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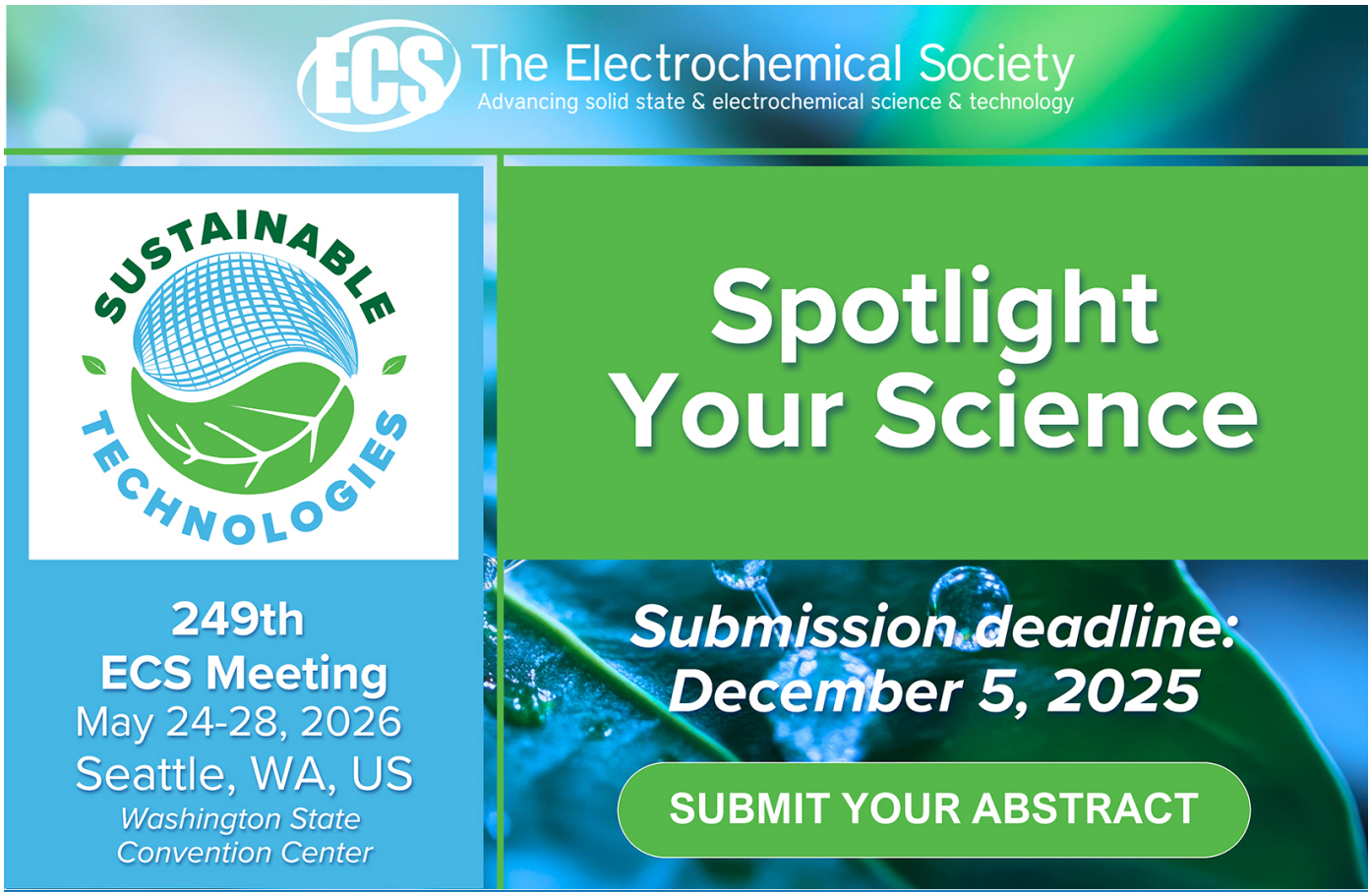
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Thermodynamic modeling of a steam generator set using the indirect method of energy losses

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Abstract. A method to thermodynamically model the behavior of a steam generator set following the guidelines of the international standard fired steam generators performance test codes. The proposed method is applied to determine the thermodynamic behavior of a steam generator set made up of two fire tube boilers operating in a dairy product processing plant. The objective of the work is to determine the efficiency of the two boilers and to know through thermodynamic analysis the behavior of the process variables such as pressure and temperature of the water at the entrance and of the steam at the exit of the generator set. The pressure in the fuel supply line, the pressure and the temperature of the exhaust gases are calculated during the operation of the boilers. The average efficiency in the generation was determined, as well as in the distribution lines and in the steam traps. The energy losses in combustion were calculated to determine the efficiency of each boiler. The application of the method makes it possible to identify the operation of each boiler in terms of its energy use and to know the points at which the greatest losses occur during steam transmission.

1. Introduction

Steam is a fluid used to provide motive force and heat energy. This is the most efficient natural means of heat transfer in the industry, and it is used in the production of electrical energy (turbines) in many industries; petrochemical, chemical, pharmaceutical, metallurgical, naval, textile, paper, brewery, tobacco, food, beverages, rubber, services, and in very diverse processes to heat, evaporate, melt, sterilize, dry, humidify, cook, wash, iron, vacuum among others [1]. In general terms, an adequate use of steam corresponds to efficient energy management [2]. Steam generation in industry is carried out in boilers or steam generators and its correct operation is crucial for the profitability of industrial plants, increasing safety, reliability, and availability [3].

The loss of efficiency in a boiler can significantly affect the process, leading to a chain of unfortunate events that can affect the safety of the plant and its operators [4]. In their work Szega and Czyz [5] followed the European standard EN 12952-15 [6], to analyze both the direct and indirect method the energy efficiency of a steam boiler that works with a dual fuel fired with blast furnace and cokegases, which operates in an industrial cogeneration plant. In addition, Rincon [7] uses the indirect method described in the ASTM PTC4 [8] to calculate the efficiency in two boilers, finding a variation of less than 5% with respect to the theoretical efficiency given by the manufacturer. On the other hand, Behbahaninia, *et al.* [9] present a new method to perform Exergy audit in steam boilers based on the criteria of [8] estimating the terms of energy loss and the efficiency of the boiler. Jiayi Lu, *et al.* [10] carried out experimental studies of heat loss by dissipation evaluating the operation in two types of 300 MW circulating fluidized bed (CFB) boilers, applying [8,11,12]. In their work Qi G, *et al.* [13]

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studied the performance of different materials as thermal insulating structures for boilers for what they considered the temperature requirements of the furnace wall in accordance with [8] and the national technical regulation Chinese [14]. Changchun Li, *et al.* [15] evaluated the efficiency in seven types of boilers including a subcritical coal boiler, a supercritical coal boiler, an oil boiler, a natural gas boiler, a concentrating solar power boiler using a configuration of The tower, a biomass boiler and a waste-derived fuel boiler used the ASME PTC4 [8] standard to determine the efficiency of each type of fuel and the heat losses in combustion, finding the efficiency in environmental terms according to the emissions of carbon dioxide CO_2. Wang Y, *et al.* [16] applied a data based computational method to measure boiler efficiency in a generation plant by incorporating fuzzy offline models and on-line operations, with the aim of determining boiler efficiency, as an important index that participates in the adjustment of the combustion process, which in general cannot be evaluated in real time due to the complexity to detect the content of unburned carbon in the ash, for which the indirect method was used to measure the composition of the exhaust gases and the ash content that is consumed in real time. Lee S, *et al.* [17] studied by means of computational fluid dynamic simulation, the use of refractory insulation in the combustion chamber to reduce the losses caused by the formation of tar in the walls, product of the increase in gases due to deficiencies in combustion. Ovchinnikova, *et al.* [18] studied the appropriate temperature for the combustion chamber in a firetube boiler used in the agricultural industry, with the aim of improving the efficiency determined by the indirect method, based on the temperature, the efficiency is determined as an indicator for make decision on fuel and air flow.

Several researchers in recent years have worked on procedures and mechanisms that allow in real time to determine the efficiency in the operation of boilers or steam generators, given their importance related to energy efficiency, environmental impact, operational safety, and quality indexes in the different production processes where they are used. In the present work, a structured methodology is proposed to determine the thermal efficiency of a steam generator set consisting of two firetube boilers, steam transmission lines and steam traps, which used in a food processing plant, the analyzes They are carried out by applying the indirect method described in [8].

2. Materials and methods

A boiler or steam generator is a device used to transform the chemical energy of a fuel into thermal energy that is subsequently transferred to the water, evaporating it through a thermodynamic process [19]. Fire tube boilers are widely used as low and medium pressure steam sources, thanks to their operational advantages including the viability of being fed by various types of fuels [20]. In this type of boiler, the combustion process takes place in the chamber and the gases generated by the combustion pass through tubes, in which the heat is transferred to the water that fills the side of the casing. The large mass of water stored in the casing provides this type of boiler with a remarkable thermal inertia [21]. The thermal efficiency of a boiler is given in terms of its effectiveness in converting fuel energy into steam thermal energy, so that it is the ratio between the thermal energy generated over the energy consumed from the fuel represented by Equation (1) [22].

$$\eta_{ter} = \frac{Q_{ent} - (Q_{p1} + Q_{p2} + Q_{p3} + Q_{p4} + Q_{p5} + Q_{p6}) + Credits}{Q_{ent}}. \quad (1)$$

Steam generation is defined in terms of the integration of the number of equipment or devices arranged to generate a certain steam flow in a process [22]. The average efficiency of the generator set is calculated by Equation (2) proposed by [8].

$$\eta_{gen} = \sum_{i=0}^{n} \frac{\eta_{ter_n}}{n}, \quad (2)$$

where, η_{gen} is the average efficiency of steam generation and n the number of steam generators or boilers used in the generation. The distribution lines are the network of pipes in charge of transporting

the steam to the different processes in which it is used according to the requirements of the process. The efficiency of the distribution lines is affected by the loss of energy generated by the path of steam in the pipeline. The efficiency in the distribution lines is calculated by applying Equation (3) to Equation (5) proposed by [8].

$$\eta_{lin} = \frac{q - q_2}{q}, \tag{3}$$

where, η_{lin} is the efficiency in the lines, q the energy lost due to heat transfer in the insulated pipe and q_2 is heat transferred in the pipe without insulation.

$$q = \frac{T_{vap} - T_{amb}}{\frac{E_{eq}}{k} + \frac{1}{h}}, \tag{4}$$

where, T_{vap} is the steam temperature, T_{amb} the ambient temperature, E_{eq} the equivalent thickness of the pipe's insulating material, k the thermal conductivity coefficient of the insulating material and h the heat transfer coefficient.

$$q_2 = P_{est} * q, \tag{5}$$

where, P_{est} is the estimated percentage of pipe without insulation. Steam traps allow the removal of air, condensate, and other non-condensable gases, in order to avoid and/or reduce the loss of energy and the amount of steam. Efficiency in steam traps can be considered by considering a thermodynamic and heat transfer analysis or by using the technical specifications provided by the manufacturer. The generator set is made up of the equipment that generates steam, in this case the boilers and the components in which the greatest energy losses are caused during the flow of the steam used in the processes. The calculation of the efficiency of the steam generator set is determined by applying Equation (6) proposed by [8].

$$\eta_{CG} = \eta_{gen} * \eta_{lin} * \eta_{tram}, \tag{6}$$

where, η_{tram} is the efficiency of the steam traps taken from the manufacturer's reference to determine the thermal efficiency of the steam generator set, it is initially necessary to perform an interpretation of the [8], in order to identify the procedure required for data collection and subsequent analysis. The methodology shown in Figure 1 is proposed to perform the efficiency calculation following the guidelines of the standard. The application of the methodology allows to determine, in addition to the thermal efficiency of steam generation, the maximum amount of generation of the system, to clearly identify the required consumption of steam to be used in the processes and the operating cost, both generators set as from generators independently. Eight points were recorded for the collection of temperature and pressure data.

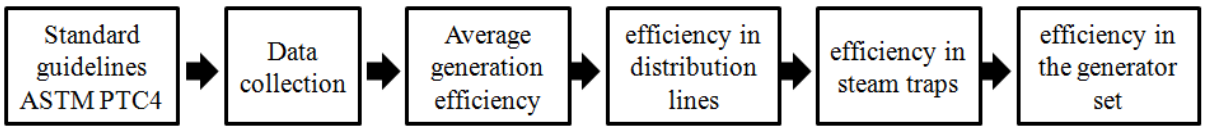


Figure 1. Proposed methodology to determine the thermal efficiency of a steam generator.

2.1. Requirements of the standard and data collection

The efficiency in steam generator sets following the indirect method, which determines the performance of the boiler by the sum of the losses and by the energy introduced by the fuel, also considers the energy delivered to the system released by the fuel based on its calorific value and

energy credits entering the system as sensible heat from air, water, and fuel. The proposed methodology was applied to determine the efficiency of the generator set consisting of two horizontal fire tube boilers, one of 200 horsepower brake (BHP) and the other of 100 BHP, which can work with natural gas, motor fuel oil or fuel oil. The standard establishes how to apply the indirect method according to the type of fuel with which the boiler operates. The process variables to be recorded to perform the analyzes and the data recording time is carried out according to the fuel used [22].

2.2. Boiler efficiency

With the data recorded in the plant, Equation (1) is used to calculate the efficiency of each boiler separately, for which it is necessary to determine the terms of the equation. Initially, the composition of the fuel is considered, in the case studied natural gas supplied by the company FENOSA in Equation (7) [20].

$$95\%\text{Methane}(CH_4) + 2.8\%\text{Ethane}(C_2H_6) + 2.2\%\text{Butane}(C_3H_8). \tag{7}$$

It is necessary to consider complete combustion with excess air, in this process the substances are capable of reacting with oxygen, interacting and generating heat. For the case, the stoichiometric complete combustion reaction with excess air is given by Equation (8), Equation (9), and Equation (10) [20].

$$C_nH_m + \lambda\left(n + \frac{m}{4}\right)(O_2 + 3.762N_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + \lambda\left(n + \frac{m}{4}\right)(O_2 + 3.762N_2), \tag{8}$$

$$n = x_i * n_i + y_i * n_i + z_i * n_i, \tag{9}$$

$$m = x_i * m_i + y_i * m_i + z_i * m_i, \tag{10}$$

where, $(x_i, y_i, z_i)$are the percentage quantities by which natural gas is composed,(n_i) the number of moles of carbon of each substance, $(m_i)$the number of moles of hydrogen of each substance and $(n + \frac{m}{4})$ corresponds to the number of moles of oxygen of each substance (Φ). Combustion efficiency is determined by Equation (11) [22].

$$\eta_{combustion} = 1 - \frac{n_{CO} - q_{CO}}{LVH_{fuel}}, \tag{11}$$

where, (n_{CO}) is the number of moles of carbon monoxide, (q_{CO}) the calorific value of carbon monoxide and (LVH_{fuel}) the calorific value of the fuel given by Equation (12) [21].

$$LVH_{fuel} = 100\ mol_{fuel}\ (x_i * q_{CH_4} + y_i * q_{C_2H_6} + z_i * q_{C_3H_8}), \tag{12}$$

where, the values of q_{CH_4}, $q_{C_2H_6}$, $q_{C_3H_8}$correspond to the lower of each of the substances that make up the gas [22]. Then the losses in the hip during combustion are determined by means of Equation (13), Equation (14), Equation (15), Equation (16), Equation (17), and Equation (18) proposed by [8].

$$Q_{p1} = n_{gs} * \Delta h_{gs}, \tag{13}$$

where, n_{gs} is the number of moles of the dry gas and the enthalpy change of the dry gas.

$$Q_{p2} = n_{H_2O} * \Delta h_{H_2O}, \tag{14}$$

where, n_{H_2O} is the number of moles of water and (Δh_{H_2O}) the enthalpy changes of water to steam.

$$Q_{p3} = n_{CO} * q_{CO}, \tag{15}$$

$$Q_{p4} = 1.5\%\ LHV_{fuel}. \tag{16}$$

In Equation (16), the estimated radiation and convection loss in the combustion chamber is determined by multiplying the calorific value of the fuel by 1.5% for the 200 BHP boiler and by 2% for the 100 BHP boiler.

$$Q_{p5} = m_{asec}(h_{vs} - h_{ae})(H_{air}), \tag{17}$$

where, m_{asec} is the mass of dry air that is equal to $\frac{m_{H_2O}}{m_{fuel}}$, h_{vs} is the enthalpy of steam at the outlet, h_{ae} the enthalpy of water at the inlet and H_{air} is moisture in the air.

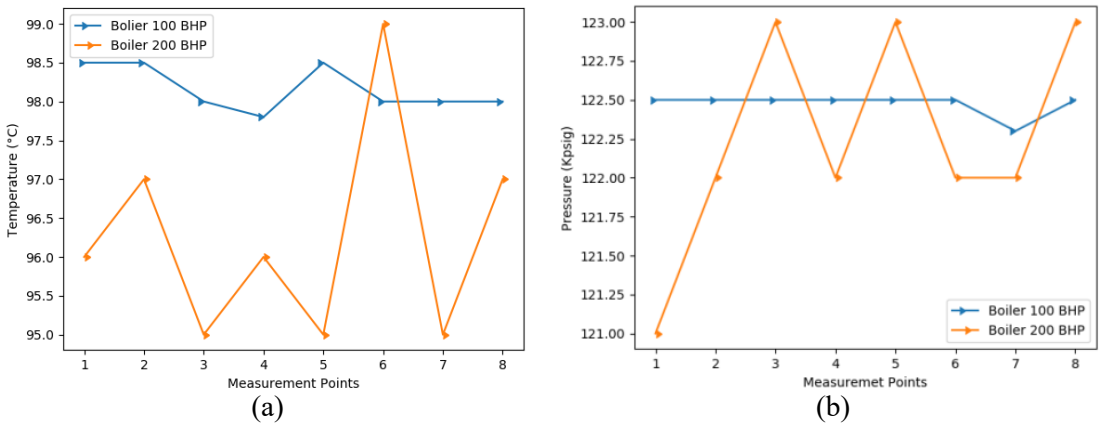
$$Q_{p6} = 1\%\ LVH_{fuel}, \tag{18}$$

$$Credits = Q_{cre} = m_{asec} * h_{asec}. \tag{19}$$

Finally, the thermal efficiency of each boiler is calculated by applying Equation (1), and the average efficiency in the generation is calculated by Equation (2).

3. Results

Figure 2(a) shows the water temperature at the inlet of each boiler and Figure 2(b) the pressure. It is observed that although the feed water flow is constant in both boilers with a value of 18 gal/min, in the 100 BHP boiler there is less variation in both temperature and pressure, and its temperature is on average two degrees superior to the water feeding the 200 BHP boiler, which affects better efficiency for the 100 BHP boiler.



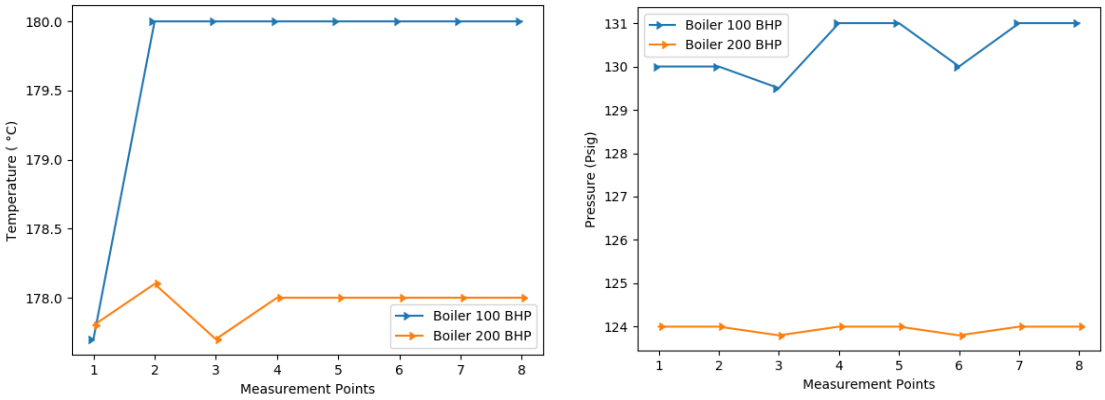
(a) (b)

Figure 2. Feed water; (a) temperature; (b) pressure.

From Figure 3(a) and Figure 3(b) it is observed that the 100 BHP boiler registers higher pressure and temperature than the other. The pressure and temperature variations are less in the 100 BHP boiler, so it can be used in processes that require steam at stable pressure. The fuel flow is constant for each boiler, for the 200 BHP it is 112 m^3/s, and for the 100 BHP it is 105 m^3/s.

Figure 4 shows the fuel supply pressure which presents practically the same variation for both boilers, only an initial phase difference that corresponds to the recording time, however, the pattern is

the same and corresponds to the line natural gas supply. Figure 5 shows the temperature in the exhaust gases and little variation is observed in the registers of both boilers. The greatest losses in combustion are produced by carbon monoxide that does not burn completely and by the heat absorbed by dry gases, as seen in Figure 6. The heat transferred by the humidity of the fuel is the third cause of energy loss in combustion and corresponds to the technical characteristics of the fuel and the flow consumed by each generator. The thermal efficiency of the boilers was calculated at 81% and 89% for the 200BHP and 100 BHP respectively, with an average efficiency in the generation of 85% for the two boilers.



(a) (b)

Figure 3. Steam outline; (a) temperature, (b) pressure.

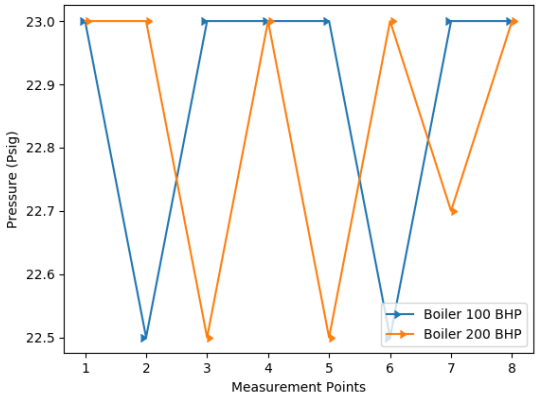


Figure 4. Pressure in the fuel line.

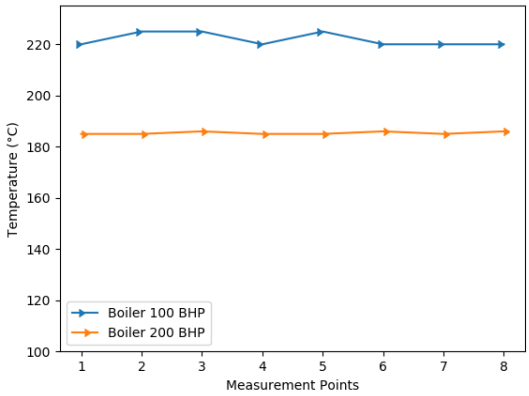


Figure 5. Exhaust gas temperature.

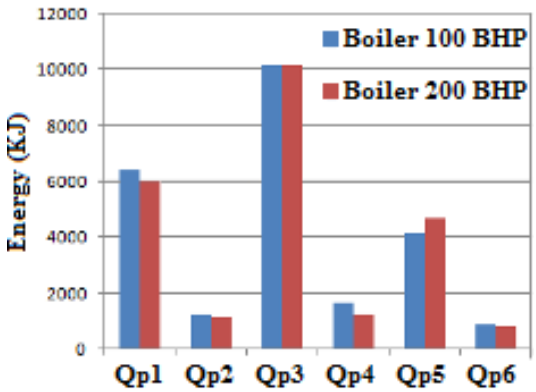


Figure 6. Exhaust gas temperature.

4. Conclusions

The proposed methodology allows determining the thermal efficiency of a steam generator set, through an understanding of the generation process integrated by more than one boiler, with systems such as transport lines and steam traps which affect the overall efficiency of the system. Energy losses caused by heat transfer or steam condensation led to increased operating costs. The study presented shows the applicability of the methodology in an integrated way to know the efficiency in steam generation in relation to energy consumption and generation capacity according to the demand for steam in an industrial plant, in order to make decisions to improve its operation and maintenance.

For the case studied, it was possible to conclude that the greatest losses during combustion are given by the amount of carbon monoxide that does not burn, followed by the loss by dry gases, which could indicate an excess of air greater than recommended for combustion to take place, this can be checked by checking for fluctuations during operation or by measuring the amount of exhaust gas flow, which could indicate an incorrect air-fuel ratio. In the same way, the condition of the burners and the piping can be verified as indicators of an inadequate combustion process, for which, this study would be of great importance when defining operation and maintenance actions.

To have reliable data, it is important to have measuring instruments for the process variables that are appropriate to the technical characteristics of the process, which guarantees better results when performing this type of analysis in an industrial plant.

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