Ochoa, Guillermo Valencia; Rojas, Jhan Piero; Avella, Juan Campos

Article

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International Journal of Energy Economics and Policy

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Ochoa, Guillermo Valencia/Rojas, Jhan Piero et. al. (2019). Energy optimization of industrial steam boiler using energy performance indicator. In: International Journal of Energy Economics and Policy 9 (6), S. 109 - 117.
http://econjournals.com/index.php/ijeep/article/download/8188/4639.
doi:10.32479/ijeep.8188.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2019, 9(6), 109-117.

Energy Optimization of Industrial Steam Boiler using Energy Performance Indicator

Guillermo Valencia Ochoa[1]*, Jhan Piero Rojas[2], Juan Campos Avella[1]

[1]Mechanical Engineering Program, Faculty of Engineering, Grupo de Investigación en Gestión Eficiente de la Energia-kaí, Universidad del Atlántico, Carrera 30 Número 8-49, Puerto Colombia 081007, Atlántico, Colombia, [2]Faculty of Engineering, Universidad Francisco de Paula Santander, #0-a Avenida Gran Colombia No. 12E-96, Cúcuta, Norte de Santander, Colombia. *Email: guillermoevalencia@mail.uniatlantico.edu.co

Received: 30 May 2019 **Accepted:** 05 September 2019 **DOI:** https://doi.org/10.32479/ijeep.8188

ABSTRACT

This article shows the application of an energy management system and the calculation of energy efficiency indicators to a pyrotubular boiler, following the guidelines of the ISO50001 standard. The actual energy consumption indicators, the theoretical consumption index, the energy baseline and the efficiency index 100 were evaluated based on gas consumption and steam production data. As for the savings measure, a 20% reduction in gas consumption can be achieved by reducing the operational variability equivalent to 186,633 m^3/month, thereby achieving a monthly savings of $70,920,717 COP and a large reduction in natural gas equivalent to a reduction in CO_2 emissions (1,318,739.05 kg CO_2/month). Also, the purges currently recorded in the boiler are higher than the recommended value for this equipment, and the excess air released varies between 6% and 11%, increasing the losses due to sensible heat. Three main implementations were applied to improve the energy performance of the steam boiler. The first saving implementation was the reduction of the generation pressure from 250 to 180 psig, achieving a lower gas temperature with a reduction of heat losses from the boiler, pipes and steam leakage losses, achieving a saving of 2% of the average natural gas consumption. The second implementation was the automation of the boiler purges, in accordance with the recommended value UNE-9075/85, achieving a total saving of 0.66%, and the third measurement allows on-line correction of the combustion air by direct measurement of O_2, which maintains the measured oxygen value at 3%, which is the recommended value. With this practical and novel method energy performance indicator on the boiler, was increased the performance of the equipment, as well as the production costs and environmental impact reduction.

Keywords: Energy Optimization, Steam Boiler, Energy Performance Indicator, ISO 50001 Standard
JEL Classification: Q42

1. INTRODUCTION

Boilers are devices widely used in industry for the steam production, which allows electricity to be generated through steam turbines (Jayamaha, 2006), (Moran et al., 2011). The efficient operation and implementation of energy management systems in these generation systems have made it possible to identify potential energy savings through good operational practices in some companies (Mecrow and Jack, 2008), (Barma et al., 2017).

Traditionally, the energy saving potential for these processes has been based on energy efficiency indicators from the thermodynamic point of view, allowing the construction of methods to obtain the exergetic losses and the exergetic efficiency of the boilers (Behbahaninia et al., 2017). However, these methods require complete knowledge of the thermodynamic state properties of the working fluids involved in the process, which in some cases requires rigorous energy simulations, computational resources and significant training times for the handling of the necessary computer tools (Zhang et al., 2010), (Dal Secco et al., 2015). In this sense, an evaluation of the boiler performance in an ethanol production plant was carried out using an exergy and irreversibility analysis in which the individual components of the system are evaluated, demanding an exhaustive evaluation of the thermodynamic properties in the process (Pambudi et al., 2017). Similarly, research based on the analytical evaluation of these properties has made it possible to estimate the thermal equilibrium of coal-fired boilers, supplemented by numerical results of energy simulations (Junga et al., 2017), (García et al., 2016). On the other hand, some studies have focused on the performance evaluation of the actual efficiency in the boiler (Baldi et al., 2017), presenting only the estimates of the actual efficiency and the expected efficiency from the historical data set of the equipment, but not presenting the recommendations or improvements to be implemented in the equipment (Shen et al., 2017), (Nikula et al., 2016).

In addition, the emissions assessment is an essential factor which play a complementary role on the energy saving indicators, facing the constant advance of alternative energies and advanced fuel regimes, for which the University of West-Virginia studied the emissions caused by ignition compression machines (Carder et al., 2017), concluding that a reduction on the energy consumption on this type of process conduct also to a reduction on the emission. Therefore, energy efficiency seeks to mitigate many current environmental problems in different industrial process, such as the greenhouse gas emission effect produced from incineration plants (Hwang et al., 2017), round wood production (Nakano et al., 2016), the construction industry (Arıoğlu et al., 2017), among others. Many researchers had been developed for its reduction, making energy and economic analyses (Feng et al., 2017), bibliometrics analysis (Geng et al., 2017), and theoretical analysis (Cucchiella et al., 2018). In addition, new control strategies oriented to obtain an optimal management of emissions was proposed (Bui and de Villiers, 2017), (Kumar and Subramanian, 2017). These strategies have been used for the industry in the creation, processing, and disposal of reagents, obtaining a reduction of 29.86% (Santín et al., 2017).

In this sense, emission control analysis was carried out using dispersion models, for which all pollutants and their emission rates are processed to show the initial distribution of the contaminant in the region, proposing a three-dimensional model to help control emissions (Skiba and Parra-Guevara, 2013). Recent innovation had been developed in this field, such as the SiC-FET technology, a silicon carbide field effect transistor for gas emission control and gas detection, which use a sensor as an alarm for ammonia emission and particle detection in diesel exhaust (Lloyd et al., 2013), but the best way to reduce the emission is implementing best energy practices in the industrial process. In current operational processes, energy is a necessary element for the operation of a plant, and should be optimized with energy efficiency practices to minimize energy consumption and production costs (Arens and Worrell, 2014). Therefore, thanks to research and implemented cases, the plants around the world have recognized opportunities for improvement at the productive and economic level, which results in an optimum thermal efficiency of the equipment, which imply the use of less energy to conserve the required production levels (Valencia, 2011). With the acceptance of the ISO 50001 standard (International Organization for Standardization, 2011), all companies around the world have established an energy policy to reach improving on the energy efficiency processes, identifying equipment and sub-processes that require a significant amount of energy, developing potential savings associated with production, with an improvement plan to be implemented (Jovanović and Filipović, 2016), (Fiedler and Mircea, 2012). Thanks to the efficiency of the system, there are many applications in different sectors of the industry. An example of this can be found in the metal-mechanical industry, where energy savings potentials close to 20% were achieved without changing equipment, which represent a saving of 565.69 kWh, while the savings potentials related to production were around 1775 kWh (Cardenas et al., 2017). Also, a case in a fertilizer company allowed finding savings potentials of 16.1%, without new technologies and approximately 26% of these improvements (Valencia et al., 2017).

The rational use of energy and implemention of energy management system plays a relevant role in the development of new tools for energy consumption reduction (Habib et al., 2016), production costs reduction (Valencia et al., 2017), identification of best energy resources (Fahad et al., 2017), (Meschede et al., 2017), and progress in approaches of sustainable development (May et al., 2015), (Miremadi et al., 2018).

Therefore, the aim of this paper is to present the results of an energy diagnosis of an industrial boiler by evaluating the energy indicators based on the energy consumption, steam production and operating data, identifying possible actions for the company and estimating the energy saving and environmental impact avoided. Also, the application of operational data analysis in detail to obtain energy efficiency indicators for an industrial steam boiler in Colombia is presented, with the propose of reducing energy consumption and pollutant emissions from energy characterization implementation strategies.

2. METHODOLOGY

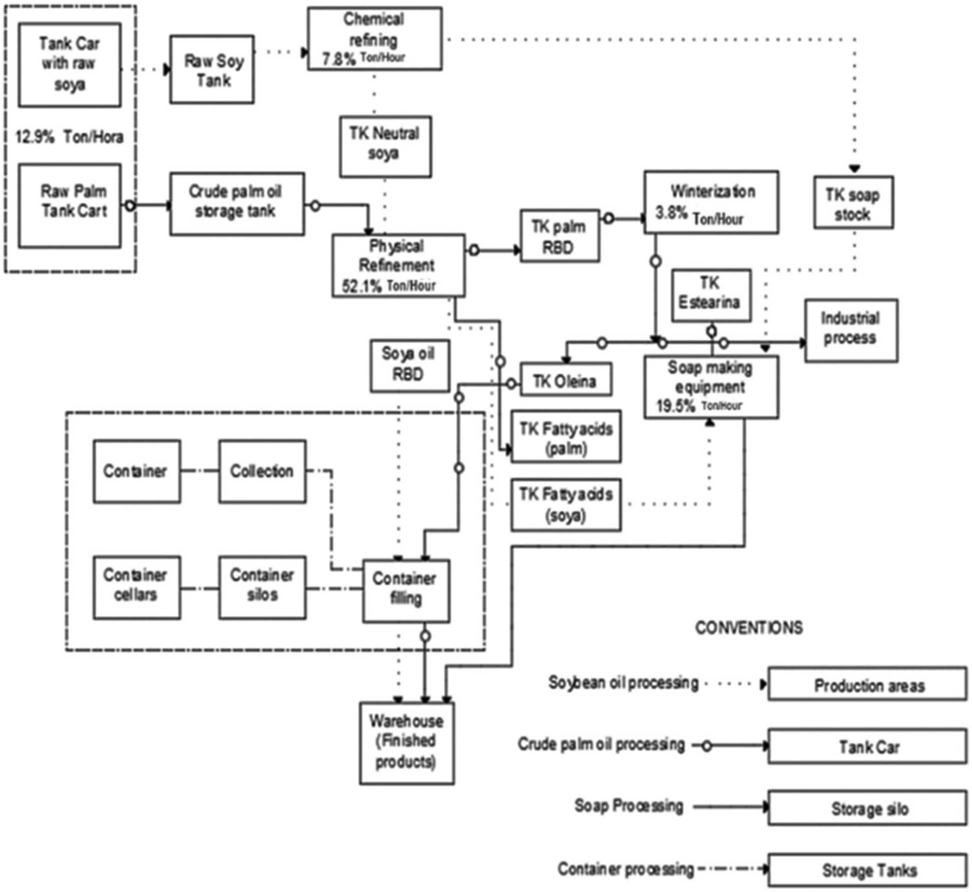
This section presents in details the methodology to implement an energy management system in an equipment or process, a particular case applied to a piro-tubular boiler with a capacity of 75,000 lb/h operating in a vegetable oils and fats production process, and the calculation of energy performance indicators to estimate the potential energy savings for this application.

2.1. Description of the Process

To process the edible vegetable oils and fats, the plant is divided into two productive sections, the refinery and packaging sub-process as shown in Figure 1.

The objective of the refinery section is to refine the raw palm and soybean, and the packaging section is responsible for filling them with processed products in the first section. This work will concentrate on the first productive section, in which primary energies from fossil sources such as natural gas and electricity are required, which are transformed to thermal energy as steam, hot and cold water. The production section is divided into four

Figure 1: Industrial production diagram



parts, the raw soybean oil processing zone which is produced in the production areas, the processing of crude palm oil which comes from tank cars, the processing of soaps which is storage in silos, and the processing of containers where the raw material and finished product is storage in tanks. The chemical processes carried out for the raw material processing is the chemical refining, where 327 tons/month (7.8%) of the total steam produced by the boiler is consumed, in which neutral soybeans and soap are produced. In the physical refinery, 2182 tons/month (52.1%) is required to process the soybean oil and palm oil, among other chemicals necessary for the Winterization process, which consumes 159 tons/month (3.8%) and soap making equipment that consumes 816 tons/month (19.5%).

2.2. Technical Detail of the Boiler

In this study, a NEBRASKA BOILER COMPANY as shown in Figure 2 boiler was considered to applied the method, which has a TODD COMBUSTION INC. Burner, with a capacity of 75,000 lb/h, a recommended excess air of 10%, a design pressure of 300 psi, an initial operating pressure of 250 psi with a current operation of 205 psi and a target operating pressure of 180 psi.

2.3. Energy Management Systems and Energy Performance Indicator

The technique proposed in this study to efficiently implement the energy management program is based on the systematic steps and procedure established in quality management, which aims to achieve continuous improvement of energy performance

Figure 2: Boiler NEBRASKA BOLER COMPANY

of equipment and processes (Cardenas et al., 2017). Since the approval of the ISO 50001 standard, there has been an increase in the industrial sector's adoption of energy management systems worldwide, motivating various companies to propose an energy policy that seeks to improve the energy efficiency of equipment that have a significant use of energy, allows the development of projections and trends of indicators for each process, and facilitates the quantification of potential savings related to production, in addition to the development of action plans to be implemented to achieve these potentials (Valencia et al., 2017).

The standard considers a cyclical model of continuous improvement made up of four well-defined stages: energy policy, energy planning, implementation of actions and verification of results. In this research, emphasis has been placed on the energy planning stage, given that it contemplates the main activities to improve the boiler's energy efficiency.

During the implementation stage of the savings opportunities identified through the energy management system, meetings were held with the plant officials and with the participation of the energy managers in charge of implementing the program, in order to plan the activities based on a preliminary assessment of the current state of energy management in that organization as opposed to compliance with ISO 50001, through a gap analysis and having determined compliance with the general requirements. An energy policy was defined to improve the energy efficiency of the processes, thus determining equipment and sub-processes that consume energy significantly, foreseeing projections and quantifying the potential savings associated with production, and their respective action plans to achieve these potentials, as well as responsibilities within the energy team. The flowchart of procedures related to energy planning is shown in Figure 3, which is the main element that forms the basis of strategies to improve energy efficiency. To calculate the Energy indicators, statistical treatment of energy consumption and production was performed, which allowed. Indicator, the accumulation trend graphs and finally the consumption index (CI) according to the equations (1-4).

The actual CI was calculated with the energy consumption (E_{Actual}) and the production (P) as follows.

$$IC_{Actual} = \frac{E_{Actual}}{P} \quad (1)$$

While the theoretical ($IC_{Theoric}$) was calculated as (Valencia et al., 2017).

$$IC_{Therioc} = \frac{E_{theoric}}{P} \quad (2)$$

Where $E_{Theoric}$ is the theoretical energy consumption of the equipment. The energy baseline is obtained from the linear regression of historical energy consumption determining the baseline and target, the efficiency determining the baseline and target, the efficiency and production data, the energy baseline has the following direct form

$$E_{Actual} = mP + b \quad (3)$$

In addition, the Base 100 efficiency index (Base 100), which is an energy management tool that helps to evaluate the performance of the energy consumption measured during a production period, is calculated as follows

$$Base100 = \frac{E_{theoric}}{E_{Actual}} \times 100\% \quad (4)$$

Through these calculations, variations in the energy efficiency of the process could be identified, facilitating the analysis of action plans to improve energy efficiency.

3. RESULTS AND DISCUSSIONS

To the study of steam production performance as shown in Figure 4, it is delimited by an upper and a lower limit, with the aim of identifying the presence of atypical points or abnormal operating conditions in the process. It can have been observed that in some periods of time the production of steam is the same, if they can have the same output with the same amount of consumption. As the study periods progress, there is a slight tendency to decrease in steam production due to the demand of the process, implying a drop in the consumption rate. In many of the periods, steam production is below the lower production line, indicating process performance problems.

During 20 days of data collection, the variables steam production and gas consumption were recorded, representing these in Figure 4a and b respectively. In the first four days of sampling, a reduction in gas consumption is noted that led to a decrease in the boiler temperature (Figure 5a) and therefore a reduction in the energy transferred to the water (Figure 5b), going from an average temperature of 95°C to 55°C, a temperature that is not optimal for steam generation in the boiler meaning a an abnormal operation condition which need to be identify by mean of the energy performance indicators.

Figure 3: Energy planning procedure based on ISO 50001 standard

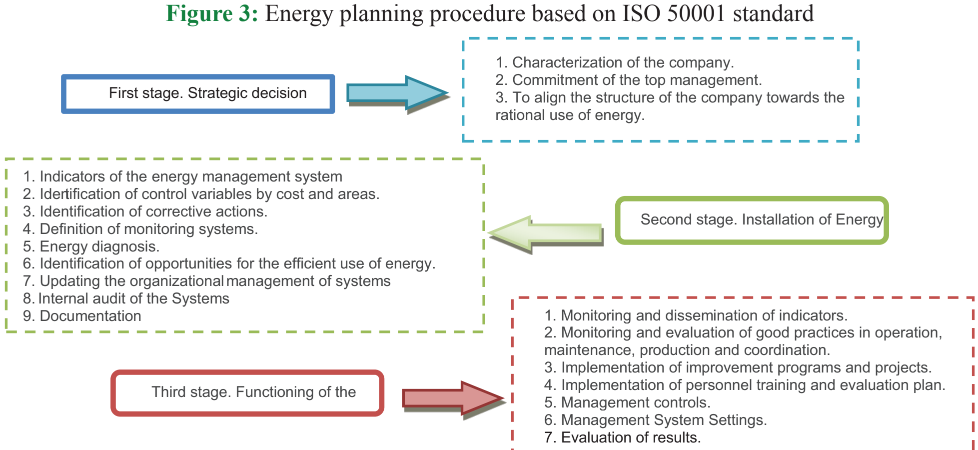


Figure 4: Control limit graph, (a) Steam production, (b) Gas consumption

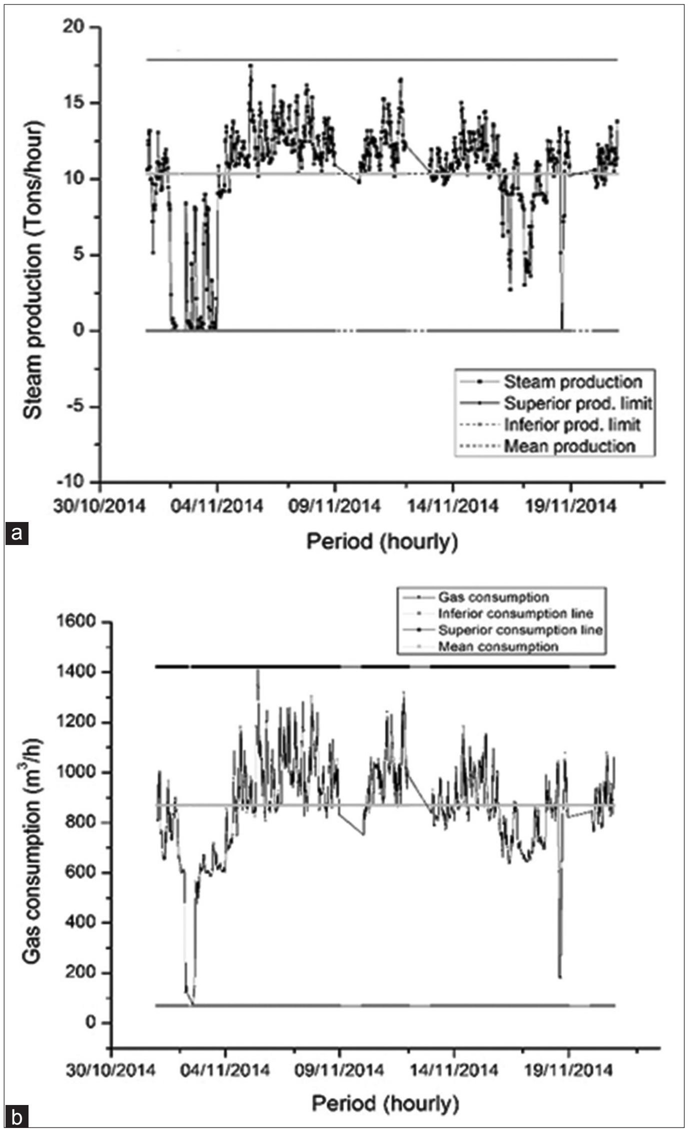
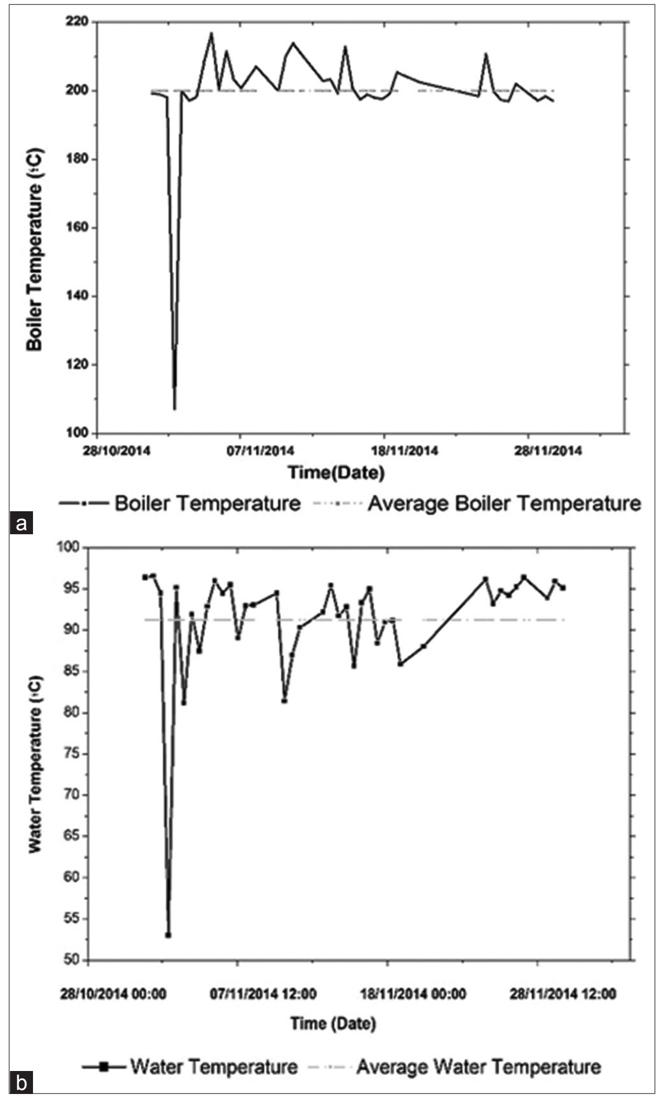


Figure 5: Steam boiler operation, (a) Boiler temperature, (b) Water temperature



The behavior at this operation point is also due to a depressurization of steam (Figure 6a) and an excess of oxygen in the combustion (Figure 6b), reaching peak values of more than 15%, implying a quantity of air sufficient for a complete combustion between the fuel and oxygen, among other things, the oxygen control system regulates the operation to provide less oxygen and therefore less combustion air with respect to the stoichiometric value. In this way, these control strategies manage to regulate the equipment operation and in an indirect way the energetic performance indicator of the system, even though they need to be monitored and managed by mean of energy management systems.

When making the energy and production graph from the data supplied, initially a base of lines with an acceptable linear correlation was obtained, since the data did not show an atypical behavior, however, it was necessary to filter the data to establish a more stable relationship, with the objective of not losing functionality between production and energy in the analysis of energy indicators. An extended base of the form E Base = 44,088x + 412.78 and a linear correlation equal to $R^2 = 0.7845$ and E Target Y = 0.0586x + 1.3814 and a linear correlation equal to $R^2 = 0.9933$, extended this is evident in Figure 7.

The baseline analysis of the boiler efficiency indicator 100, showed satisfactory energy efficiency peaks, as shown in Figure 8, these are those above the 100% average, in the same way, variations below the efficiency rate are considered energy inefficiency peaks. It is important to note that the low-efficiency peaks that occurred in the period from November 1 to November 4 are related to the variation in the energy management system.

A statistical analysis, taking into account the reduction of operational variability and the management of production, showed that it is possible to achieve a natural gas saving of 20%, monthly, equivalent to 186,633 m^3/month, with a reduction of 401,260.95 CO_2/month to the environment, for an average consumption of 800,000 m^3/month (1,720,000 CO_2/month) and with this, achieve monthly COP savings of $70,920,717 and a significant

Figure 6: Steam boiler operation, (a) Boiler steam pressure, (b) oxygen concentration

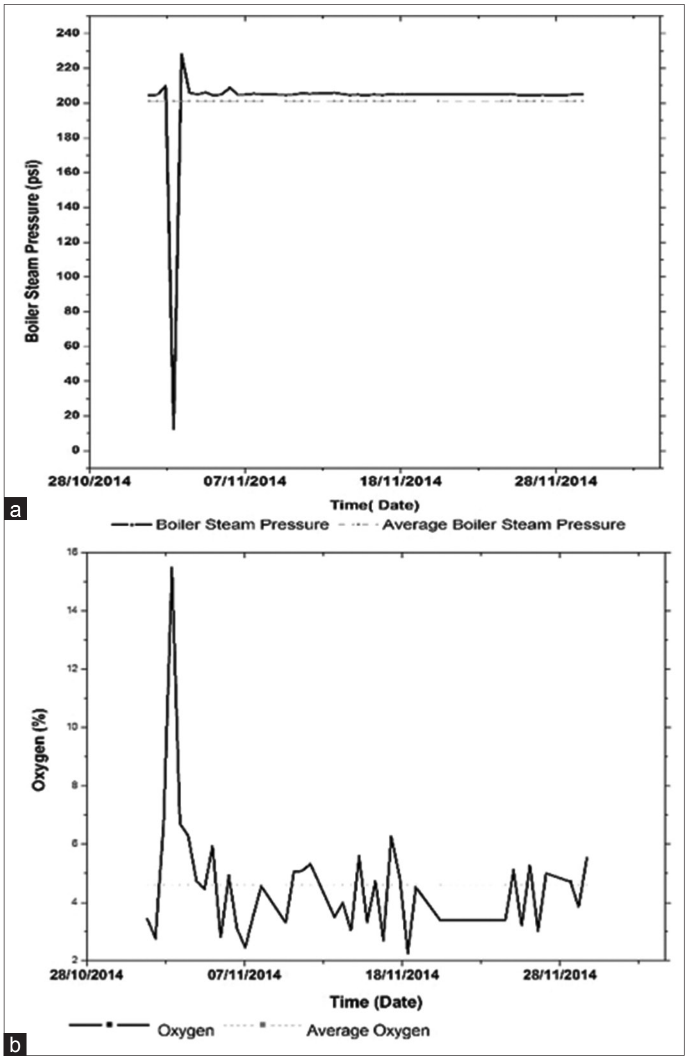


Figure 7: Energy performance indicator: Base line graph

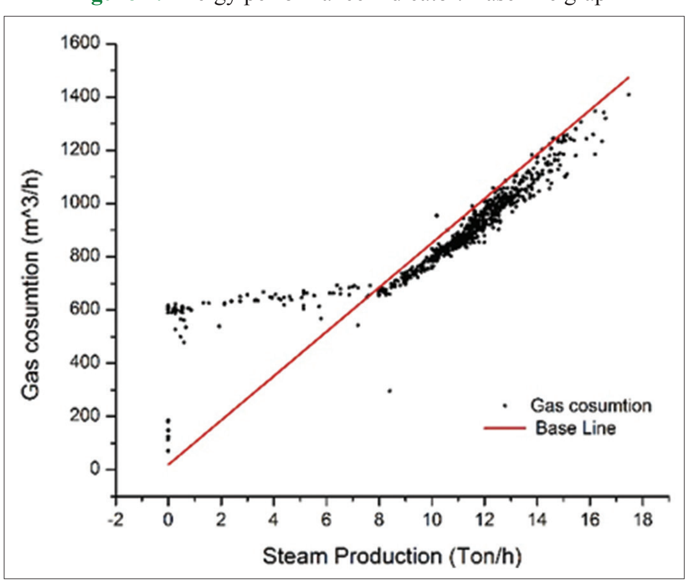


Figure 8: Base 100 efficiency index

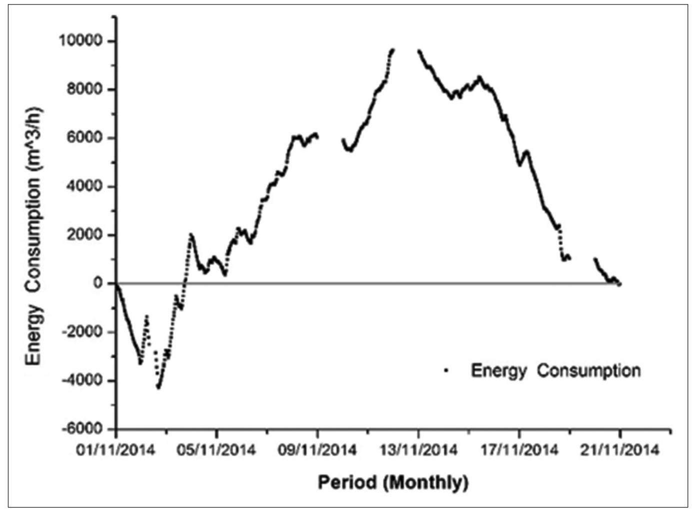


Figure 9: Boiler pressure reduction NEBRASKA

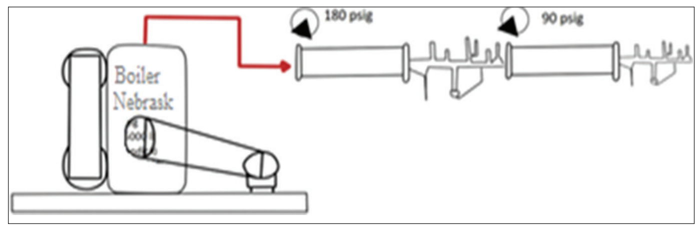
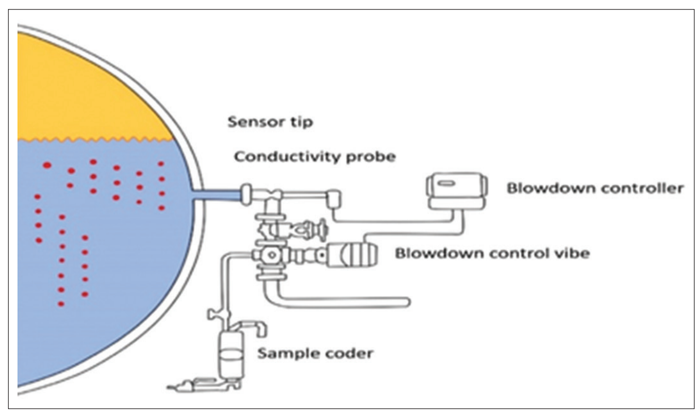


Figure 10: Purge reduction system for the implemented measure



reduction in natural gas equivalent to a reduction in CO_2 emissions (1,318,739.05 CO_2/month).

3.1. Natural Gas Consumption Regulation (Strategy Implemented 1)

Natural gas consumption is limited to steam production and thermal oil boilers for heating in deodorization towers. The analysis of results shows that savings measures should be taken for own generation pits due to their high impact and centralized application.

Currently, approximately 45,000 lb/h of steam is generated at 250 ppm, of which only 2% (1150 lb/h) at this pressure level, this causes additional energy to be spent on heating the steam to a higher pressure. In the vacuum generation of the refining towers, 26% of the steam generated is used at 150 psig and the 72% is used in the process at a pressure that does not exceed 90 psig. The purges currently registered in the boiler are above the recommended value for this equipment, which has a value of about

Figure 11: Control strategy implemented

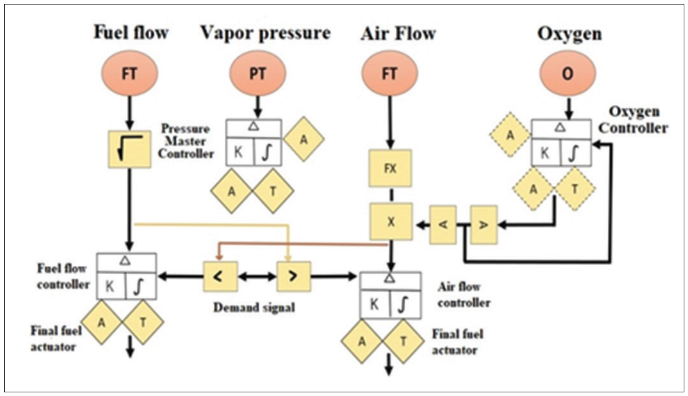
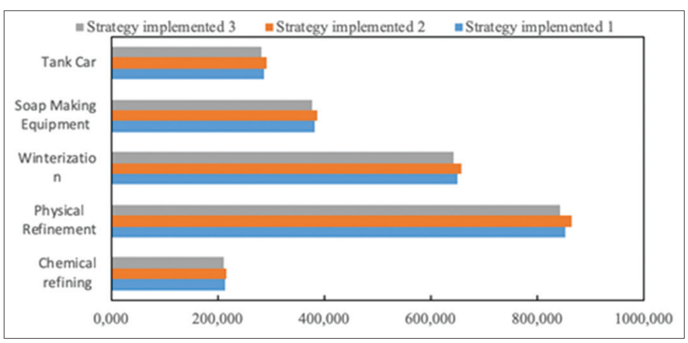


Figure 12: Control strategy implemented for the NEBRASKA boiler

Figure 13: Emission reduction of CO_2 by strategy implemented in the subprocess



30% of the total steam generated. The excess air manifested by the high levels of O_2 oxygen in the combustion gases ranges from 6% to 11%, causing increased losses due to sensitive heat.

3.2. Automation of the Boiler (Strategy Implemented 2)

The second measure is the automation of the boiler purges according the schematic diagram show in Figure 9.

The system monitors dissolved solids by not letting them rise above a certain point, which will help reduce purging base on the system shown in Figure 10. Because steam boiler purge losses were identified, consideration was given to changing the operating conditions by changing the total purge (P = 1662 lb/h), the percentage of condensate return (64%) and the full steam generated (Psteam = 5541 lb/h), so that, in accordance with the recommended value UNE-9075/85, obtaining a current drain of 2,494 to achieve a total saving of 0.66%.

3.3. Direct Measurement of O_2 (Strategy Implemented 3)

The third measure to be implemented allows in-line correction of the combustion air by direct measurement of O_2. This maintains the measured oxygen value at 3%, which is the recommended value to ensure complete combustion of natural gas. A control strategy was implemented to achieve the measure as shown in Figure 11.

In addition, another decision to the three measures presented above to improve the process performance, the feed water was increased from 70°C to 90°C, correcting steam leaks, and correcting steam trap leaks under a practical control loop as shown in Figure 12, where the basic components of control systems are presented to regulate the operation of the boiler.

4. ENVIRONMENTAL IMPACT ANALYSIS

The environmental impact analysis is based on the reduction of CO_2 presented by applying each of the strategy and the energy improvements on the process as shown in Figure 13; a reduction of the generation pressure to 2%, reduction of purge to 0.66% and finally control strategy to 3%. All these percentage are based on savings in the average consumption of natural gas.

For each sub-process, the potential environmental impact was evaluated in relation to each improvement suggested. In this analysis, the subprocess that stops emitting lower ranges of emission related to the category of climate change in units of kg of CO_2 corresponds to chemical refining 213,849 kg of CO_2, 215,829 kg of CO_2 and 211,869 kg of CO_2 for each strategy implemented respectively.

The sub-process with the greatest impact is the physical refinement with 853,418 kg of CO_2, 865,299 kg of CO_2 and 843,518 kg of CO_2 for each strategy implemented. These results are consequence of the longest duration and higher energy consumption of the process.

5. CONCLUSIONS

This study allowed to find three important opportunities for improvement in the boiler, thus obtaining possibilities for increasing its performance, as well as reducing production costs and reducing the environmental impacts that were previously presented.

As for the energy saving potentials obtained, which were evaluated using the tools available in the ISO 50001 energy efficiency standard, it was found that this boiler has a good level of measurement in its energy. However, the plant lacks policies at company level that prioritize energy efficiency and continuous improvement of energy performance in relation to the production process and production indicators are designed without taking into account energy consumption, which is reflected in total savings potentials identified about 20% per month, equivalent to 186,633 m^3/month of natural gas without technological change.

Through the elaboration of an action plan it was possible to contemplate a set of measures for operational control, maintenance management and production management, which do not require the purchase of technologies, but the introduction into the company's organizational management of new energy performance indicators and energy performance management tools, established as requirements in the new international and national standard ISO 50.001.

To reduce the energy consumption of the steam boiler, some measures were implemented based on the study, such as the reduction of the generation pressure from 250 to 180 psig thus achieving a saving of 2%, the automation of the purges in the boiler guarantees the value recommended by the UNE-9075/85 and a saving of 0.66%, and finally the correction in the supply line of the combustion air obtaining an oxygen value measured of 3% which is the recommended value for the combustion of natural gas.

Furthermore, using a methodology dependent on a global assessment of the process, it can be structured and implemented by improving the management of energy systems, reducing CO_2 emissions and contributing to the control of climate change, as proposed by ISO 50001.

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