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ENERGY AND EXERGY ANALYSIS OF THE REAL COGENERATION PLANT OF A LARGE REFINERY

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Abstract.*Electricity is an essential input for industrial activity. However, the Brazilian electricity represents a high cost for national companies. According FIRJAN (2011), the average cost of energy in Brazil is 329.0 R$/MWh. Because of this problem, the industries are planning to efforts to reduce energy expenses, and the principal alternative is the cogeneration systems. This paper aims to perform the thermodynamic analysis, based on the First and Second Laws, of a cogeneration plant of a large refinery. And demonstrate an economic evaluation of this system based on exergy results. This analysis used the real data of 2011 and demonstrated average energy efficiency, based in first law, was 69.67%.*

Keywords:*Cogenaration, Exergy,Thermodynamic analysis.*

1. INTRODUCTION

The increase in power consumption is proportional to the increase of the population and this is directly linked to increased consumption of primary energy sources, such as fossil fuels. Currently, about 80% of the world's electric power is produced through of fossil fuels in thermal power plants in the form of coal, oil and natural gas.(Aljundi, 2009).

Thus we see the importance of energy analysis through the first law and second law of thermodynamics, using the concepts of exergy in order to assess how the available energy is consumed. The exergetic performance through the methods based on the second law of thermodynamics allows us to quantify the irreversibility of processes, and thus analyze the reasons of inefficiency. But not always the irreversibility can be avoided as the level of exergy is limited by the availability and status of each process, techniques and manufacturing equipment of materials and the cost of investment.(Zang,2005).

2. MATERIALS AND METHODS

2.1 The Cogenaration Plant

The cogeneration plant, as presented in Figure 1, serves a large national refinery. In this plant, three coal fired boilers produce superheated steam that are targeted to three turbo generators, one of 30 MW and two 29.8 MW. After the turbo generators, the superheated steam passes through three desuperheating systems to become saturated steam and thus meet the process conditions.

Due to the high steam consumption by the processes, the boiler outputs are greater than the steam required by the turbo generators. So, the remainder superheated steam produced is directed to three pressure regulating valves to supply the demand for the process.

2.2 Data Analysis

This paper is a continuation of the work done by Carmo (2012).The data used in this paper were obtained by the refinery supervision system, which allows to collect the actual data of the cogeneration plant. The year refer was 2011.For the processing of data, were excluded all the data on which the equipment had failed, or were in service or were starting its operation.

They were obtainedthe temperature, pressure and flow information in the inlet and outlet of each equipment described in Figure 1. From these data,was used the Computer Aided Thermodynamic Tables software to determine the entropy and enthalpy values of each reference obtained.

The results presented are calculated from the average of the data points.

2.3 Energy Analysis

To carry out a full First Law analysis, mass and energy conservation equations for a control volume must be applied on each system component. Energy balance is shown as Eq. (1).

$$\dot{Q} + \sum \dot{m}_{in}\left(h + \frac{v^2}{2} + gZ\right)_{in} = \dot{W} + \sum \dot{m}_{out}\left(h + \frac{v^2}{2} + gZ\right)_{out} \quad (1)$$

The Eq.(1) is applied to each component of the described plant and it can be rewritten as:

$$\sum \dot{Q}_{fuel} = \sum \dot{W}_{turbo\ generator} + \sum(\dot{m} \times h_{out})_{Desuperheating\ Output} + \sum(\dot{m} \times h_{out})_{Valve\ Output} - \sum(\dot{m} \times h_{out})_{Condensed} - \sum \dot{Q}_{Losses} \quad (2)$$

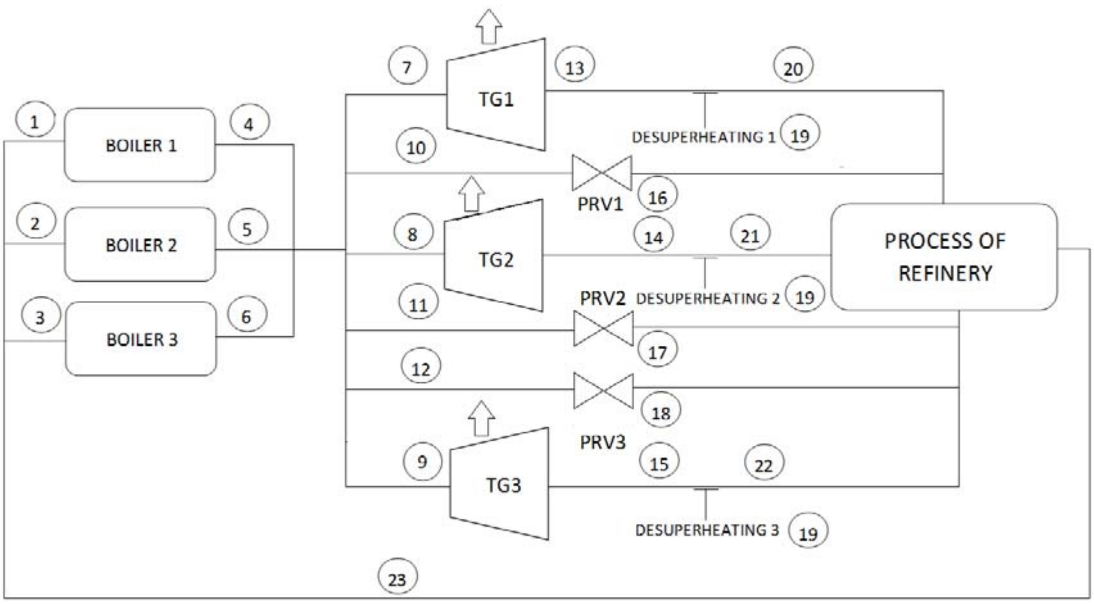

Figure 1. Diagram of Coal Fired Power Cogenaration Plant

The heat provided by the fuel in the boilers is given by:

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \times PCI_{fuel} \quad (3)$$

Heat losses in a boiler can be described as:flue gases, ashes, radiation, convection and leaks in steam lines distribution. The waste heat in flue gases can be determined by:

$$\dot{Q}_{flue\ gases} = \left(\dot{m}_{CO_2}c_{p_{CO_2}} + \dot{m}_{SO_2}c_{p_{SO_2}} + \dot{m}_{O_2}c_{p_{O_2}} + \dot{m}_{CO_2}c_{p_{CO_2}} + \dot{m}_{N_2}c_{p_{N_2}}\right) \times (T_{chimney} - T_{environment}) \quad (4)$$

However, a very common useful assumption is to consider the flue gases as air, represented by Eq.(5):

$$\dot{Q}_{flue\ gases} = \left(\dot{m}_{Gases}c_{p_{air}}\right) \times (T_{Chimney} - T_{environment}) \quad (5)$$

According Nogueira et al. (2005), the losses by radiation and convection represent about 1% to 4% of the heat provide by the fuel. Therefore, these losses can be represented by:

$$\dot{Q}_{Rad-Conv} = 4\% \times \dot{Q}_{Fuel} \quad (6)$$

The heat loss by ash can be determined through Eq. (7):

$$\dot{Q}_{Ash} = \dot{m}_{Ash} \times h_{Ash} \quad (7)$$

According toNogueira et al. (2005), the ash enthalpy is 1170 kJ/kg.

The total leakage losses in the distribution lines could not be determined due to the great extension of the plant. On the other hand, losses in the stretch between the boilers and turbines and pressure regulating valves were determined. These losses can be described as:

$$\dot{Q}_{Leaks} = \left(\sum \dot{m}_{Steam\ produced} - \sum \dot{m}_{Steam\ at\ the\ turbine\ inlet} - \sum \dot{m}_{Steam\ at\ the\ valve\ inlet}\right) \times h_{steam} \quad (8)$$

Applying Equation (1) in turbo generators, the work produced in each turbo generator is:

$$\dot{W}_{Turbo\ Generator} = -\dot{m}_{super\ heating\ steam} \times (h_{super\ heating\ steam\ output} - h_{superheating\ steam\ input}) \quad (9)$$

The heat delivered to the process bythe desuperheater and the pressure regulating valves, can be expressed respectively by Eqs. (10) and (11).

$$(\dot{m} \times h_{out})_{Desuperheating\ Output} = (\dot{m}_{superheating\ steam} + \dot{m}_{added\ water}) \times h_{saturated\ steam\ in\ valve\ output} \quad (10)$$

$$(\dot{m} \times h_{out})_{Valve\ Output} = \dot{m}_{superheating\ steam} \times h_{steam\ in\ valve\ output} \quad (11)$$

There is a heat loss in the pressure reduction valve due to its energy dissipation, that can be determined by the energy difference between its inlet and outlet streams.

$$\dot{Q}_{Heat\ Loss\ in\ Valve} = \dot{m}_{superheating\ steam} \times (h_{superheating\ steam} - h_{saturated\ steam}) \quad (12)$$

According to the refinery process engineers, 80% of the steam mass flow rate returns condensate at 95°C and 1atm from the process to the boilers. The condensate energy content can be determined by:

$$(\dot{m} \times h_{out})_{Condensed} = (80\% \times \dot{m}_{process\ steam}) \times h_{water\ at\ 95\ °C\ and\ 1\ atm.} \quad (13)$$

The $\dot{m}_{process\ steam}$ is the total steam outputfrom the three pressure regulating valves and three desuperheating systems.

According the First Law, the efficiency can be determined by:

$$\eta = \frac{\text{Useful Energy Transformed}}{\text{Provided Energy to Transformation}} = \frac{\dot{E}_{Useful}}{E_{Provided}} \quad (14)$$

Following the concept of Equation (14), the boiler efficiency can be defined as:

$$\eta_{Boiler} = \frac{\dot{m}_{steam}(h_{steam\ output} - h_{water\ input})}{\dot{m}_{fuel} \cdot PCI_{fuel}} \quad (15)$$

The efficiency of the turbo generator is:

$$\eta_{turbo\ generator} = \eta_{turbine} \times \eta_{generator} = \frac{\dot{W}_{Real}}{\dot{W}_{Isentropic}} \times \frac{\dot{W}_{electrical}}{\dot{W}_{the\ input\ shaft}} \quad (16)$$

Analyzing the cogeneration system and considering all the energy transferred by the boiler steam is use as process heat and the generation of electricity, can be determined the cogeneration plant efficiency by the following relationship:

$$\eta_{cogeneration} = \frac{\sum \dot{W}_{turbo\ generator} + \sum(\dot{m} \times h_{out})_{Desuperheating\ Output} + \sum(\dot{m} \times h_{out})_{Valve\ Output} - \sum(\dot{m} \times h_{out})_{Condensed} - \sum \dot{Q}_{Losses}}{\sum \dot{Q}_{fuel}} \quad (17)$$

2.4 Exergy Analysis

According Kaushik et al. (2011), exergy is a generic term for a group of concepts that define the maximum possible work potential of a system, a stream of matter and/or heat interaction. This interaction occurs when two systems, that are in different thermodynamic states are related, and one of them there is an increased ability to produce work. The difference in capabilities means that there is exchange of energy, which is developed by these two systems until they reach the equilibrium. Here, the reference system chosen for this interaction is the environment, which is fixed at 25°C and 0,101325 MPa.

The exergy balance based in the Second Law is:

$$\sum\left(1-\frac{T0}{T}\right)Q+\sum \dot{m}_{in}\varepsilon_{in}=\varepsilon_W+\sum \dot{m}_{out}\,\varepsilon_{out}+T_0S_{ger} \quad (18)$$

Where:

$$\varepsilon=(h-h_0)-T_0\times(s-s_0) \quad (19)$$

$$\dot{X}=\varepsilon\times\dot{m} \quad (20)$$

Applying Eq. (18) and Eq. (19), the exergetic balance of a boiler can be represented by:

$$\dot{X}_{fuel}+\dot{X}_{water}=\dot{X}_{fuel\ gases}+\dot{X}_{steam}+\dot{X}_{heat\ loss} \quad (21)$$

According Graciano (2007), the fuel exergy is:

$$\varepsilon_{fuel}=\varepsilon_{work\ mass}+\varepsilon^Q_{ash}+\varepsilon^Q_{H_2O(l)}=\varepsilon^Q_{fuel}\times m_{work\ mass}+\varepsilon^Q_{ash}+\varepsilon^Q_{H_2O(l)} \quad (22)$$

Where:

$$\varepsilon^Q_{fuel}=(PCS)_{mc}-T_o\left[(s)_{mc}+X_{O_2}\bar{s}_{O_2}-X_{CO_2}\bar{s}_{CO_2}-X_{NO}\bar{s}_{NO}-X_{SO_2}\bar{s}_{SO_2}-X_{H_2O}\bar{s}_{H_2O}-X_{N_2}\bar{s}_{N_2}\right]+\left(X_{CO_2}e^Q_{CO_2}+X_{H_2O}e^Q_{H_2O}+X_{SO_2}e^Q_{SO_2}+X_{NO}e^Q_{NO}+X_{N_2}e^Q_{N_2}-X_{O_2}e^Q_{O_2}\right) \quad (23)$$

$$(s)_{mc}=\bar{C}^c\left[37{,}16-31{,}47\exp\left(-0{,}564682\times\frac{\bar{H}^c}{\bar{C}^c+\bar{N}^c}\right)+20{,}1145\left(\frac{\bar{O}^c}{\bar{C}^c+\bar{N}^c}\right)+53{,}3111\left(\frac{\bar{N}^c}{\bar{C}^c+\bar{N}^c}\right)+44{,}6712\left(\frac{\bar{S}^c}{\bar{C}^c+\bar{N}^c}\right)\right] \quad (24)$$

The boiler exergetic efficiency is:

$$\psi_{boiler}=\frac{\dot{m}_{steam}\times(\varepsilon_{steam}-\varepsilon_{water})}{\dot{m}_{fuel}\times\varepsilon_{fuel}} \quad (25)$$

The turbine exergeticefficiency is:

$$\psi_{tubine}=\frac{W_{turbine}}{\dot{m}_{turbine}\times\varepsilon_{turbine}} \quad (26)$$

The exergy balance analysis of the superheating is:

$$\dot{X}_{superheating\ steam}+\dot{X}_{water}=\dot{X}_{saturated\ steam}+\dot{X}_{destroyed} \quad (27)$$

The exergy balance analysis of the pressure reducing valves is:

$$\dot{X}_{superheating\ steam}=\dot{X}_{saturated\ steam}+\dot{X}_{destroyed} \quad (29)$$

And the exergy of the condensate water is:

$$X_{Condensate}=\dot{m}_{condensate}\times\varepsilon_{condensate}=(h_{water\ at\ 95°C\ and\ 1\ atm}-h_o)-T_o\times(s_{water\ at\ 95°C\ and\ 1\ atm}-s_o) \quad (30)$$

The total exergetic efficiency for cogeneration plant is:

$$\psi_{cogeneration}=\frac{X_{turbo\ generator}+X_{Desuperheating\ output}+X_{Valves\ output}}{X_{fuel}} \quad (31)$$

The coal used came from the Cerrejón mine in Colombia and the data on its composition were obtained fromSadeven (2012

Table 1. Cerrejón's Coal data by Sadeven (2012).

PROPERTIES	VALUE
High Heat Value (kJ/kg)	26147
Low Heat Value (kJ/kg)	24784
Carbon (%)	64,18
Hydrogen (%)	4,63
Sulfur (%)	0,61
Oxygen (%)	7,91
Nitrogen (%)	1,16
Ash (%)	8,93
Humidity (%)	12,58

Based on this data, the work mass of the coal is $0{,}7849 kg_{fuel}/kg_{coal}$.

2.5 Results

$$(C_{5,343}H_{4,594}O_{0,494}N_{0,082}S_{0,019}ASH_{0,0893} + 0{,}698H_2O) + 6{,}305(O_2 + 3{,}76N_2) \rightarrow 5{,}343CO_2 + 2{,}995H_2O + 0{,}019SO_2 + 0{,}082NO + 25{,}02N_2 + 0{,}0893ASH \quad (31)$$

Table 2. Resume of the energy plots of cogenaration plant.

Figure 1	EQUIPMENT	ENERGY PLOTS	EXERGY PLOTS
1 → 4	Provided Energy by Coal Boiler 1	270,53 MW	267,5 MW
2 → 5	Provided Energy by Coal Boiler 2	204,54 MW	202,3 MW
3 → 6	Provided Energy by Coal Boiler 3	205,20 MW	203,0 MW
7 → 13	Produced Power by Turbine 1	24,04 MW	27,02 MW
8 → 14	Produced Power by Turbine 2	21,77 MW	27,46 MW
9 → 15	Produced Power by Turbine 3	26,35 MW	31,07 MW
13 → 20	Energy supplied to the process by Dessuperheating 1	191,83 MW	60,99 MW
14 → 21	Energy supplied to the process by Dessuperheating 2	192,42 MW	65,28 MW
15 → 22	Energy supplied to the process by Dessuperheating 3	207,55 MW	74,84 MW
10 → 16	Energy supplied to the process by Pressure Regulating Valve 1	34,95 MW	11,05 MW
11 → 17	Energy supplied to the process by Pressure Regulating Valve 2	36,92 MW	8,9 MW
12 → 18	Energy supplied to the process by Pressure Regulating Valve 3	50,71 MW	14,95 MW
-	Losses in Boiler 1	21,95 MW	111,87 MW
-	Losses in Boiler 2	23,8 MW	78,26 MW
-	Losses in Boiler 3	23,7 MW	84,02 MW
-	Losses by Leaks	76,79 MW	30,85 MW
-	Losses in PRV 1	26,51 MW	6,5 MW
-	Losses in PRV 2	19,45 MW	5,83 MW
-	Losses in PRV 3	31,86 MW	9,66 MW
20 → 23	Energy Returning as Condensate (Desuperheating 1)	21,83 MW	1,63 MW
21 → 23	Energy Returning as Condensate (Desuperheating 2)	23,57 MW	1,74 MW
22 → 23	Energy Returning as Condensate (Desuperheating 3)	25,74 MW	2,00 MW
16 → 23	Energy Returning as Condensate (PRV 1)	4,01 MW	0,30 MW
17 → 23	Energy Returning as Condensate (PRV 2)	3,39 MW	0,25 MW
18 → 23	Energy Returning as Condensate (PRV 3)	5,65 MW	0,42 MW

Table 3. Resume of efficiencies

Figure 1	SYSTEM	FIRST LAW	SECOND LAW
Boiler 1	Coal Boiler 1	91,60%	41,90%
Boiler 2	Coal Boiler 2	84,10%	38,80%
Bolier 3	Coal Boiler 3	87,53%	41,50%
TG 1	Turbo Generator 1	81,91%	88,95%
TG 2	Turbo Generator 2	67,64%	78,81%
TG 3	Turbo Generator 3	73,00%	82,93;5
-	Cogeneration Plant	69,67%	47,79%

2.6 Conclusion

Analyzing the efficiency of the plant, calculated for the first law, we obtain the value of 69.67%. This result shows that much of energy supplied by coal combustion process is lost by leaks and the pressure regulating valves.

The boilers had an average efficiency of 86%, which appeared satisfactory, since a significant portion of the energy supplied by the fuel is lost in the effluent gases and ashes.

The turbine efficiencies showed distinct, despite having the same input parameters: steam at 485 ° C and 85 bar. This shows that there was a failure in quality control of superheated steam that enters is thesesequipment. This lack of control is due to leakage losses in the distribution pipes.

The analysis done by the second lawdemonstrated that the efficiency of the system is 47.79%. This shows a very low level of energy use.Unlike the first law presented, the boiler had a low efficiency. This demonstrated that the energy use of such equipment is very low and the losses in the process of steam producer is more significant than presented by first law.

However, the turbines obtained a good efficiency, showing that the quality of the equipment compensated for lack of control of the steam power process. But, that does not relieve the fact that the steam was supplied under operating conditions the efficiency of the turbines would be even greater.In analyzing the exergy, losses in boilers and leaks in distribution piping were the most significant.

By comparing the analysis between the first and second law of thermodynamics we realize that the two point losses leak as a factor to be fought.Another important point is the continued use of regulatory pressure valves. These devices should serve as diversions when the boilers were in maintenance. However, as the high demand for steam operation is continuous, which is not recommended, a large portion of the energy that has been dissipated in these devices.To remedy the problem, despite the high investment, it is recommend use one more boiler.

About the equipment, the first law states that the turbines should be the main targets of investment improvements, because they have the smallest efficiencies. However, when we analyze the exergy, we see that the energy recovery boiler is too low and that the real focus of investment should be in such equipment, as approximately 280 MW are lost and/or destroyed in the boilers.

This shows that the lack of precise control on parameters such as air-fuel ratio or the composition of the exhaust gases or control the design parameters, can be a determining factor in the efficiency of equipment and loss or gain on investment.

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