PROJECT 3 OF THE CAREER

INTRODUCTION

3.1 **Project:** Evaluation of the efficiency of steam generators by direct, indirect and exergy methods.
Company: Lloreda S.A.
Name: Miguel Angel Paz Rosero.
Job position: Shift engineer.
Location: Yumbo, Valle del Cauca – Colombia.
Date: December 14, 2020 - November 19, 2022.

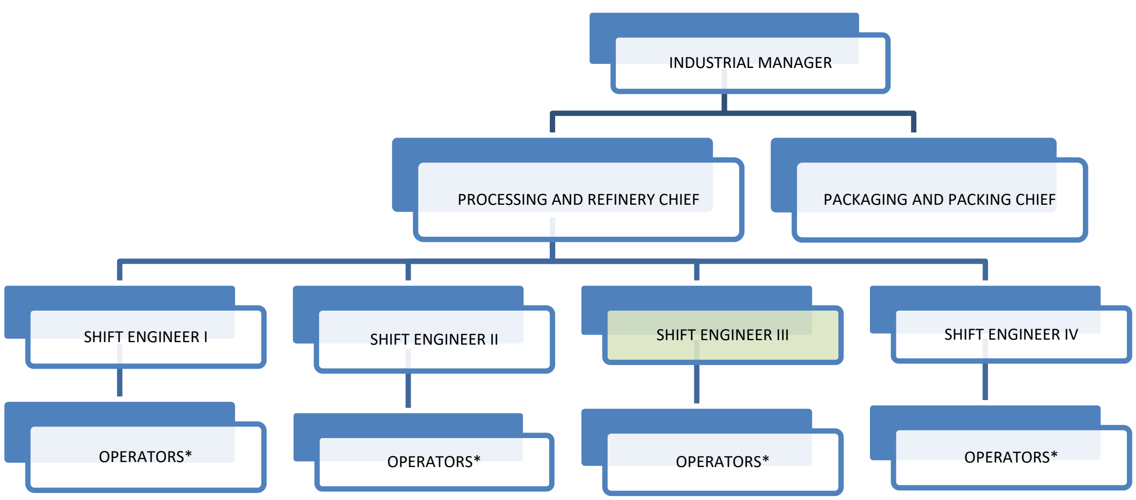
BACKGROUND

3.2 Lloreda S.A. is a Colombian company dedicated to the refining, processing, and packaging of edible oils and fats (margarines) with 68 years of experience in mass consumption products of edible oils and fats, which integrates from the agricultural process to the sale of finished product to the end customer. It focuses on adding value to its products recognized in the national market such as: Premier, Oleocali, Riquísimo, Natura, Practis, Canola Life and GRG6040. It has close to 1,000 employees in factories in Yumbo, Cali and Barranquilla, and an African palm plantation in Puerto Wilches. Its sales are distributed in two basic businesses: Food: 85% and cleanliness: 15%.

3.3 The project arose as a concern at a production meeting regarding the annual increase of the cubic meter of natural gas, and due to the company had presented cost overruns of 15 million COP in 2020 compared to the previous year. Additionally, in the current year (2021) I was doing my postgraduate (specialization) that gave me the tools to solve this problem.

3.4 While working for this company, I developed a tool to identify shortcomings in the operation of steam generators and locate losses, overconsumption of natural gas and cost overruns; and that allows tracking of industrial service operators by the direct, indirect and exergy method to determine the efficiency of production processes.

3.5 Organizational structure for the project:



***About 50 operators who rotate in different shifts and with different shift engineers.**

3.6 As Shift Engineer, my responsibilities were:

- Control the processes of liquid filling (edible oils), preparation and packaging of margarines and spreadable to ensure compliance with the company's standards and specifications of quality, safety, productivity, environmental and industrial safety.

- Validate operating parameters, record production information in the company's management systems, support the Human Resources department in the identification of training needs of the personnel in charge.
- Actively participate in continuous improvement programs, lead month end inventories, guarantee and control the execution of production programs, complying with established standards of quality, safety and productivity.
- Ensure the correct flow of processes in terms of information (from crude oil to packaging and packing - quantities and costs) both physically and virtually (SIESA).

PERSONAL ENGINEERING ACTIVITY

3.7 One of the most important industrial services for Lloreda (see ***Figure 1***) is the use of steam for its processes, among which the following stand out:

- The use of tracers in all pipelines in the different plants of refinery and processing to prevent solidification of fats and plugging of pipelines.
- The use of live steam (injection) that interacts directly with edible oils and fats at high temperatures (220-240°C) and in vacuum (Maximum 10 mmHg), for the volatilization of components that affect the flavor, odor and useful life of the product.
- Heating storage tanks of fats (margarines) to a melting point of 60°C for the preparations.

Figure 1. Lloreda S.A. (Company's documentation)

The company has three boilers for steam generation. Boiler #1 uses coal as fuel, and was out of service. Boiler #2 and #3 use natural gas as fuel and are water tube boilers. The boilers are intercalated each 15 days for its operation, meanwhile the other one is on stand-by, because the processes require steam. I analyzed boiler #3 in use:

Figure 2. Boilers at Lloreda S.A. (Company's documentation)

Figure 3. Boiler #3 (Company's documentation)

3.8 I realized compilation of information on the following elements:

- ✓ Composition of combustion gases.
- ✓ Composition of the fuel used.
- ✓ Conditions of steam generator design and site variables (Yumbo).

I participated in the testing of boiler #3 to determine the composition of the exhaust gases with an external company. The steam generation, through of boiler #3 and I realized on May 26, 2021 an efficiency diagnostic. In the analysis of the exhaust gases, I determined 9.8% of CO_2; 3.6% of O_2 = and T_{gases} = 220°C. The fuel used was natural gas. For steam generation I obtained the following information: P_{domo} = 160 psia; $P_{pump\ fw}$ = 200 psia; T_{fw} = 90°C; q_4 = 0 % (natural gas); m_{fuel} = 45 MBTU/h; Relative density of gas =0.68 Kg/m^{3}N; $Cp_{cold\ air}$ = 1.0051 kJ/Kg*K; T_o = 28°C; $T_{air\ cold}$ = 28 °C; P_o = 0.902 bar (Yumbo). The nominal capacity of the steam generator is 40000 lb/h; generation in the test was 24754 lb/h; purge flow = 8.0 % of the feedwater flow; temperature of heat source 1320 °C constant. The parameters of saturated generated steam: Pv= 160 psia. Surface temperature of boiler is measured by thermography at 1.5 m distance: 62.1°C, ambient temperature at 1.5 m from the boiler: 28°C. With two water walls as it is a water tube boiler and is semi shielded from the environment (See ***Figure 3***).

3.9 I determined the project scope to estimate the thermal efficiency of the steam generator by the direct, indirect, and exergy methods; the losses by radiation and convection to compare these methods, I estimated the losses of steam generator using the next Equation[1].

<u>Equation 1</u>: Fuel flow:

$$m_{fuel} = \frac{m_{fuel}\left(\frac{MBTU}{h}\right)}{Q_i} * Relative\ density\ of\ gas \quad ; \quad \frac{Kg}{h}$$

Table 1. Generator information. Part #1

Steam generation conditions	
m_{gv} nominal (lb/h)	40000
m_{gv} nominal (Ton/h)	18,14
m_{gv} (lb/h)	24754
m_{gv} (Ton/h)	11,23
Capacity (%)	62
m_{fuel} (MBTU/h)	45
m_{fuel} (m^{3}N/h)	1164,57
Relative density of gas (Kg/m^{3}N)	0,68
m_{fuel} (Kg/h)	791,90

Table 2. Generator information. Part #2

Steam conditions	
P_v (psi)	160
Status?	Saturated steam
Dome conditions	
P_{domo} (psi)	160
Water supply conditions	
m_{fw} (lb/h)	26906,5
$P_{pump\ fw}$ (psi)	200
T_{fw} (°C)	90
Cold air conditions	
Cold air temperature (C)	28
Cold air temperature (K)	301,15
*Cp at T (Kj/Kg*K)*	1,0051
Assumptions	
q_4 (%)	0

Input variables of the information collected:

- ✓ $Q_d = 40768.5\ \frac{kJ}{m^3}$ Calorific value of fuel
- ✓ $q_2 = 9.34\%$ Losses of sensible heat with exhaust gases
- ✓ $q_3 = 2.90\%$ Losses of heat due to incomplete combustion
- ✓ $q_4 = 0\%$ Losses due to unburned fuel, being natural gas is negligible

I analysed the losses that affected the efficiency of steam generator, including: heat losses due to radiation, convection, radiation to the environment, purges, sensible heat from exhaust gases, incomplete combustion, and unburned fuel, as follows:

[1] The equations used from page 4 to 9 are taken from the book: *Borroto Nordelo, A., & Rubio González, A. (2007). Combustión y generación de vapor (Chapter 3, pp. 65-81). Habana, Cuba: Editorial Universo Sur.*

- **Heat losses for radiation and convection - q_5** I established the relationship between the theory and the actual experimental data obtained, so I chose the appropriate graphs and determined the losses that impacted the boiler's efficiency. (See Graph 1, 2 and 3).

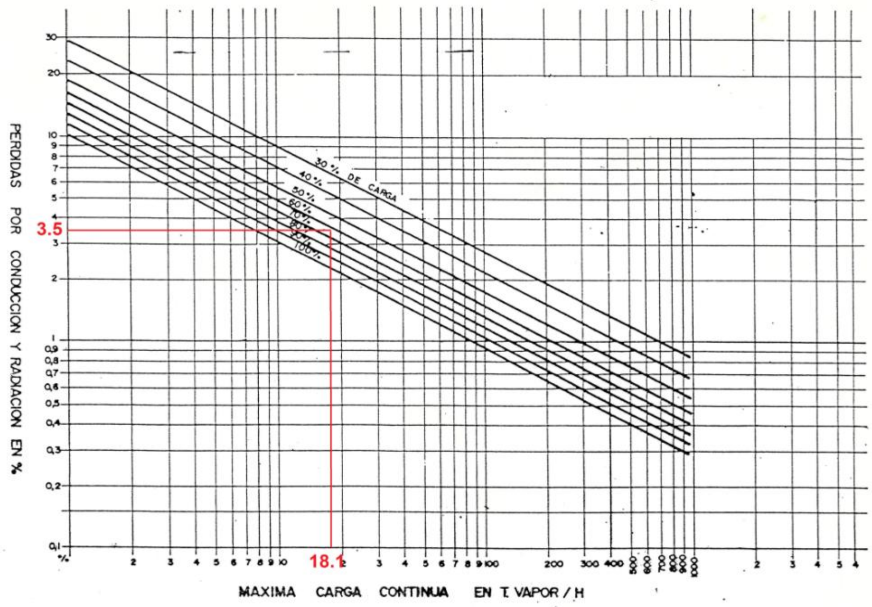
- **Simple method**:

Table 3. Information to calculate q_5 - Simple Method

Heat losses for radiation and convection - q_5	
$m_{gv\ nominal}$ (Ton/h)	18,14
Capacity (%)	62

I calculated it with the help of a monogram:

Graph 1. Diagram of radiation losses q_5



Therefore:

$$q_5 = 3.5\%$$

- **Detailed method**:

Table 4. Information to calculate q_5 - Detailed method

Heat losses for radiation and convection - q_5	
h_{steam} (kJ/Kg)	2779,773
h_{fw} (kJ/Kg)	377,950
$m_{gv\ nominal}$ (Kg/h)	18143,7
m_{gv} (Kg/h)	11228,2
Np	2

Equation 2: Calculation of nominal useful heat:

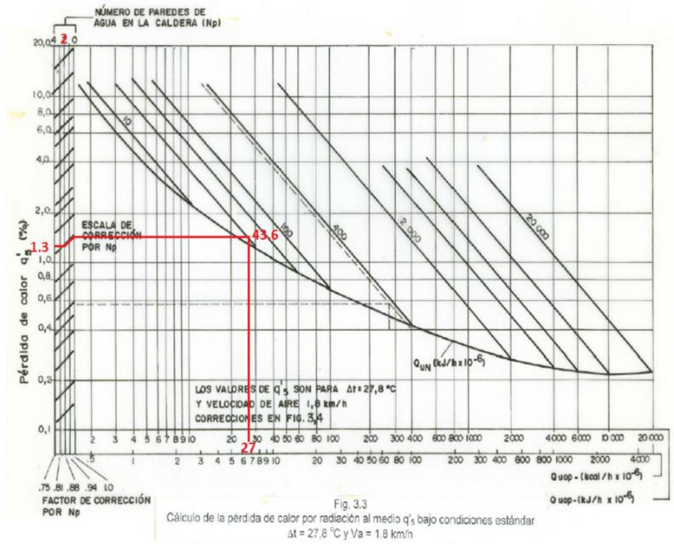
$$Q_{UN}x10^{-6} = \frac{m_{gv\ nominal}(h_{steam} - h_{fw})}{1000000} = 43.58\ \frac{kJ}{h}$$

Equation 3: Useful heat of operation:

$$Q_{UOP}x10^{-6} = \frac{m_{gv}(h_{steam} - h_{fw})}{1000000} = 26.97\ \frac{kJ}{h}$$

With the following graph:

***Graph 2*. Monogram to determine q_5 in the boiler**



I determined the heat loss:

$$q'_5 = 1.3\%$$

Taking into account the following external conditions at the boiler:

Table 5*. *Information to calculate q_5 - Detailed method

Heat losses for radiation and convection - q_5	
q´₅ (%)	1,30
T_0 (°C)	28
T_s (°C)	62,1
Condition of the premises?	Open, little wind
V_a (km/h)	3

<u>Equation 4</u>: Temperature delta between boiler surface and environment

$$\Delta T = T_s - T_0 = 34.1\ °C$$

With the Graph 3, I determined the variable Kc:

$$K_c = 1760\ \frac{kJ}{m^2 h}$$

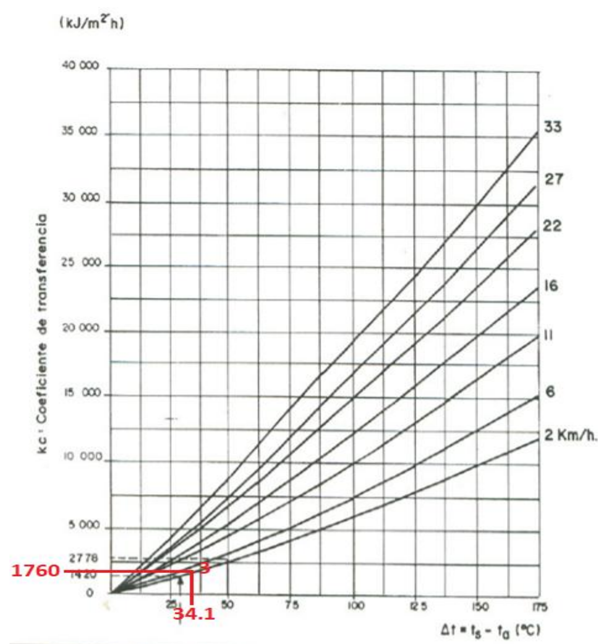
To determine the value of the correction factor of heat transfer:

<u>Equation 5</u>: Correction factor of heat transfer:

$$F_c = \frac{K_c}{1420} = 1.239$$

<u>Equation 6</u>: Radiation loss to the environment:

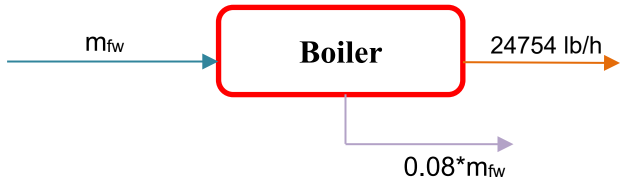
$$q_5 = F_c q'_5 = 1.61\ \%$$



Graph 3. Monogram to determine the coefficient considering the ambient temperature and air velocity for q_5

I calculated the feed water flow with the following mass balance, considering that the purges represent 8.0% of the feed water:

Figure 4. Mass balance in boiler #3 on the test day



Equation 7: Mass balance establishes:

$$m_{fw} = 24754\ \frac{lb}{h}\ + 0.08m_{fw} = 26906{,}5\ \frac{lb}{h}$$

I calculated the heat losses q_7 considering the parameters in ***Table 6***:

Table 6. Information to calculate of q_7

Heat losses for purges - q7	
m_{fw} (Kg/h)	12204,61
M_{fuel} (Kg/h)	791,90
h_{ls} (kJ/Kg)	781,689
h_{fw} (kJ/Kg)	377,950

Considering:

$$m_{purges} = 0.08m_{fw} = 976.37\ \frac{Kg}{h}$$

Equation 8: Heat losses for purges:

$$q_7 = \frac{m_{purges}(h_{ls} - h_{fw})}{m_{fuel}Q_i} x100\ = 1.22\%$$

Equation 9: Total losses:

$$\Sigma q_n = 15.071\%$$

Equation 10: Efficiency by direct method:

$$\eta_{direct} = \frac{m_{gv}(h_{steam} - h_{fw})}{m_{fuel}Q_d} x100\%\ = 83.53\%$$

Equation 11: Efficiency by the indirect method:

$$\eta_{indirect} = 100\% - \Sigma q_n\ = 84.93\%$$

Equation 12: Error between the efficiency of the two methods:

$$Error = \left|\frac{\eta_{direct} - \eta_{indirect}}{\eta_{direct}}\right| x100 = 1.67\%$$

Table 7. Rate of steam generation for the boiler #3 of the company

Rate of steam generation	
I_{gv} (Kg steam/Kg fuel)	14,2
I_{gv} (Kg steam/m3N fuel)	9,6

3.10 In determinate the efficiency of the boiler, I concluded that I could calculate it by the direct and indirect method, which I applied and compared the results obtained to demonstrate the relevance of the two methods. The thermal efficiency of the steam generator by the direct method was 83.53% and by the indirect method 84.93%, with an error of 1.67%, which is not significant for the company. The indirect method discriminates the heat losses given the conditions of the boiler, being in this case the highest losses in q_2 (losses of sensible heat with the exhaust gases) being 9.34% due to the high temperature of the gases (220°C); followed by the losses in q_5 (heat losses by radiation and convection in the simple method) which is at 3.5% given a low capacity of the boiler (62%). I consolidated the parameters of the exergy balance of boiler #3 to apply to the following expressions to determine the efficiency for the exergy method:

Then, **Equation 13**:

$$e_{xq} = \frac{Q_d}{I_{gv}}\left(1 - \frac{T_0}{T_{source}}\right) = 2328.19\ \frac{kJ}{Kg\ of\ steam}$$

Also, **Equation 14**:

$$\Delta e_x = e_{xfw} + e_{xq} - e_{xsteam} - e_{xpurge} = 1422.88\ \frac{kJ}{Kg\ of\ steam}$$

Table 8. Exergy balance of boiler #3 of the company

In the dead state - T_o = 28°C	
h_0 (kJ/Kg)	117,3
s_0 (kJ/Kg)	0,409
Exergy of steam - ex_{steam}	
h_{steam} (kJ/Kg)	2779,773
s_{steam} (kJ/Kg)	6,54873
ex_{steam} (kJ/Kg)	801,16
Exergy of feed water – ex_{fw}	
h_{fw} (kJ/Kg)	377,950
s_{fw} (kJ/Kg)	1,19158
e_{xfw} (kJ/Kg)	23,36
Exergy of the purge - ex_{purga}	
h_{purge} (kJ/Kg)	781,689
s_{purge} (kJ/Kg)	2,17984
ex_{purge} (kJ/Kg)	127,51
Exergy of heat - ex_q	
T_{source} (°C)	1320

For exergy efficiency, **Equation 15**:

$$\eta_{exergetic} = \frac{e_{xsteam}}{e_{xfw} + e_{xq}} x100\% = 34.07\%$$

An exergy efficiency of 34.07% corresponds to the quality of the thermal energy utilized by inputting a quantity of energy by the feed water and for the low heat source incorporated into the steam generated. It is important to see the difference between calculating the efficiency of steam generator using the method simple and the method detailed, which is why I created the following comparative table and drew the respective conclusions:

Table 9. Comparison of simple and detailed methods for evaluation of efficiency

	Method simple q_5	**Method detailed q_5**
m_{fuel} (m3N/h)	1164,57	1164,57
I_{gv} (Kg steam/Kg fuel)	14,2	14,2
I_{gv} (Kg steam/m^3N fuel)	9,6	9,6
q_5 (%)	3,5	1,61
q_7 (%)	1,22	1,22
Σq_n (%)	16,96	15,07
η_{direct} (%)	83,53	83,53
$\eta_{indirect}$ (%)	83,04	84,93
Error (%)	0,59	1,67

Table 9 shows that both the direct and indirect methods produce very similar results, with an error of 0.59% for the method simple and 1.67% for the method detailed. Therefore, I concluded either method can be used to obtain a very accurate result for the efficiency of steam generator.

3.11 I created the digital format with the described procedure and adapted it so that, when entering the information on composition of natural gas, gas analysis, conditions of steam generation, conditions of dome, water supply, etc., (See ***Figure 5***). I delivered this file and trained the industrial service operators' personnel. Finally, I met with the manager and the processing and refinery chief to communicate to them the following recommendations having created this tool about the current status of the steam generator:

- ✓ The highest losses of 9.34% occur in the flue gas. As the temperature is 220°C, a large amount of energy is wasted to the environment that can be used through an economizer to heat the inlet air (28°C) and improve the efficiency of the boiler. For this type of steam generator, the minimum temperature of exhaust gas must be 121°C, so there is a temperature gradient of 99°C to be exploited.

- ✓ For the case of radiation and convection losses of 3.5% is mainly due to the oversizing of the boiler. Since the capacity of steam generation is 40000 lb/h and at the time of the test, it generates 24754 lb/h, representing 62% of the operational capacity. The difference of surface temperature with that of the environment is 34.1°C, which represents a deficiency in the insulation of the equipment due to pass of time. The recommendation is to change the insulation at boiler, intervene the generator and work at a higher capacity.

- ✓ The gas analysis during the test showed a percentage of O_2 of 3.6%, higher than the recommended range for steam generators of natural gas (between 1 and 2%), so the excess air should be between 5 and 10%, and not as in this case that is at 15.6%, and therefore increases the volume of exhaust gases and losses.

Formato para el cálculo de la eficiencia de la caldera — LLOREDA S.A.

Ingrese la información requerida en las celdas de este color

Componente	% en volumen	m	n
CH_4	82,41355	1	4
C_2H_4	0,00000	2	4
C_2H_6	10,49258	2	6
C_3H_8	3,48290	3	8
C_4H_{10} - i	0,51613	4	10
C_4H_{10} - n	0,48000	4	10
C_5H_{12} - i	0,09903	5	12
C_5H_{12} - n	0,04323	5	12
C_6H_{14} - n	0,02290	6	14
H_2	0,00000		
H_2S	0,00000		
CO	0,00000		
CO_2	1,95839		
N_2	0,49129		
TOTAL	100,00000		
Tipo de combustible	Gas		

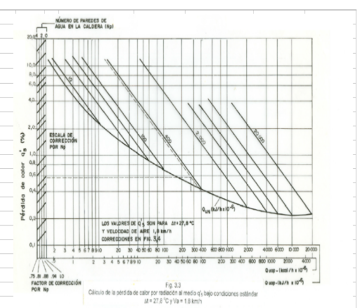
Poder calorífico inferior del combustibe	
Q_{it} (KJ/m3N)	40768,5
Volumen de aire teórico	
V°a (m3N/m3N)	10,84
Coeficiente de exceso de aire	
β	0,6690
RO2 (%)	10,0
CO (%)	0,2430
N2 (%)	85,76
α	1,1958
Exceso de aire	
EA (%)	19,6
Volumen de aire real	
Var (m3N/m3N)	12,9632

Productos de calor específico por la temperatura de aire, gases		
Componente	kcal/m3	kJ/m3
IRO_2	92,69	387,81
IN_2	68,34	285,93
IH_2O	79,93	334,43
Ia	69,91	292,49

Análisis de gases	
Componente	% en volumen
CO_2	10
O_2	4
H_2	0
CH_4	0
SO_2	0
Temperatura gases (°C)	220
Condiciones de la generación de vapor	
m_{gv} nominal (lb/h)	40000
m_{gv} nominal (Ton/h)	18,14
m_{gv} (lb/h)	25000
m_{gv} (Ton/h)	11,34
Capacidad (%)	63
$m_{combustible}$ (MBTU/h)	45
$m_{combustible}$ (m3N/h)	1164,57
Densidad relativa gas (Kg/m3N)	0,68
$m_{combustible}$ (Kg/h)	791,90
I_{gv} (Kg vapor/Kg combustible)	14,3
I_{gv} (Kg vapor/m3N combustible)	9,7
Condiciones del vapor	
P_v (psi)	160
¿Estado?	Vapor saturado
Condiciones del domo	
P_{domo} (psi)	160
Condiciones de la alimentación del agua	
m_{aa} (lb/h)	27173,9
$P_{bomba\ aa}$ (psi)	200
T_{aa} (°C)	90
Condiciones del aire frío	
Temperatura del aire frío (C)	28
Temperatura del aire frío (K)	301,15
Cp a la T (Kj/Kg*K)	1,0051
Suposiciones	
q_4 (%)	0

Volumen de gases de combustión	
$V°RO_2$ (m3N/m3N)	1,206
$V°N_2$ (m3N/m3N)	8,57
V°gs (m3N/m3N)	9,77
$V°H_2O$ (m3N/m3N)	2,166
VH_2O (m3N/m3N)	2,234
Vgs (m3N/m3N)	11,897
Vg (m3N/Kg)	14,13
Entalpías	
I°g (kJ/m3N)	3642,02
I°a (kJ/m3N)	3170,81
Ig (kJ/m3N)	4262,77

Pérdidas de calor		
Calor disponible - Qd		
Qi (kJ/Kg)	40768,5	
Qc (kJ/Kg)	0,00	No se incluye
Qpca (kJ/Kg)	0,00	
Qvat (kJ/Kg)	0,00	
Qd (kJ/Kg)	40768,5	
Pérdidas de calor sensible con los gases de salida - q2		
q_2 (%)	9,57	
Pérdidas de calor por combustión incompleta - q3		
q_3 (%)	0,89	
Pérdidas por combustible no quemado o incombustión mécanica - q4		
q_4 (%)	0,00	
Pérdidas de calor por radiación y convección - q5		
h_{vapor} (kJ/Kg)	2780,280	
h_{aa} (kJ/Kg)	376,996	
m_{gv} nominal (Kg/h)	18143,7	
m_{gv} (Kg/h)	11339,8	
Q_{UN} x 10-6 (kJ/h)	43,60	
Q_{UOP} x 10-6 (kJ/h)	27,25	
Np	2	
q'_5 (%)	1,30	
T_0 (°C)	28	
T_s (°C)	62,1	
ΔT (°C)	34,1	
¿Condición del local?	Abierta, poco viento	
V_a (km/h)	3	
K_c (kJ/m2*h)	1760	
F_c	1,239	
q_5 (%)	1,61	
Pérdidas con el calor físico de los residuos del horno - q6		
q_6 (%)	0,00	
Pérdidas de calor por purgas - q7		
maa (Kg/h)	12325,89	
m_{purgas} (Kg/h)	986,07	
$m_{combustible}$ (Kg/h)	791,90	
h_{ls} (kJ/Kg)	781,550	
h_{aa} (kJ/Kg)	376,996	
q_7 (%)	1,24	
Pérdidas totales - Σqn		
Σq_n (%)	13,309	
Eficiencia		
Método directo		
h_{vapor} (kJ/Kg)	2780,28	
$\eta_{directo}$ (%)	84,41	
Método indirecto		
$\eta_{indirecto}$ (%)	86,69	
Error (%)	2,70	



Balance exergético	
En el estado muerto - To = 28°C	
h_0 (kJ/Kg)	117,3
s_0 (kJ/Kg)	0,409
Exergía del vapor - exvapor	
h_{vapor} (kJ/Kg)	2780,280
s_{vapor} (kJ/Kg)	6,5618
ex_{vapor} (kJ/Kg)	797,71
Exergía del agua alimentada - exvapor	
h_{aa} (kJ/Kg)	376,996
s_{aa} (kJ/Kg)	1,1801
ex_{aa} (kJ/Kg)	25,89
Exergía de la purga - expurga	
h_{purga} (kJ/Kg)	781,550
s_{purga} (kJ/Kg)	2,1793
ex_{purga} (kJ/Kg)	127,54
Exergía del calor - exq	
T_{fuente} (°C)	1320
ex_q (kJ/Kg vapor)	2305,28
Pérdidas exergéticos	
Δex (kJ/Kg vapor)	1405,92
Eficiencia exergética	
$\eta_{exergética}$ (%)	34,22

Método de Qi - q5 simple | Gráfica q5 simple | Método de Qi - q5 detallado | Gráfica q5 detallado. Parte #1 | Gráfi ...

Figure 5. Interface for the daily calculation of the efficiency of steam generators

SUMMARY

3.12 The digital format for the daily calculation of the efficiency of steam generators was a tool I created to control and establish strategies regarding heat losses that affected the efficiency of steam generators, thus achieving a lower consumption of natural gas that was reflected in lower costs for the company. My experience acquired in production processes, and in the operation of industrial equipment were key to achieve this tool; my formation in chemical engineering combined with the elements of energy efficiency acquired in the postgraduate allowed me to propose a step by step to follow with theoretical and practical bases sustainable enough to be able to capture a logical algorithm that in real time detects the shortcomings reducing the efficiency of this equipment, the heart of industrial processes, as is the steam.