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CASE REPORT

Thermo-exergetic evaluation of a compact pyrotubular steam generator

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ABSTRACT

One of the most important variables to know how efficient a thermal machine is the exergy. In practice, it is one of the least controlled variables. In this research, a thermal exergy study was carried out in a compact pyrotubular steam generator. To achieve this, an energy mass balance and entropy balance were carried out. The energy balance was carried out by direct and indirect methods. The percentages of the exergies of each working substance in the process are specified. The energy yield by the direct method was 0.901 and by the indirect method was 0.882, since each method has its role in the energy analysis. The irreversibilities in the process were 26%. The exergetic efficiency was 0.39, conditioned by a complete combustion in the hearth. It was demonstrated that the steam generator for the real operating conditions is oversized.

Keywords: Pyrotubular Steam Generator; Energy; Entropy; Exergy; Irreversibilities; Performance

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1. Introduction

In the early 1960s, there was a growing worldwide awareness that industrial growth and energy production from fossil fuels are accompanied by the release of potentially harmful pollutants into the environment[1].

There is a strong relationship between energy efficiency and environmental impact, since for the same services or products, lower resource use and pollution are usually associated with higher energy efficiency[2].

The growing concern for energy savings has encouraged a critical examination of the methods used to evaluate and increase the efficiency of industrial processes. In response, attention has recently focused on analysis techniques based on the Second Principle of Thermodynamics, in particular, on the concept of exergy[3]. Exergy is fundamentally the property of the system that provides the maximum potential that can be extracted from the system when brought to a thermodynamic equilibrium state from a reference state[4,5].

In recent years, due to the scarcity of fossil fuels and their logical increase in price, the importance of developing thermal systems that make effective use of these non-renewable energy resources such as oil, natural gas and coal has become evident. The method of exergetic analysis is particularly suitable to achieve an efficient use of energy resources, since it allows determining the location, type and real magnitude of their loss and waste. A pyro-tube or fire-tube steam generator is a thermal machine that produces steam. This steam is generated when the combustion gases pass through the inside of the tubes, which are bathed in water, from where the saturated steam is produced, which is conducted through the distribution lines to the consumers, which are generally: kitchens, dry cleaners, hospitals, among others.

The efficient use of energy resources will be achieved by reducing as much as possible the destruction of exergy in the systems, i.e., reducing the irreversibilities of the processes occurring within the systems. This will allow focusing attention on those aspects of the operation of the system under analysis that offer the greatest opportunities for improvement.

The objective of the research was to determine if the steam generator is adequate for the real operating and process conditions, as well as the opportunities to increase its efficiency. It was hypothesized that by determining the energetic and exergetic performances of the steam generator, it is possible to know the magnitude of the influence of the operational variables that affect it.

2. Materials and methods

The investigation was carried out on a compact pyrotubular steam generator model CMS-660. This works with regular diesel fue[6] and its gravimetric composition was obtained from the data sheet provided by the supplier. It has a nominal capacity for steam production of 660 kg/h, produces saturated steam with a pressure of 0.49 MPa and has a heat exchange surface with the fluid to be heated of 19.6 m^2. The cylindrical outer walls have an operating temperature of 34 ℃ and the rest of the walls 42 ℃. The feedwater is preheated by saturated steam extraction and enters the generator at 80 ℃. Condensate from the process is not recovered due to a design error in the plant. The exhaust gas temperature is 200 ℃. The properties of all working substances entering and leaving the steam generator must be known in order to perform mass, energy, entropy and exergy balances (**Figure 1**).

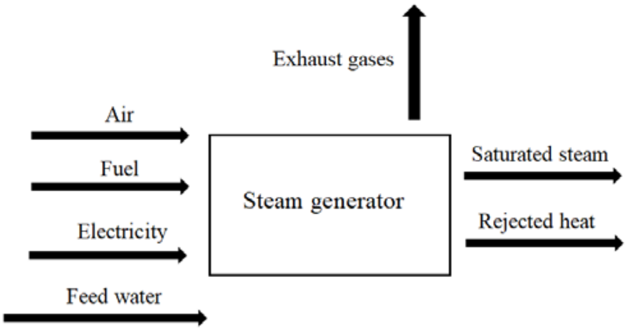

Figure 1. Basic scheme of the system to be studied.

2.1 Mass balance

Fuel, feedwater and saturated steam flows were obtained from direct measurements and others by applying mass balance. To determine the mass flow of air, the combustion was considered to be complete, the actual excess air coefficient was measured and the theoretical air volume to combust one kilogram of fuel was determined. By multiplying the theoretical air volume by the excess air coefficient, the actual air volume was obtained. The actual air volume was multiplied by the mass flow of the fuel entering the boiler and the volumetric air flow was obtained. This volumetric flow rate is multiplied by the air density to obtain the air mass flow rate. The exhaust gas mass flow is obtained by equation (1):

$$G_{aire} + G_{aa} + G_{comb} = G_{vap} + G_{esc} \tag{1}$$

2.2 Energy balance

Applying the law of conservation of energy, equation (2) is obtained:

$$G_{aire} \cdot h_{aire} + G_{aa} \cdot h_{aa} + G_{comb} \cdot PCI + Pelect = + \dot{q}_{rech} + G_{vap} \cdot h_{vap} + G_{esc} \cdot h_{esc} \tag{2}$$

The enthalpy of air was obtained from Cengel table A17[1,7], those of feed water and water vapor were obtained from table A4 of the Cengel book[7]. The enthalpy of the exhaust gases was determined from gas analyzer measurements. The lower heating power (LHP) of the fuel was checked by equation (3)[8,9].

$$PCI = 339.2C + 1030.4H - 108.9(0 - S) - 25.14W \tag{3}$$

The rejected heat was calculated by Newton's cooling equation (equation 4). The boiler walls are at relatively low temperatures, therefore, only the heat rejected by the natural convection mechanism was taken into account (equation 4)[7,10].

$$\dot{q}_{rech} = h \cdot A_s \,(T_s - T_f) \tag{4}$$

Where:

h = Overall heat emission coefficient (W/(m^2·K))

A_s = Heat exchange surface with the environment (m^2)

T_s = Surface temperature (K)

T_f = Surface surroundings temperature(K)

2.2.1 Calculation of energy yield by the direct method

The calculation of the energy efficiency of the steam generator was calculated by equation (5)[11]:

$$\eta_{gv} = \frac{G_{vap} \cdot h_{vap} - G_{aa} \cdot h_{aa}}{G_{aire} \cdot h_{aire} + G_{comb} \cdot PCI + P_{elect}} \tag{5}$$

2.1.2 Calculation of energy yield by the indirect method

This method can be applied without the need to know steam production and fuel consumption[12].

The yield η_{gv}^{bruto} in this case was determined by equation (6):

$$\eta_{gv}^{\text{bruto}} = 100 - (q_2 + q_3 + q_4 + q_5 + q_6 + q_7), \% \tag{6}$$

Table 1. Equations used to test the different types of losses[9]

Type of loss	Equation	
q_2	$q_2 = \dfrac{(h_{esc} - \alpha_{ge} \cdot h_{af})(100 - q_4)}{Q_d}$	(7)
q_3	$\dfrac{V_{gs} \cdot (126 \cdot CO + 108 \cdot H_2 + 358.2 \cdot CH_4)(100 - q_4)}{Q_d}$	(8)
q_4	This loss is due to the fact that sometimes, in a real combustion, a small part of the combustible substances do not combust.	
q_5	$q_{5\,\text{nom}} \dfrac{D_{nom}}{D_{\text{real}}}$	(9)
q_6	This loss generally occurs when solid fuels are burned and to a lesser extent in liquid fuels.	
q_7	This loss is disregarded, since for pyro-tubular steam generators it does not reach 2% of the total losses.	

Where[13]:

q_2 = Heat losses with exhaust gases

q_3 = Heat losses due to incomplete chemical combustion

q_4 = Heat losses due to incomplete mechanical combustion

q_5 = Radiation and convection heat losses to the environment

q_6 = Losses with the physical heat of the ashes

q_7 =Losses due to purging

The equations used to determine the energy losses are shown in **Table 1**.

(1) Energy balance

It was carried out to know the irreversibilities of the system. The reference environment is 298.15 K temperature and one technical atmosphere pressure.

$$\sum B_{ent} = \sum B_{sal} = I \tag{10}$$

The exergy of a matter flow can be divided into different components[14-16]:

$$B = B_C + B_P + B_F + B_Q \tag{11}$$

Where:

B, B_C, B_P, B_F and B_Q equal the total exergy of the substance, kinetic exergy, potential exergy, physical exergy and chemical exergy respectively (kW).

For the installation to be analyzed, the resulting equation (12) is:

$$B_{\text{aire}} + B_{\text{aa}} + B_{\text{comb}} + B_{\text{elect}} = B_{\text{qrech}} + B_{\text{esc}} + B_{\text{vap}} + I \tag{12}$$

For air, the physical exergy was neglected because it has practically the same properties as the reference environment (**Table 2**). With the outlet pressure of the saturated steam and with the title, the entropy of the feedwater is located in Table A4 of the book by Çengel and Boles[7]. In fuel**,** for the specific chemical exergy**,** there is a general expression given in Annex C of the book of Kotas[15]. Szargut and Styrylska[17] assume that the ratio of chemical exergy to the net calorific value of solid and liquid industrial fuels, is the same as that of pure chemicals having the same proportions of chemical components[15]. For exhaust gases (**Table 2**). The equations used to determine the exergies of each substance are presented in **Table 2**.

Table 2. Equations used to determine the different types of exergies of working substances[15]

Working substance	**Equation**	
Air	$b^q_{aire} = \sum (n_i b^q_{xi}) + RT_0 \sum x_i \, ln \, x_i$ $b_{aa} = b^q_{aa} + b^f_{aa}$	(13)
Feed water	$b^f_{aa} = h_{aa} - h_0 - T_0(s_{aa} - s_0)$ $b_{aa}^{q \text{ st corrg}} = b^{qst}_{aa} \frac{T}{T_0} - h^{st} \frac{T - T_0}{T_0}$	(14)
Saturated steam	$b_{\text{vap}} = b^q_{vsat} + b^f_{\text{vap}}$	(15)
Fuel	$\varphi = \frac{b^q_{\text{comb}}}{PCI}$ $b^f_{\text{comb}} = c_{pcomb} \left[(T - T_0) - T_0 \, ln \left(\frac{T}{T_0} \right) \right] + v_m (P - P_0)$	(16)
Electrical power	Electrical energy can be completely converted into work[18].	
Rejected heat	$b_{rech} = b_{pl} + b_{ff}$ $b_{pl} = \dot{q}_{pl} \left(1 - \frac{T_0}{T_{pl}} \right)$ $b_{ff} = \dot{q}_{ff} \left(1 - \frac{T_0}{T_{ff}} \right)$	(17)
Exhaust gases	$b^q_{esc} = \sum (n_i b^q_{xi}) + RT_0 \sum x_i \, ln \, x_i$	(18)

Note: The values of b^{qst}_{aa} and h^{st} are obtained from Table A.3 of the book by Kotas[15].

Table 3. Equations used to determine the different types of entropies of working substances[7]

Working substance	**Equation**	
Air	$s_{\text{aire}} = s^0 + c_p \, ln \left(\frac{T}{T_0} \right)$	(20)
Feed water	Table A-4	
Saturated steam	Table A-4	
Fuel	$s_{comb} = c_{p \text{ comb}} \, ln \left(\frac{T_{\text{combustion}}}{T_0} \right)$	(21)
Rejected heat	$\frac{\dot{q}_{pl}}{T_1} + \frac{\dot{q}_{ff}}{T_2}$	(22)
Exhaust gases	$s_{esc} = \frac{h_{esc}}{T_{esc}}$	(23)

(2) Entropy balance

It was carried out to determine the irreversibilities from the entropy generated in the process.

$$\dot{S}_{aire} + \dot{S}_{aa} + \dot{S}_{comb} + \dot{S}_{Gen} = \dot{S}_{esc} + \dot{S}_{vap} + \frac{\dot{q}_{pl}}{T_1} + \frac{\dot{q}_{ff}}{T_2} \tag{19}$$

The equations used to determine the entropy of each substance are shown in **Table 3**.

Table 3. Equations used to determine the different types of entropies of working substances[7]

Working substance	Equation	
Air	$s_{\mathrm{aire}} = s^0 + c_p\, ln\left(\frac{T}{T_0}\right)$	(20)
Feed water	Table A-4	
Saturated steam	Table A-4	
Fuel	$s_{comb} = c_{p\,\mathrm{comb}}\, ln\left(\frac{T_{\mathrm{combustion}}}{T_0}\right)$	(21)
Rejected heat	$\frac{\dot{q}_{pl}}{T_1} + \frac{\dot{q}_{ff}}{T_2}$	(22)
Exhaust gases	$s_{esc} = \frac{h_{esc}}{T_{esc}}$	(23)

According to Gouy[19] irreversibilities of the process:

$$I = T_O \cdot S_{Gen} \tag{24}$$

Exergetic performance was determined ε_{GV}:

$$\varepsilon_{GV} = \frac{B_{\mathrm{vap}} - B_{aa}}{B_{\mathrm{aire}} + B_{\mathrm{comb}}} \tag{25}$$

3. Results and discussion

The plant has an actual steam production of 457.2 kg/h with a fuel consumption of 0.008 kg/s. The steam demand of the process was 114.3 kg/h (**Table 4**).

The substances that had the greatest impact on the energy and energy yields of the process were fuel and saturated steam (**Table 4**). The energy yield of the generator calculated by the direct method was 0.901 and by the indirect method was 0.882 (**Table 4**). The error between the results for both methods was 2.11%, which was negligible.

The most significant substance in the exergy yield is fuel with 46%; this is due to its high energy content (**Figure 1**). Feedwater, when its temperature was varied from 80 °C to 151 °C to become saturated steam at a pressure of 0.49 MPa, increased its exergy potential by 18%; it is the second most important substance in the exergy yield (**Figure 1**). The effects of the remaining substances are practically negligible, although they must be taken into account when the air is not preheated. Irreversibilities represent 26% of the exergies, mostly due to transformations occurring in combustion and heat transfer processes (**Figure 1**)[20].

It is known that the exergy efficiency for such a steam generator should be close to 0.27[21]. For the actual operating conditions of the steam generator the exergy efficiency is 0.39. As can be observed, the exergy efficiency calculated for the steam generator studied has a value above that published in the literature[21]. When comparing the values of the measurements of this research with the reviewed one, it can be noted that for values of 2.012 of the coefficient of excess air at the exhaust gas outlet and the presence of gases such as carbon monoxide, which indicates incomplete combustion, an exergetic efficiency of 0.27 is obtained. Therefore, it is concluded that, for the operational variables and the conditions of complete combustion, the efficiency of the steam generator is higher.

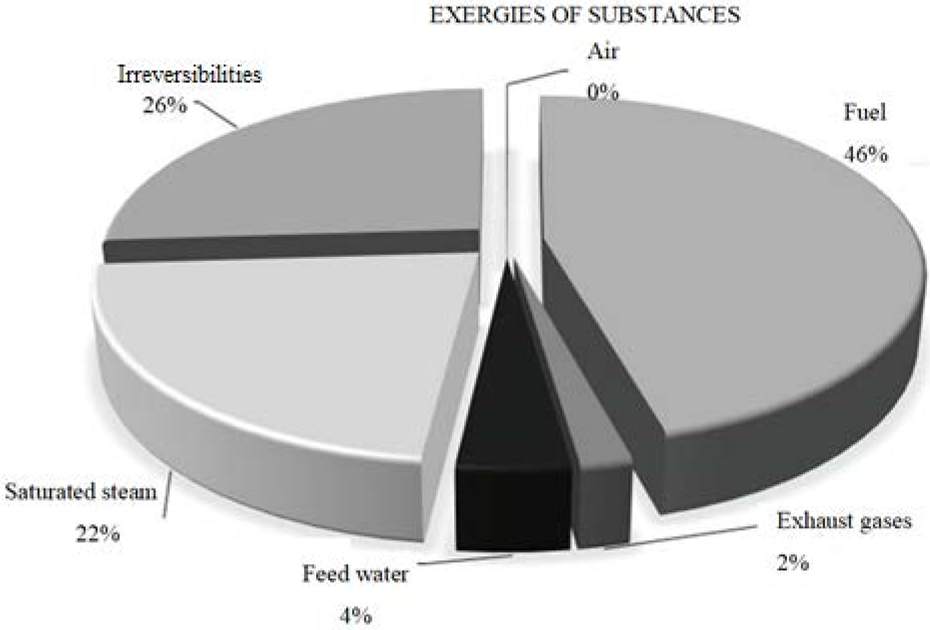

Figure 1. Percentage graph of the exergies of each substance in the process.

Table 4. Results for the different variables of the process

Variables	**Energy (kW)**	**Exergy (kW)**	**Entropy (kW/K)**
Air	31.057	0.575	0.1684
Fuel	339.590	362.664	0.0265
Exhaust gases	52.365	14.838	0.1107
Feed water	42.545	32.194	0.1366
Saturated steam	348.806	175.393	0.8670
Rejected heat	0.259	0.0126	0.0008
Performance direct method		0.901	
Performance indirect method		0.882	
Irreversibilities (kw)		206.190	
Gouy-Stodola irreversibilities (kw)		200.589	
Exergetic performance		0.394	

To determine the effect of saturated steam pressure on energy yields, exergy yields and irreversibilities, the above calculations were replicated for the range of 0.1 MPa to 1.3 MPa (**Figure 2**). Both the energetic and exergy yields increase with increasing saturated steam pressure. The increase in the exergy yield is more significant, with a positive variation of 13% (**Figure 2**). Irreversibilities decrease significantly in the range of 0.1 MPa to 0.4 MPa; above that value their decrease is less pronounced in relation to the increase in saturated steam pressure and experiences a total negative variation of 45 kW (**Figure 2**).

For the environmental and operating conditions of the steam generator, the energy analysis made it possible to identify, classify and measure the energy losses (**Tables 1** and **4**). The steam flow offered by the generator is four times greater than that demanded by the process. This suggests a replacement of the steam generator by another one with a lower steam production.

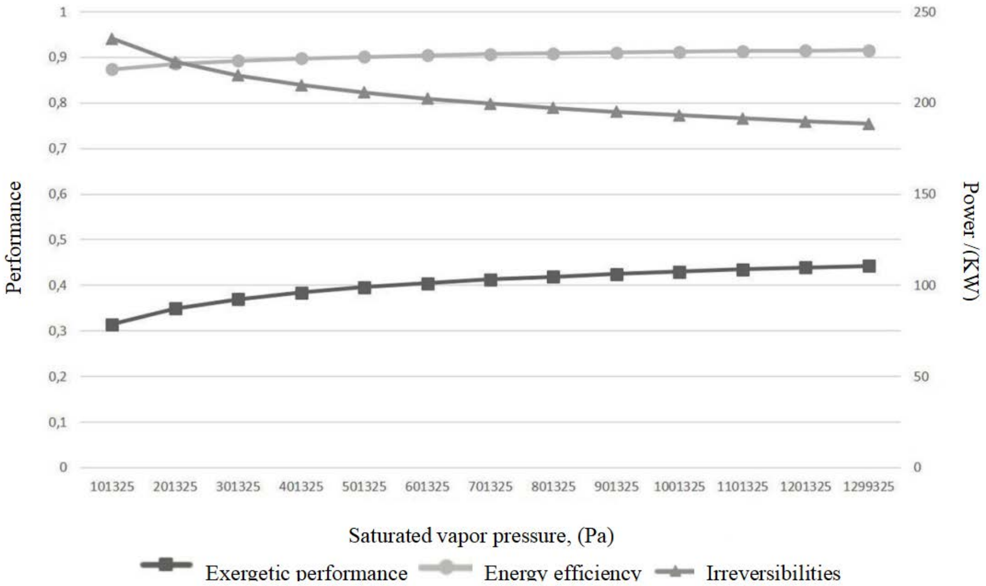

Figure 3. Behavior of energy yield, exergy yield and irreversibilities as a function of vapor pressure.

4. Conclusions

This paper describes a series of logical steps to calculate the energy efficiency of a steam generating plant. Normally, energy studies of steam generating facilities are applied to one of two methods (direct or indirect). In this case, both methods are applied to compare the results and demonstrate the relevance of using both methods indistinctly. The energy efficiency of the steam generator by the direct method is 0.901 and by the indirect method is 0.882, with a difference of 2.11%, which indicates that either method can be used. To determine the exergetic efficiency, equations were used that allow working with real values of ambient temperature, since they help to correct the difference between the parameters of the reference environment and the real environment. The exergetic efficiency of the steam generator was 0.39 and the substance that most influenced it is the fuel with 46%, then the irreversibilities of the process with 26%. These can be reduced by taking advantage of the condensed steam that is lost due to a design error in the installation. In general, but with equal importance, it was demonstrated that the steam generator is oversized for the real operating and process conditions, so it is recommended to replace it with another one of lower steam production.

Nomenclature

G	Mass flow
h	Specific enthalpy or convective heat transfer coefficient
P_{elect}	Electric power
PCI	Lower caloric value
Q	Heat flux
A_s	Heat exchange surface with the
T	Absolute temperature
η	Energy efficiency
V	Volume
Q	Heat or energy
D	Request
B	Exergy
b	Specific energy
I	Irreversibilities
n	Amount of substance
χ	Proportion of quantity of substance
R	Universal gas constant
S	Specific entropy
φ	Szargut-Styrylska relationship
c_P	Specific heat at constant pressure
v	Specific volume
P	Absolute pressure
Chemical symbols	
C	Carbon

H	Hydrogen
O	Oxygen
S	Sulfur
W	Humidity
C	Carbon

Subscripts and superscripts

Aire	Air substance
Aa	Feed water substance
Comb	Combustible substance
Vap	Saturated vapor substance
Esc	Exhaust gases
Rech	Rejected
S	Surface
F	Surface surroundings
Gv	Steam generator
Bruto	Gross
Ge	Gases at the steam generator outlet
Af	Cold air
D	Available
Gs	Dry gases
Nom	Nominal
Real	Real
Ent	Entry
Sal	Output
C	Kinetics
P	Potential
F	Physics
Q	Chemistry
I	Chemical components of the substance
Q	Chemistry
F	Physics
0	Reference environment
St	Standard
Corrg	Corrected
Comb	Fuel
Pl	Sidewall
Ff	Front and back wall
Combus	Combustion process
Gen	Generated

Conflict of interest

The authors declared no conflict of interest.

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