ENERGETIC AND EXERGETIC ANALYSIS OF A THERMOELECTRIC POWER PLANT

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Abstract. *In this work a methodology, was developed for energy and exergy evaluation of a thermoelectric power plant that uses high furnace gases and tar as fuel. The implementation of the calculation routines was made with aid of the computational program EES – Engineering Equations Solver in its academic version. As an example, this methodology was applied in the evaluation of the project for the implantation of the Thermoelectric Power Plant of Barreiro, co-generation unit lead by CEMIG, COPASA and Vallourec & Mannesman Tubes Steel – V&M of Brazil. The results presented in this work show the efficiency of individual equipment and the cycle, as a whole, as a function of the variation of the supplied power. Fuel burning and the exhaust gases also are evaluated. Future on-line monitoring of the efficiency using the software developed can assist in the determination of the best operational conditions and the most opportune moment for preventive interventions. The analysis of the exhaust gases make better control of fuel burning possible, reducing the level of polluting gases and increasing the energy availability, resulting in an increase of the global efficiency and less atmospheric pollution.*

Keywords*: thermoelectric power plant – rankine cycle - availability analysis – ees - engineering equations solver*

1. Introduction

Wall (1986) applied the concepts of exergy in a paper and cellulose industry, entering the exergetic losses in the main equipment. It also compared the costs of the energy and exergy of some common forms of energy and presented a program in BASIC code to calculate the exergy, energy, enthalpy and entropy of the vapor and the energy and termochemical exergy of some substances.

Negri et al (1999) had applied the concepts of exergy in a thermal power plant operating with gas in agreed cycle. In that study, the efficiency of the diverse equipment had been calculated. It was seen, still, that through the analysis of the plant for the method of the availability it is possible to identify the magnitude and the probable causes of the thermodynamic losses in each equipment, characterizing this method as an excellent tool for evaluation and improvement of the installations.

The focus of this work is the development of a methodology for an energetic and exergetic evaluation of thermoelectric power plants for co-generation based on the first and second laws of thermodynamics. Such a methodology permits evaluating, besides thermal losses, the quality of the energy consumed in the industrial processes. In the evaluative process, energy availability is compared to practical results. As an example, the developed methodology is applied to the implementation project for the Barreiro power plant was evaluated. This power plant is a co-generation unit maintained by CEMIG in partnership with COPASA and the siderurgical company; Vallourec & Mannesman – V&M do Brasil S.A. The project, with a nominal power of 12,9 MW, uses blast furnace gases and tar (both residual fuels from the production processes) in a Rankine cycle. Besides these, natural gas is used in the startup of the boiler or in the event of an interrupted supply of the original fuels. The unit operates continuously, supplying electrical power to the primary loads of the plant (blower and pumps of the blast furnace, cooling system) in parallel to the CEMIG electrical network.

In this work, a methodology for energetic and exergetic evaluation of the main equipments and the Rankine Cycle of thermoelectric power plants was developed. The Engineering Equations Solver software was used with the purpose of identifying processes critical to the generation of irreversibility, aiming to implement improvements and adaptations to the industrial layout.

2. Mathematical modelling and computational program

Based on concepts from thermodynamics, specific equations were developed for efficiency calculations for the main equipments of the plant and the Regenerative Rankine cycle of the Barreiro thermal plant, for determining the energy availability and the combustion analysis of the residual fuels in use (blast furnace gas and tar). The equations were implemented using the Engineering Equations Solver software – EES.

In figure 1, the basic cycle of the Barreiro Thermoelectric power plant is presented with its main equipments: boiler, turbogenerator system, condenser, high-pressure pump and regenerative heat exchangers (deairing, high pressure and low pressure heat exchangers). The numbered points correspond to the thermodynamic states mentioned in the figure and equations.

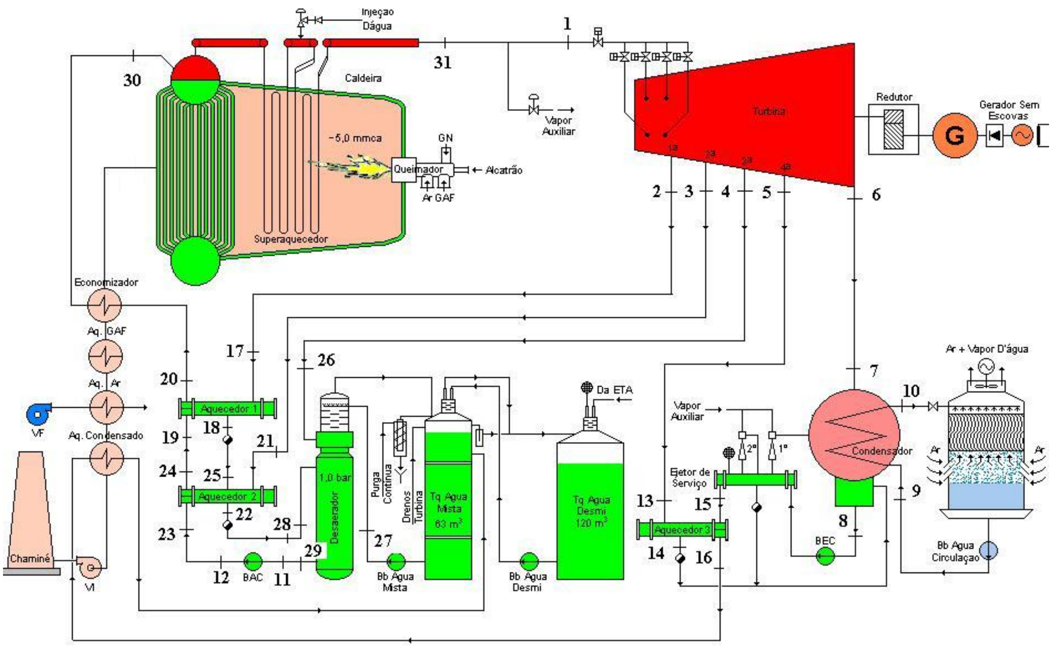

Figure 1. Regenerative Rankine Cycle of the Barreiro Thermoelectric Power Plant

2.1. Analysis of the Boiler

The efficiency of the boiler (η_b) is defined by the First Law of Thermodynamics as:

$$\eta_b = \frac{\dot{Q}_b}{\dot{m}_{GAF}.PCI_{GAF} + \dot{m}_{tar}.PCI_{tar}} \tag{1}$$

where $\dot{m}$: mass flow (kg/s), LHV: lower heating value(kJ/kg). The subscripted GAF and tar correspond to the blast furnace gas and tar respectively. $\dot{Q}_b$: heat transfer rate to the boiler, defined as:.

$$\dot{Q}_b = \dot{m}_{31}\, h_{31} - \dot{m}_{30}\, h_{30} \tag{2}$$

where h : specific enthalpy (kJ/kg). The subscripted 30 and 31 refer to the entry and exit off the boiler, respectively.

The efficiency, by the Second Law of Thermodynamics, is defined by:

$$\varepsilon_b = \frac{A_b}{\dot{m}_{GAF}\ .a_{fGAF} + \dot{m}_{tar}\ .a_{tar}} \tag{3}$$

where a is the specific flow availability (kJ/kg)

The rate at which the availability of the boiler water varies; $\dot{A}_b$ equated as:

$$A_b = \dot{m}_{31}\, a_{31} - \dot{m}_{30}\, a_{30} \tag{4}$$

The availability balance for the boiler is reduced to:

$$A_h + I = A^{ch}_{total} - A_b \tag{5}$$

where A_h: destruction of availability due to external irreversibility; I : destruction of availability due to internal irreversibility; A^{ch}_{total} : Total chemical availability of the fuels A_b : total availability absorbed by the working fluid in the boiler.

In figure 2, the efficiency results are shown for the boiler under various loading conditions – Min (1751kW), 25% (4032kW), 50% (6985kW), 75% (9943kW) and 100% (12907kW). Note that the efficiency of the boiler, by the First Law exceeds the efficiency given by the Second Law. This occurs because the First Law only takes the energy balance on the boiler into account, whereas losses due to heat transfer through the sides and unburnt fuel amount to approximately 12% of the ideal conditions.

When calculating the efficiency by the Second Law, the total availability of the fuels used is compared to the availability that is effectively absorbed by the working fluid.

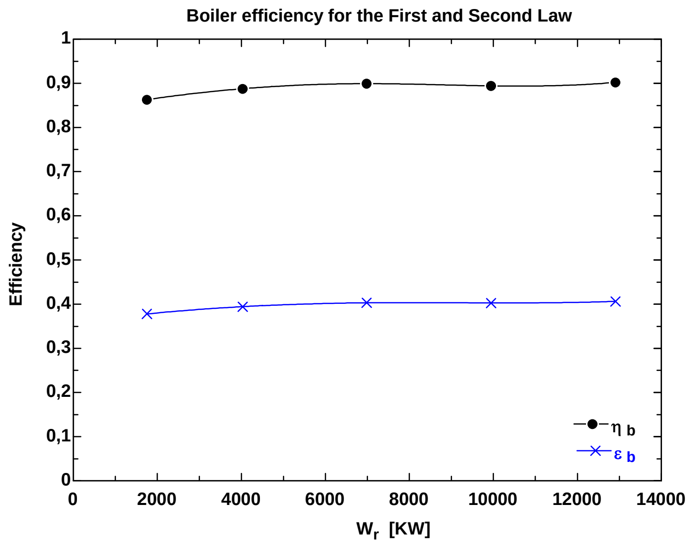

Figure 2 – Evolution of the boiler efficiency for different loading conditions

2.2. Analysis of the turbogenerator system

The turbine, illustrated in figure 1, has four steam extractions of which two are directed to the regenerative high-pressure heaters another to the deairer and the last leads to the low-pressure heater. The efficiency of the turbogenerator system, by the First and Second Law of Thermodynamics, is expressed as follows:

$$\eta_t = \frac{\dot{W}_R}{(h_1.\dot{m}_1)-(h_{21}.\dot{m}_2)-(h_{31}.\dot{m}_3)-(h_{41}.\dot{m}_4)-(h_{51}.\dot{m}_5)-(h_{61}.\dot{m}_6)} \tag{6}$$

$$\varepsilon_t = \frac{\dot{W}_R}{(a_1.\dot{m}_1)-(a_2.\dot{m}_2)-(a_3.\dot{m}_3)-(a_4.\dot{m}_4)-(a_5.\dot{m}_5)-(a_6.\dot{m}_6)} \tag{7}$$

where $\dot{W}$: generated power. The subscripted I and R correspond to the isoenthropic and real process that occurs in an turbine and the indexes from 1 to 6 refer to the inlet and exits of the turbine, as shown on figure 1.

The destruction of availability in the turbine, in total is caused by internal irreversibility and heat loss to the environment and can be calculated through the availability balance as follows:

$$A_h + I = A_1 - (A_2 + A_3 + A_4 + A_5 + A_6) - A_w \tag{8}$$

where the subscripted w refers to work.

The efficiency of the turbogenerator system project, using the First Law of Thermodynamics for its ideal load (12904kW), is equal to 74,69%, including the speed reducer, generator and bearings (Toshiba, 2001). This value was confirmed by calculations done using EES, which also included the determination of the efficiency using the Second Law. Figure 3 shows the decrease in efficiency with the reduction of the applied load. This decrease is expected since the turbine is designed to function primarily with its nominal load (12907kW). Besides this, an increase in irreversibility is noticed resulting from of the expansion control valve at lower powers. The use of the Second Law, in this case, gives a higher efficiency than the First Law. This is unusual, but documented by Li (1996) and Kotas (1995). This occurs because the First Law uses the isoenthropic power as the maximum whereas, while the Second Law uses the maximum power limit is considered to be the variation of the availability between two real states. In this case, only part of the availability flow can be transformed into work, the rest being consumed in the process due to its irreversibility. These irreversibility can be measured and make an analysis of the quality of the process in question possible.

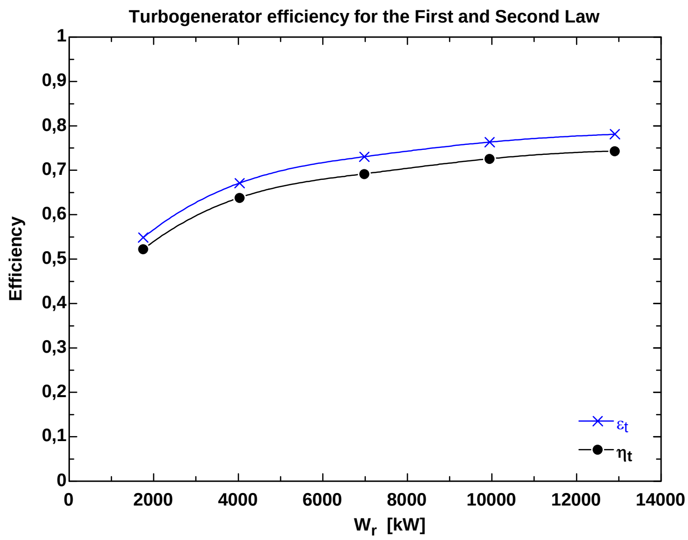

Figure 3 – Evolution of the efficiency of the turbogenerator system for different loading conditions

2.3. Analysis of the high-pressure pumps

The efficiency, using the First and Second Law of Thermodynamics, for pumps is written as follows:

$$\eta_p = \frac{\dot{m}_{11}(h_{11} - h_{121})}{\dot{m}_{11}(h_{11} - h_{12R})} = \frac{(h_{11} - h_{121})}{(h_{11} - h_{12R})} \tag{9}$$

$$\varepsilon_p = \frac{\dot{m}_{11}(a_{11} - a_{12})}{\dot{W}_R} \tag{10}$$

The subscripted 11 and 12 refer to the entry and exit of the high-pressure pumps.

The availability balance for the adiabatic pumps is reduced to:

$$I = A_{11} - A_{12} + A_w \tag{11}$$

The efficiency of the project, using the First Law, for the high-pressure pumps at nominal power is equal to73,3%. Analogous to the turbine it can be seen, in figure 4, that the efficiency of the pump, using the Second Law, is higher than that found through the use if the First Law, phenomenon also described by Li (1996).

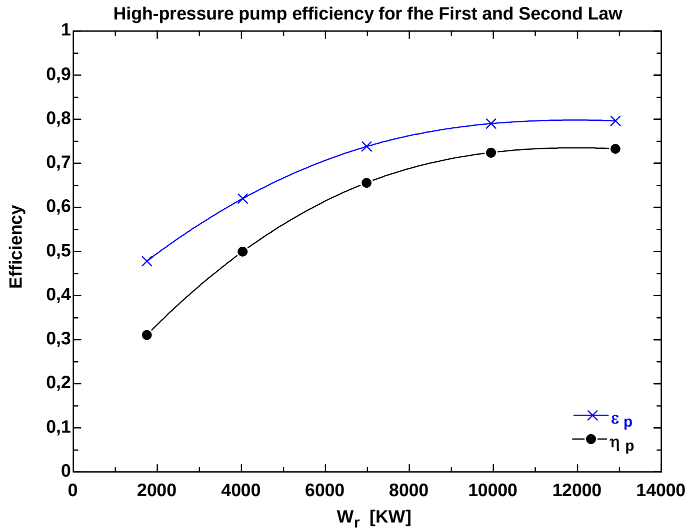

Figure 4 – Evolution of the efficiency of the high-pressure pump

2.4. Analysis of the condenser

In the condenser, the flow of steam and dissolved gases to the ejector was not taken into account. Thus, its efficiency, using the Second Law, is calculated as follows:

$$\varepsilon_c = \frac{\dot{m}_9(a_{10} - a_9)}{\dot{m}_7(a_7 - a_8)} \tag{12}$$

The availability balance for the condenser is reduced to:

$$A_h + I = A_9 + A_7 - (A_{10} + A_8) \tag{13}$$

Note, in figure 5, that a reduction in efficiency, calculated through the Second Law, takes place for higher loading conditions. This is explained by the increase in irreversibility of the working fluid. This behavior is associated with the difference between the saturation and working fluid temperatures at the condenser exit. It is noted that, for larger loads, an increase both in the difference between temperatures and rejected heat transfer rate. These factors contribute to an elevation of the irreversibility in the thermal equipment and, subsequently, the lowering of its efficiency. The efficiency of the condenser, calculated using the model and the Second Law at nominal conditions (12907kW) is of 47,24% while, at minimum load (1751kW), equal to 72,62%.

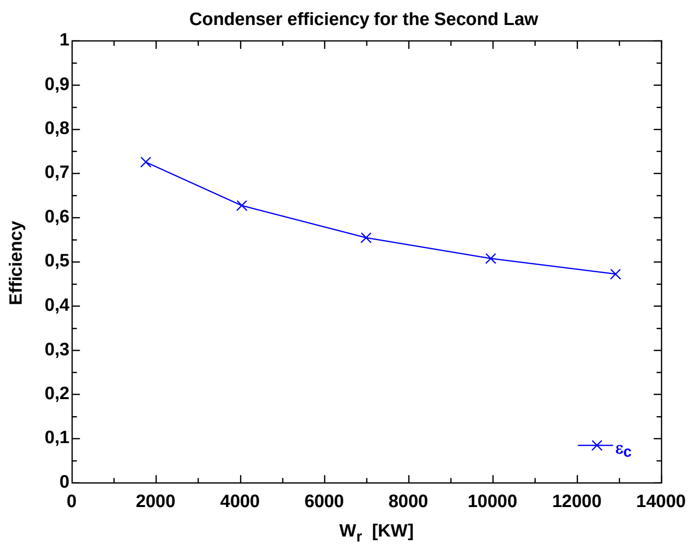

Figure 5 – Efficiency of the condenser using the Second Law

2.5. Analysis of the regenerative heat exchangers

The equations employed for calculating the respective efficiencies and availability balances, according to the numbering presented in figure 1, are shown here.

For the High-Pressure Heater (Heater n° 01):

$$\varepsilon_{hph01} = \frac{\dot{m}_{19}(a_{20} - a_{19})}{\dot{m}_{17}(a_{17} - a_{18})} \tag{14}$$

$$A_h + I = A_{17} + A_{19} - (A_{18} + A_{20}) \tag{15}$$

In figure 6, it is shown that the efficiency of high-pressure heat exchanger 01, using the Second Law, increases when the load is augmented and is practically constant beyond 6985kW. This amount represents 50% of the nominal load. In accordance with the previous analysis of the condenser. The efficiency curve follows the behavior of the mean temperature difference between the hot and cold working fluids. During nominal conditions, the efficiency obtained by the Second Law is of 88,42%. The remaining heat exchangers behave similarly.

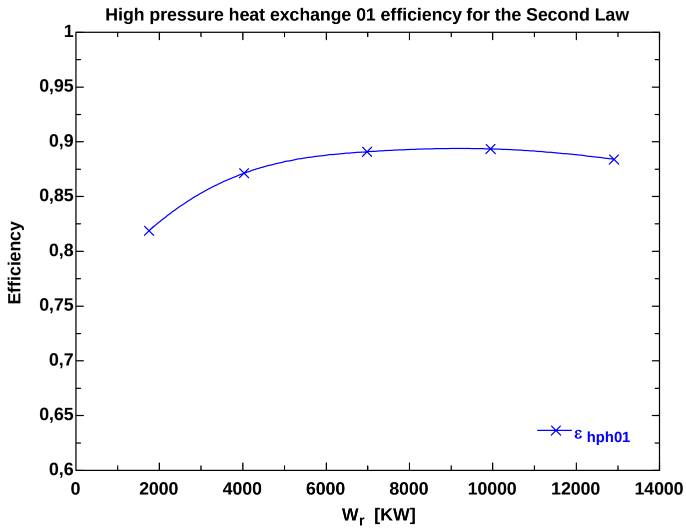

Figure 6– Evolution of the efficiency of high pressure heat exchanger 01 for different loading conditions

2.6. Analysis of the Regenerative Rankine Cycle

In figure 7, large variations in global efficiency is seen, using both Laws of Thermodynamics, as a result of different loads. This occurs primarily because of the expansion of the turbine's inlet valve and the influence of the steam extractions. The efficiency, using the Second Law, in all cases, is lower than what is obtained using the First Law for the same conditions. This is explained by the large irreversibility created by the boiler in all loading situations. This behavior is foreseen in the studied literature, Li (1996). The global efficiency of the system, using the First Law (Toshiba, 2001), is equal to 25,79% for nominal loading (12907kW). This is in accordance with the value found through simulation using EES. The global efficiency of the thermoelectric generation cycle is the result of the product between the cycle's efficiency and the respective boiler efficiency (Li, 1996), expressed by the First and Second Law:of Thermodynamics as:

$$\eta_{glo} = \eta_{cy} . \eta_b \tag{16}$$

$$\varepsilon_{glo} = \varepsilon_{cy} . \varepsilon_b \tag{17}$$

The subscripted *glo* corresponds to the global value, for the entire cycle.

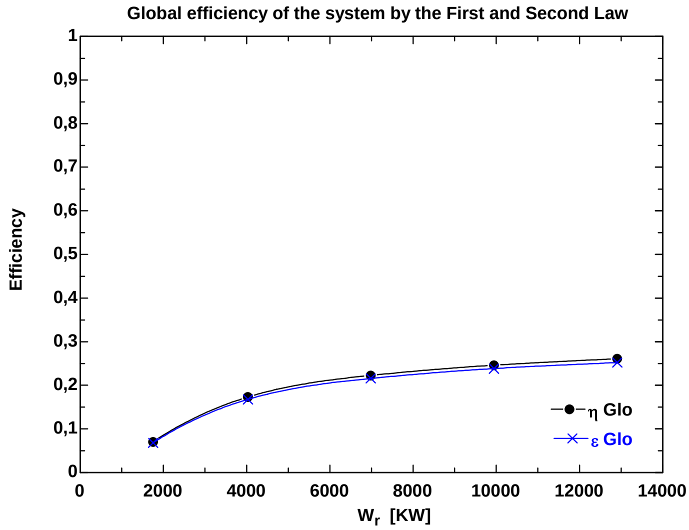

Figure 7 – Evolution of the global efficiency of the system by the First and Second Law

2.7. Analysis of irreversibility

The graph in figure 8 shows the participation of each equipment in the total irreversibility generated where the total sum is of 100%. The boiler and the turbogenerators are notably seen as the equipments with the largest potential for optimization. For other loads, the percentual participation of each equipment is very similar.

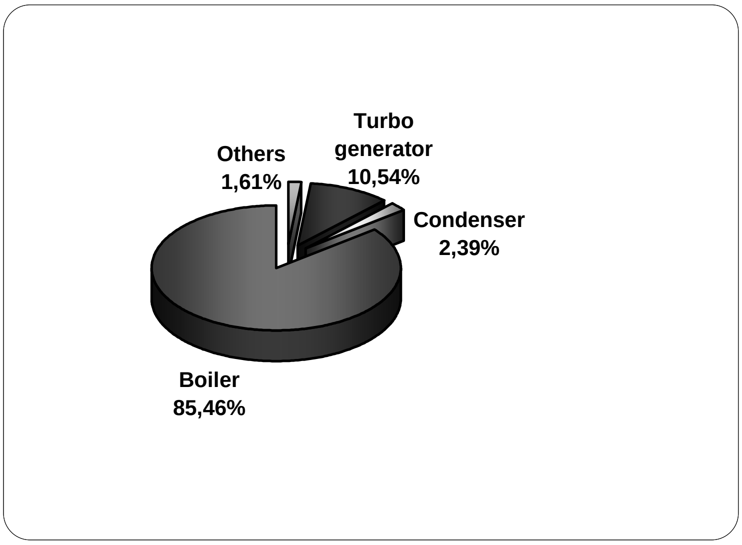

Figure 8 – Influence of each equipment in the total irreversibility generated under nominal loading conditions

2.8. Analysis of the chemical availability of the fuels

The calculations performed with the EES software demonstrate that the concentration of carbon monoxide has a substantial influence on the availability of the blast furnace gas. It is made evident that the specific availability of the gas increases linearly with the CO concentration, considering the proportional reduction of the remaining elements of the blast furnace gas.

Using the obtained availability value, the lower heating value of the blast furnace gas was calculated in relation to its chemical composition. These calculations are based on the chemical composition specified in the boiler manufacturer's report (Equipalcool Sistemas, 2002) and result in an lower heating value of 3923 kJ/Nm³. The LHV, obtained for the blast furnace gas, are in agreement with the levels specified in said report: between 3349 and 4189 kJ/Nm³.

The calculation of the specific availability of the tar was made in relation to its chemical composition, the mass flow data (Equipalcool Sistemas, 2002) and the chemical composition of the dry tar (Li 1996). The results obtained from simulation using EES demonstrate that the humidity present in the tar significantly alter its availability. Its specific availability decreases linearly as the humidity levels rise, as expected.

According to technicians at the Barreiro power plant, the humidity present in the tar used there varies between 15 to 25%. Calculations made through EES show that these levels of humidity are expected to produce LHV between 26879 and 20434 kJ/kg, respectively.

2.9. Analysis of combustion

The volumetric fraction of oxygen in the exhaust gases indicate the quality of the combustion. Real values that greatly exceed the calculated values indicate incomplete burning in the boiler which lead to unwanted irreversibility, and the expulsion of noxious gases into the atmosphere (CO, NOx). Air excess coefficients deemed too high lead to lowering the boiler efficiency and, consequently, the global efficiency of the system. This is a result of lower temperatures in the combustion chamber.

Using EES, a program was created to calculate the stoichiometric air flow for any given mix of the residual fuels employed. Calculating the air excess coefficients for a real air flow was then made possible. The calculation of the ideal parts of the exhaust gases was made from an analysis of the corresponding burning. The ideal volumetric part of oxygen in the exhaust gases varies linearly with the air excess coefficients.

2.10. Conclusions

In this work, the boiler's large influence on the irreversibility of the co-generation cycle was verified, it being the cause of practically 86% of the total availability destruction for all loading conditions analyzed. A methodology for calculating energetic availability and the LHV of the fuels: Blast Furnace Gas and Vegetable Tar was developed in this work. This made it possible to determine the importance of the physical properties and respective chemical compositions in the global efficiency of the industrial plant. Continued monitoring is therefore recommended for evaluation of the lower heating value and availability. Furthermore, this monitoring will allow the creation of subsidies for the implementation of improvement processes in both obtaining and burning tar.

The developed methodology also make the calculation of the stoichiometric air flow for a mixture of both residual fuels, in any proportion, possible. By comparing the real and simulated values for air flow, the air excess coefficient is obtained, along with the expected volumetric composition of the exhaust gases.

The implementation of a program for monitoring these gases, by means of which the best air excess coefficient can be found in order to avoid unnecessary emission of polluting gases (CO, NOx and others) which are caused by incomplete combustion as well as excessive air flow into the boiler.

The program for calculating availability and the LHV of fuels can be used in the siderurgical sector with the purpose of showing the energetic potential of residues, that are currently gone to waste, through decentralized electrical power generation and elimination of difficult problems regarding environmentally harmful residue.

3. Acknowledgements

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4. References

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