxidizer presented the major irreversibilities, and it is the equipment with the greatest potential for improvement and the key to reducing fuel consumption.

Keywords: *Optimization, Efficiency, Indicators, Block, Quantify*

Nomenclature

Latin Symbols

Efl *effluents exergy losses* .... *kJ/kg*
Ex *exergy* .... *kJ/kg*
H *enthalpy* .... *kJ/kg*
Irr *Irreversible exergy losses* .... *kJ/kg*
S *entropy* .... *kJ/kg K*
Pot *Improvement potential* .... *kJ/kg*

Greek symbols

ε *Effectiveness* ....
ζ *Performance* ....
η *Efficiency* ....
Δ *difference*

Subscripts

ntp *net produced* ....
nts *net supplied* ....
tte *total input* ....
tts *total output*
uts *useful outlet exergy*
0 *reference, dead state*

1. Introduction

The industry sector is sensitive to the variability of the energy prices; as a result it adjusts the production priority to an efficient energy consumption to obtain advantages in cost. The economic factor is not the only reason to reach an efficient energy consumption in a country. The environmental negative impact as a result of an inefficient use of an energy resource is important as well [1,2].

Efficient energy use in the industry sector is possible with energy consumption analysis. Two problems promptly arise: the scarce information about an optimum use of energy in the industrial processes and the use of inefficient technology. [3,4].

The exergy analysis is especially useful when it is necessary to detect equipment, systems or processes that use a high quality energy source that is unnecessary for the objective, because in this case important exergy losses arise [3]. Exergy analysis has been applied since the early 1970's with the aim of finding the most rational use of energy, which means at the same time reducing fossil fuel consumption, applying energy efficiency and matching the quality levels of the energy supplied and demanded [5]. The exergy method is useful for improving the efficiency of energy-resource use, for it quantifies the locations, types and magnitudes of wastes and losses. Also it is useful in identifying the causes, locations and magnitudes of process inefficiencies [6].

This paper discusses an exergy analysis of a flavoring industry plant (FIP) located in Morelos, Mexico. The monitoring of energy utilization of different equipments used in the process was necessary in order to investigate, analyze, verify and compare the data so as to try to understand the actual condition. The monitoring and data collection lasted from March to December, 2009. Table 1 shows the analyzed equipment:

Table 1. Identify and capacity of the analyzed equipment.

Identification	Capacity	Units
Distillation column A-001	700	l
Distillation column A-002	700	l
Distillation column A-004	70	l
Distillation column A-009	1900	l
Extractor A-103	2734	l
Extractor A-104	2734	l
Extractor A-106	7570	l
Extractor A-107	7570	l
Dryer S-01	30	kg/h
Dryer S-02	40	kg/h
Dryer S-03	150	kg/h
Dryer S-05	100	kg/h
Boiler CA-01	250	hp(S)
Boiler CA-02	100	hp(S)
Oxidizer		

l: liters, kg/h: kilograms per hour, hp(S) Boiler horsepower

These five kinds of equipments have the following function in the FIP:

- *Distillation column*: To separate mixtures based on differences in their volatilities in a boiling liquid mixture.
- *Extractor*: To separate a substance from a matrix. In the case of the FIP we refer to solid phase extraction.
- *Dryers*: To eliminate the liquid in a substance. The powder production starts by atomizing the emulsion in a hot air stream inside the dryer chamber in which the liquids evaporate instantly. The active material in the emulsion is encapsulated inside the film material.
- *Boiler*: To generate steam with the liquefied petroleum gas (LPG) combustion. The liquid water changes to vapor phase due to the high temperatures obtained.

2. Methodology of exergetic analysis

Exergy is defined as the maximum theoretical work obtainable from the interaction of a system with its environment until the equilibrium state between both is reached [7], it can also be seen as the departure state of one system from that of the reference environment [8]. Therefore, exergy is a thermodynamic potential dependent on the state of the system under analysis and its surrounding environment, so called “reference state”. The environment is regarded as a part of the system surroundings, large in extent so that no changes in its intensive properties, pressure P_0 and temperature T_0 mainly, occur as a result of the interaction with the system considered.

The exergy method quantifies the energy degradation using six different indicators. We assume the equipment, system or process to be a block that is interacting with the surroundings through heat, work and mass transfer. The work and the heat refer to the energy such as electricity solar radiation, mechanic work, etc. The mass transfer is the inflow and outflow of chemical substance, flows like vapor and fuel [9]. In the analyzer equipments in the flavor industry, the required work and heat are provided by LPG.

The exergy is the quality of energy in the block and is defined as:

$$Ex = (H - H_0) - [T_0(S - S_0)] \quad (1)$$

In Eq (1), the first term is the total enthalpy of the system that includes the thermal, mechanical, chemiscal, kinetic and potential energy. The second term, on the right -hand side, is the total entropy. The enthalpy (H_0) and entropy (S_0) of the reference state are defined by its pressure, composition, velocity, position and temperature.

2.1. Exergetic indicators

In order to quantify the energy degradation of the block, a series of exergy indicators were used. These indicators were: exergy losses (Irr), efficiency (*η),* effectiveness (*ε),* performance (*ζ),* potential of improvement (*Pot).* These are the relationship between the reality and the ideality expressed by fraction or percentage [4]. Table 2 shows the corresponding indicators:

Table2. Exergetic indicators to quantify the energy.

Exergy indicator	Equation
Exergy losses	$Irr = \sum (Ex_{tte} - Ex_{tts})$
Efficiency	$\eta = \frac{\sum Ex_{tts}}{\sum Ex_{tte}}$
Effectiveness	$\varepsilon = \frac{Ex_{ntp}}{Ex_{nts}}$
Performance	$\zeta = \frac{Ex_{uts}}{Ex_{tte}}$
Potential improvement	$Pot = Irr(1-\varepsilon) + Efl$

Below is a brief explanation of each indicator:

- *Exergy losses.* The measure of the total exergy provided by the inflow such as fuel and raw material, and the total exergy at the outlet such as products and effluents.
- *Efficiency.* The ratio of the total exergy at the outlet of the block in relation to the total exergy of the inlet.
- *Effectiveness.* It evaluates if the analyzed block satisfies its function, considering the term “net” means difference (Δ). The net exergy produced is the one obtained by the products and the net exergy supplied is provided by the energy resource, for instance LPG.
- *Performance.* Relation of the useful outlet exergy and total entrance exergy.

- *Potential improvement.* It is the measurement of block improvement. The equation has been obtained through the combination by exergy losses and the system effectiveness. The exergy losses are due to two different sources, the first one derives from the internal use of the block and is referred to as irreversibilities (Irr) and the last one arises from the effluents (Efl), that are released into the environment like wastes.

To obtain the reference temperature, the actual hourly temperature in the process plant was registered for a week. The value was 29.3 ºC±1.9°C. The pressure was considered constant at 101.325 kPa.

2.2. Blocks

As mentioned in the introduction, five different equipments were analyzed. The exergetic balance of each equipment was different and depended on the way that it operated, the energy quantities they require, and the energy wasted in irreversibilities, so it was necessary to consider an exergetic balance for each case.

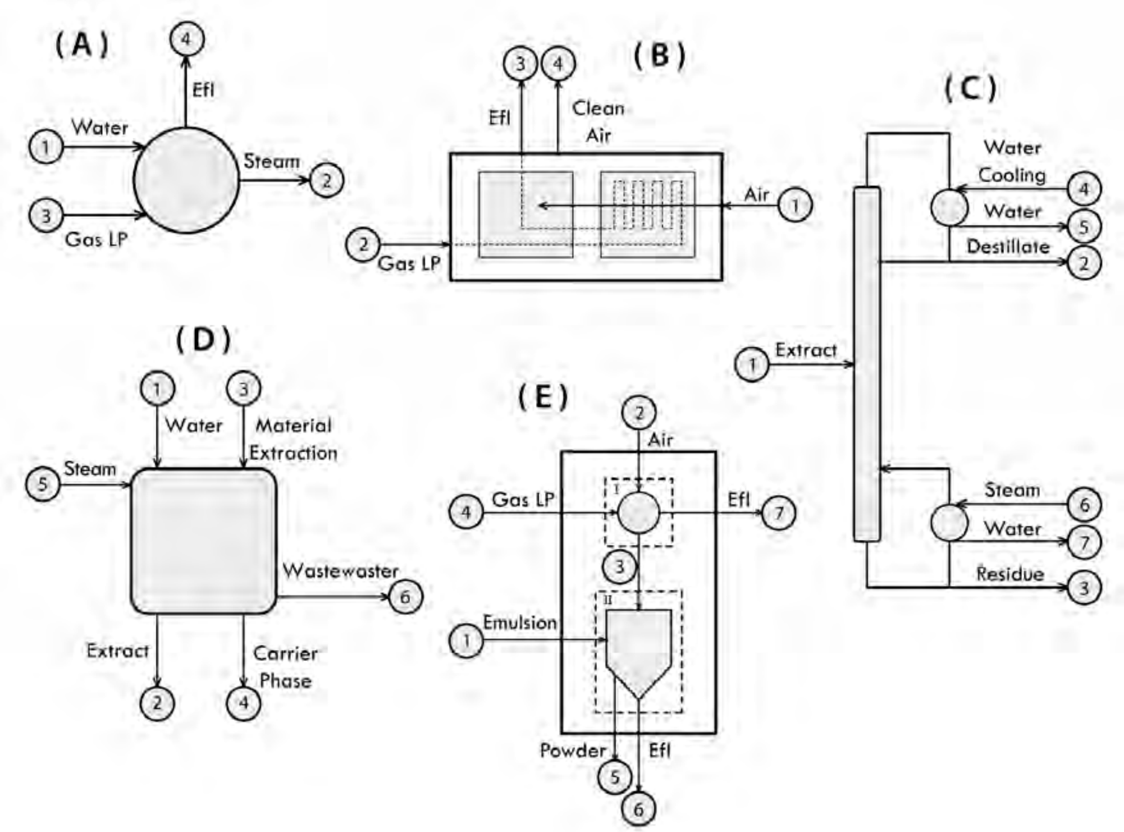

Fig. 1. Diagrams of the blocks. Boiler (A), Oxidizer (B), Distillation tower (C), Extractor (D) and Dryer (E)

Figure 1 shows the diagrams of the different blocks to be analyzed. The numbers represent the process streams of each case. When the arrows point inwards, it refers to the stream with the exergy that enters the equipment; it could be fuel, vapor or fluid. Conversely, when the arrow points outwards, it refers to the stream with the exergy that goes to the environment, such as products, effluents or wastes. Table 3 shows all the exergetic balances obtained for the blocks.

Table 3. Exergetic balance

Block	Ex_{tte}	Ex_{tts}	Ex_{nts}	Ex_{ntp}
Distillation tower	$Ex_1 + Ex_4 + Ex_6$	$Ex_2 + Ex_3 + Ex_5 + Ex_7$	$(Ex_6 - Ex_7) + [Ex_1 - (Ex_2 + Ex_3)] + (Ex_4 - Ex_5)$	$(Ex_2 + Ex_3) - Ex_1$
Extractor	$Ex_1 + Ex_3 + Ex_5$	$Ex_5 + Ex_4 + Ex_6$	$Ex_5 - Ex_6$	$(Ex_2 + Ex_4) - (Ex_1 + Ex_3)$
Dryer	$Ex_1 + Ex_2 + Ex_4$	$Ex_5 + Ex_6 + Ex_7$	$Ex_4 - Ex_7$	$Ex_5 - Ex_1$
Boiler	$Ex_1 + Ex_3$	$Ex_2 + Ex_4$	$Ex_3 - Ex_4$	$Ex_2 - Ex_1$
Oxidizer	$Ex_1 + Ex_2$	$Ex_3 + Ex_4$	$Ex_2 - Ex_3$	$Ex_4 - Ex_1$

Finally, with the exergy balance of each block it is necessary to calculate the exergetic indicators with the equations presented in Table 2.

3. Results

The values of the indicators in all the equipments studied were plotted with the objective of analyzing and comparing the behavior in the FIP.

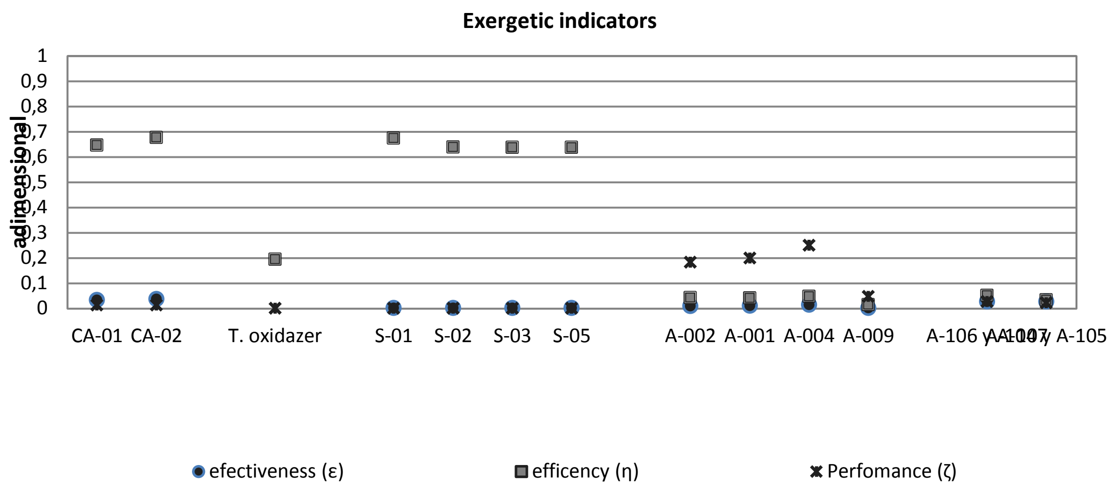

Fig. 2. Effectiveness, efficiency, performance of the analyzer blocks in the FIP

Figure 2 presents the dimensionless indicators: the effectiveness, efficiency and performance. The effectiveness is near a zero value in all the blocks as a consequence of the important quantity of exergy required to carry out their objective. This happens commonly with old equipment where the design does not have priority on saving fuel. The performance is larger in the distillation columns 0,2 to 0,3 because they do not require high temperatures for their function and the effluents are smaller than in others blocks. The efficiency of the combustion equipment is estimated at 0.7 which shows a large amount of effluent in the total output exergy, with up to 65% of exergy provided by the LPG thrown into the atmosphere as combustion gases.

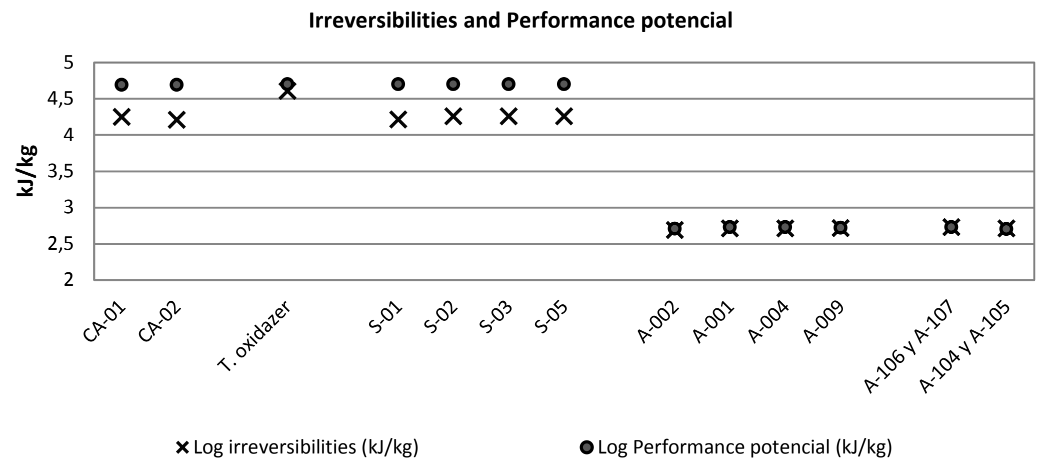

Fig. 3. Irreversibility and improvement potential of the analyzer blocks in the FIP

In Figure 3, the distillations columns and extractors present similar improvement potential values and irreversibilities due to the fact that the effluents are insignificant, a slight flow of water between 60°C to 80°C from the steam used to obtain the process temperature circulating in the insulation of the equipments. In contrast in the combustion equipment their improvement potential is higher than the irreversibbilities because of the large quantity of effluents, 33000 kJ/kg. These blocks have an important feasibility of optimization, by recovering heat from the effluents to preheat the water used in the boiler.

As a result of the method, the global exergy flow of the plant can be represented with a Sankey diagram; this diagram is a summary of the exergy analysis of all equipments of the FIP. The width of the arrow gives the flow, specifies the effluents (arrows pointing upwards), irreversibilities (arrows pointing downwards) and the net exergy produced (arrows pointing to the right), the numbers outside the arrows in parenthesis describe the percentage of the total exergy in the FIP, and the numbers inside the blocks in parenthesis describe the quantity of equipment that represents each block. The indicators represent a specific aspect of the equipment and the Sankey diagram the interaction of all the blocks in the FIP. In Figure 4, an expansion in scale from the steam of the oulet of the boilers to the inlet of the extractors and distillation tower was necessary, because only the 0.35% is the net produced exergy as steam.

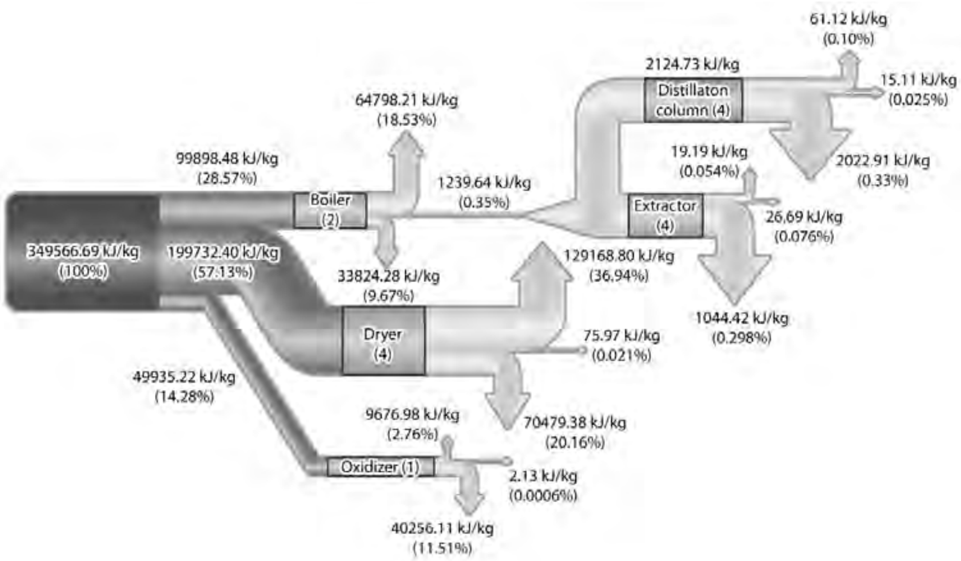

Fig. 4. Sankey diagram for the global exergy flow in a FIP

The diagram shows that the exergy provided by the LPG energy source is 349,566 kJ/kg, and is distributed to the process blocks. Over half of the exergy 57.1% is used for the driying process in which only 0.021% of the net exergy produced is obtained as powder.

The distillation columns and extractors have small effluents of approximately 20 kJ/kg per equipment, compared with the combustions blocks with 33000 kJ/kg. On the other hand. they have more important irreversibilities, as compared to the combustion blocks. To optimize these equipments it is necessary to analyze how they operate and find an improvement in their design. [10].

4. Conclusions

In this paper a second law analysis in a flavor industry was carried out. The process blocks with higher efficiency, close to 0.7, were the boilers and the dryers. This is to the fact that the total output exergy includes the effluents, that represent 90% of the total of the exergy that is provided by the fuel.

The thermal oxidizer does not present important losses in effluents (9,676.98 kJ/kg), but its irreversibilities are the largest with 40,256.11 kJ/kg and an effectiveness close to zero. As a result, this block has the highest performance potential 49,933.6 kJ/kg and is the main equipment in which to focus in order to achieve a low fuel consumption. It is possible to use other kind of equipment for the same objective (eliminates unpleasant odor) without using combustion.

The distillation towers and extractors present low effluents (20 kJ/kg) per equipment approximately as compare with combustion blocks (33,000 kJ/kg). This means that the energy is degraded in the distillation columns due to the presence of significant irreversibilities. To optimize these equipments it is necessary analyze their performance and find a design improvement, owing to the fact that they are more than 30 years old with no technological improvements. The best solution is to upgrade the equipments.

The indicators in all equipments such as efficiency, effectiveness, and performance are close to zero. This means that the FIP requires a high exergy source and a large quantity forcarried out its objective, approximately 350,000 kJ/kg. This consumption decrease at least 68% applying waste heat recovery of the effluents of the combustion equipments, like boilers, dryers and oxidizer, to warm currents in other processes such as in the extractors where the optimal temperature is 60 °C. [10].

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