SUSTAINABLE TECHNOLOGIES FOR RELIABILITY: AN EXERGETIC ANALYSIS IN A COGENERATION POWER PLANT

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ABSTRACT
Since the oil crisis in the seventies the importance of the energy in the industry and in the tertiary services has been growing. Factors like globalization of the markets, the internal birth of similar industries, the need to cut costs to be competitive, the national energy planning for industry sectors and the environment protection, produces a continuum effort by the industry to centre investigation resources in the optimization of the energy production and utilization. One of technology used to achieve these goals is the combined heat and power – CHP. This work describes the energy and exergy analysis performed in a 4 MW cogeneration plant of a cane sugar refinery. Improvements in the overall plant efficiency were achieved.

Keywords: CHP, exergetic analysis, sustainability.

INTRODUCTION
The cogeneration technique is nowadays widespread in terms of energy analyses (Afonso, 2014, 2016). The application of this technology takes in account only the energetic analysis of the plant, always useful, and it is the first approach. However, the energetic analysis by itself doesn’t enable to look for the irreversibility’s that occurs in the several components of the CHP. This is an important issue as it enables to look for the components of the plant where there is a possibility for improvements. A powerful tool in the pursuit of sustainability energy technologies is the exergetic (or 2nd law) analysis of operating systems. This kind of analysis is a practical utilization of classical thermodynamics, opening horizons to the determination and distribution of cost through sub-systems, identifying the critical irreversibility’s localization and suggesting possible ways of improvement (Kotas, 1995, Afonso, 2012).

The system under consideration is a plant composed by the firsts two natural gas reciprocating engines installed and operating in Portugal, each one with a power of 2 MW. Each engine has a recovery system transferring heat from the cooling water, lubricating oil and intercooler circuits, to a heat exchangers network disseminated along the plant. Common to both engines, there is a recovery boiler that uses the exhaust gas line, producing low-pressure steam that is consumed in the process. With this tool, improvements in the overall plant efficiency were achieved.

THE CHP SYSTEM AND THEORETICAL ANALYSIS
The layout of the power plant is shown in Fig.1.
Each system was analyzed making in this way possible to compare the effectiveness of each sub-system and engine, identifying the critical points for irreversibility’s. A special attention is given to the recovery systems since it is a direct way to reduce losses without major changes in the engine's conception.

The energy balance was done by means of mass balances and the calculations of individual energy loads of the different streams. In order to calculate the exergy associated with each different type of input and output it’s necessary to apply different formulations.

The exergy associated with heat transfer is:

$$E^0 = Q_{in} \frac{T_i - T_2}{T_1}$$

The exergy associated with work transmission is by definition equal to its value.

Exergy associated with pressure and temperature is:

$$E^{\text{pr}} = C \left[ (T - T_0) - T_0 \ln \frac{T}{T_0} \right] - RT \ln \frac{P}{P_0}$$

$$E^{\text{pr}} = C \left[ (T - T_0) - T_0 \ln \frac{T}{T_0} \right] - V(P - P_0)$$

Exergy associated with chemical reactions:

$$E_0 = -\Delta G_f - \sum nE_{\text{feed}}^{\omega} + \sum nE_{\text{products}}^{\omega}$$

The irreversibility’s can be calculated by means of an exergy balance or using directly the Gouy-Stodola (Kotas, 1995) equation:

$$I = \frac{1}{T_0} \sum \left( S_{\text{out}} - S_{\text{in}} \right) - \sum \frac{Q}{T}$$

Fig. 1 - Layout of the cogeneration power plant.
After evaluation of each individual irreversibility’s, it is necessary to calculate the efficiency of the overall installation. Three types of formulations can achieve that purpose (Kornelissen, 1995):

Classical formulation:
\[ \eta = \frac{\sum E_{\text{out}}}{\sum E_{\text{in}}} \]  

(6)

Rational formulation:
\[ \varphi = \frac{\sum E_{\text{Devatio}}}{\sum E_{\text{in}}} \]  

(7)

The Transiting energy formulation:
\[ \psi = \frac{E_{\text{in}} - E_{\text{Tr}}}{E_{\text{in}} - E_{\text{Tr}}} \]  

(8)

which can be written as:
\[ \psi = \frac{\sum (E_{\text{in}}^0 - E_{\text{Tr}}^0) + \sum (E_{\text{in}}^w - E_{\text{Tr}}^w) + \sum \sum (E_{\text{out}}^0 - E_{\text{Tr}}^0) + \sum (E_{\text{out}}^w - E_{\text{Tr}}^w)}{\sum (E_{\text{in}} - E_{\text{Tr}}^0) + \sum (E_{\text{in}} - E_{\text{Tr}}^w) + \sum \sum (E_{\text{out}} - E_{\text{Tr}}^0) + \sum (E_{\text{out}} - E_{\text{Tr}}^w)} \]  

(9)

where in equations 8 and 9 \( E_{\text{Tr}} \) is the transiting exergy, and is calculated by equation 10:
\[ E_{\text{Tr}}^w = \min [E_{\text{in}}^w; E_{\text{out}}^w] \]  

(10)

METODOLOGY AND RESULTS

This study was divided in two parts, first it was performed an analysis of the project conditions, and then measurements were carried out in order to determinate the actual performance. The analysis was performed in both engines, the boiler and the heat recovery system.

In design conditions, the engines achieved an electrical efficiency of 40 %, while the boiler was responsible for the production of steam corresponding to 20 % of the total energy, the heat exchangers network corresponding to 23 % and the losses were 17%.

The system consists in a circulating pump, the intercooler and an air cooler system that cools down the water from 45.4°C to 40 °C. The hot water flows from the intercooler into the air coolers and then after been cooled goes into the intercooler again. The heat it’s transferred from the engine to the atmosphere without recovery.

In this work it has been proposed the installation of one heat exchanger in each engine increasing the temperature of the boiler’s feed water. The investment is 11.000 € and the time to install and working at full operation is of 2 months. The annual recovery will be of 3.66 GJ which is the thermal equivalent to 100.000 kg of thick fuel oil used to heat this water. The annual economy will be of about 13.000 € and the payback period will be less than one year, which is very satisfactory.

The second part consists in the measurement of operating parameters and the execution of the energy and exergy balance. The system was divided into three main areas: the recovery boiler, the heat recovery system and the engine itself. The calculation of the efficiencies was done with the First Law of Thermodynamics (Çengel, 1998, 2001), and with the ones presented by equations 6-8. The efficiencies of the plant, boiler and the heat recovery system are represented in Figs. 2, 3 and 4 respectively for three different loads (100%, 80% and 50%).
Fig. 2 - Plant efficiency

Fig. 3 - Boiler efficiency

Fig. 4 - Heat recovery system
For all kinds of formulations, and from the above figures it’s concluded that the higher is the working charges the better will be the efficiency of every system, being that the value of the system’s efficiency depends on the type of formulation used. If the classical equation is used, the obtained value of the efficiency would lead to somehow not exact conclusions, due to the fact that not all of the inlet flows of exergy are used and it does not take into account the objective of the system. But it has a purpose, for it can be a tool for comparison between installations that only have been taking into consideration this type of definition. The efficiency values obtained by the rational and transiting exergy are better approximations to the process reality due to fact that this type of equations takes into account the exergy necessary for the objective, or the effectively decrease.

The rational form can only be compared to the classic way since it is a different combination of the same elements, but that clearly marks the objective of the process. This is the better way to know exactly which exergy currents were necessary to achieve the desired exergy flow.

The transition form is the way to calculate the plant efficiency that implies, however, more calculations. It characterizes the exergy exchange in the process, not all of it, but only the changes operated in the plant (the real changes), and not the exergy necessary for the transformations. It can be somehow compared to the heat released by steam in a water/steam heat exchanger: the heat that flows from the steam to the water is the heat of vaporization, not the total heat of the steam, only the difference between the vapor and the liquid state. The liquid heat is necessary to the operation but it goes through the system without participation in the process, and that way is not considered.

The results of the exergy balance allow the distribution of exergy through the different parts of the system as shown in Fig. 5.

This is the distribution of the participant’s exergy flows. The value of the irreversibility’s is very representative outnumbering the electric production and will be the next part of the study. The irreversibility’s of the turbochargers will be a part of the "Others" in the Fig. 6, as well as the irreversibility’s associated with the combustion equation.

The analysis of figure 6 clearly states that the distribution achieved plays a vital role in the optimization of the system. The highest values were obtained by the cooling system, and boiler and some irreversibility’s were found in the heat recovery system and alternator. As
the cooling system represent a major place in the irreversibility’s, it was studied for each engine. Fig. 7 shows the irreversibility’s of engine 1. For engine 2 the results are almost the same. In spite of the operating conditions of the motors being slightly different, about 1% in some systems, the low temperature air coolers are responsible for about half of the irreversibility’s of this system.

After having spotted the irreversibility’s, the next phase is the optimization of the engine. This was made in 3 stages: plant re-testing in different operating conditions, project of control changes, and the project of modifications that imply the installation of additional equipment.

At first, some tests were made and controllers were set to more favorable conditions, namely the main controller for the heat recovery circuit that caused an increase in heat recovery from about 800 kWh to 950 kWh. The heat recovery is set by a controller that varies the frequency of the circulating pumps. The value set by installing the controller was a minimal set point that causes the operation of the air cooler and heat circuit to operate partially. The change was to transfer more heat to the recovery system and less to the air cooler, by stopping some fans and heating less water in the CHP.
Another change proposed is the change in the operating conditions of the high temperature circuit of the intercooler that would minimize the work of the engine’s air coolers. The only function of this equipment must be minimized - transferring heat to the atmosphere. The less it is spread, the better efficiency the system will have. The measured conditions stated that the water was cooled below the necessary engine’s temperature, because of the transducer misplace. In that way some more hot water was being taken apart from the recovery system in order to compensate this sub-cooling.

Another change proposed is the automatic control of the heat recovery system. In this way the efficiency would be greater since the negative exergy flows would be absent from normal work. If the valves before the heat exchangers were automatic, and the temperature in each side of the unit measured, by means of a PLC, it would be possible to automatically switch the flow from the less interesting units, to the ones that maximize the exergy flow. The study of the interaction of this system with the CHP has revealed that in some cases there are some of the units that must be shut-off in order to maximize the operation. For example, there was a unit that sometimes instead of cooling the engine’s water, in reality it was heating it, as the secondary water flow was hotter that the engine’s system. In this way, it should be chosen more efficient units that send automatically the hot flow in. The calculations done during the test period revealed that there would be an increase of about 3,8 % in the recovery system efficiency and the investment will be about 10.000 Euro.

During the study there were found some more points of improvement like the efficient lighting, thermal protection of the plant, and the total increase in the efficiency would be of 5,86 % if all of the measures would be executed.

CONCLUSIONS

As major conclusions of this 12 months’ work, besides the important thermodynamic characterization of the plant, with the determination of global and local irreversibility’s, there were achieved an improvement in the overall efficiency.

This is one of the first studies of this kind performed in the Portuguese industry and reveals to be of significant importance as it is an example to follow by other initiatives and also it understates that the co-operation between the university and the industry can produce positive practical results. Some other similar project will occur in the near future in the same CHP.

AKNOWLEDGEMENTS

The authors are grateful to R.A.R. - Refinarias de Açúcar Reunidas S.A. Porto, Portugal, for the opportunity given to use their CHP facilities to carry out the analysis.

REFERENCES


