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THERMOECONOMIC DIAGNOSIS AND AVOIDABLE EXERGY DESTRUCTION IN A COMBINED CYCLE PLANT

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Abstract. *In this paper the thermoeconomic diagnosis of thermal systems for power generation is proposed aiming the identification of the elements of the cycle (gas turbines, steam turbines, heat exchangers, etc.) with an abnormal behavior and consequently causing fuel over-consumption for the same level of power production. Such malfunctions are expressed as irreversibilities of a system that are quantified through the exergetic analysis. Thus, the purpose of thermoeconomic diagnosis is to identify and act over those components that are destroying exergy (due to a malfunction) and to return them to their optimal operational state after maintenance. However, not all the exergy destruction can be avoided, so that one can divide the exergy destroyed in two types: the unavoidable and avoidable exergy destruction. Only latter kind of exergy destruction deserves serious efforts to achieve savings in fuel consumption. In this paper is applied the methodology of Fuel Impact Formula for thermoeconomic diagnosis of a Combined Cycle, which is compared with the result obtained used a simulator. Also this paper presents an analysis of a combined cycle to identify and quantify the avoidable exergy destruction, and how this type of exergy is affected by the presence of malfunctions associated with each equipment and malfunctions induced by the other components of the cycle.*

Keywords: *Thermoeconomic diagnosis, Avoidable exergy destruction, Malfunction*

1. INTRODUCTION

Today the thermoelectric plants are being questioned because of their high production of pollutants. This is one of the most important points to be considered when dealing with power generation worldwide. Especially when taking into account that the demand for electricity globally grew 2,7% between 1980 and 1997, and is expected to maintain a yearly growth rate of at least 1,8% until 2020 (Correas, 2001).

It is well known, that emissions can be reduced by improving the energy efficiency of the power plants, what means the production of the same power with lower fuel consumption, and consequently less pollutant emissions in the exhaust gases to the atmosphere.

Another way to reduce the emissions is to use clean energy, but the use of fossil fuels is expected to continue on an high level until at least 2050 (CEC, 2007), because in spite of having lower environmental impact, the renewable sources have higher costs per installed kW, ensuring that fossil fuel plants will have many years ahead. Thus, there is a need to improve the technologies used in the thermal generation installations. With this object the information technology can be used to monitoring these generation processes and to assure that they will always operate with a high efficiency. With the data obtained, with the help of computational tools and using technical analysis the efficiency of these plants can even be improved. Among the methodologies that help achieving this goal one can find the thermoeconomic diagnosis. This methodology measures and interprets the signs that indicate a presence of a malfunction on an equipment of the system. Thermoeconomic diagnosis strategies have been the basis of many papers presented during the 80's by many authors (Usón, 2011). The goal of the diagnosis is to identify the equipment, in a production system, that causes deviations in fuel consumption and then estimate the amount of exergy destroyed in the system, and that can be retrieved with the corrective actions on the elements of the thermoelectric plant.

2. TERMOECONOMIC DIAGNOSIS

Thermoeconomic Diagnosis is the procedure applied to a power system to detect, quantify and locate anomalies that causes reduced efficiency of the system (Pacheco et al., 2007). These anomalies have a direct impact on the system in two ways: (i) Reduction of power and therefore increasing the amount of resources provided to the system to obtain a product unit, (ii) If the production remains constant, the anomaly causes a rise in fuel. The main causes of the increase in the consumption of system resources are: (i) changes in environmental conditions, (ii) defective programming of control systems, (iii) degradation or loss of equipment performance (Remiro and Lozano, 2007).

2.1 Fuel impact formula

According to Usón and Valero (2011), the fuel impact formula, shown in Eq. (1), is very important for diagnosis because it relates the variation of fuel consumption ΔF_T of a system with the variation of unit exergy consumptions $\Delta\langle \boldsymbol{KP}\rangle$ of the devices of the system and the production variation $\boldsymbol{\Delta P_S}$. This equation was suggested by Valero et al. (1990), Valero et al. (1999) and developed by Reini (1994), Lozano et al. (1994) and Torres et al. (1999).

$$\Delta F_T = (\Delta^t\kappa_e + {}^t\boldsymbol{k}_P^*(\boldsymbol{x})\Delta\langle \boldsymbol{KP}\rangle)\boldsymbol{P}(\boldsymbol{x_0}) + k_P^*\,{}^t\boldsymbol{\Delta P_S} \qquad (1)$$

2.2 Malfunction and dysfunction

Malfunction is the increase in the irreversibility of a component due to an increase in its unit exergy consumption $\Delta\kappa_i$, Eq. (2).

$$MF_i = \Delta\kappa_i P_i(x_0) \qquad (2)$$

Dysfunction is a variation in the irreversibility of a component due to the variation of its product ΔP_i, Eq. (3) (Usón and Valero, 2011).

$$DF_i = (\kappa_i(x) - 1)\Delta P_i \qquad (3)$$

3. DESCRIPTION OF COMBINED CYCLE FOR CASE STUDY

The development of this work is based on a study case. So, a combined cycle with gas turbine and steam turbine was simulated, using the commercial software GateCycleTM 5.51 in order to calculate the value of the flow of exergy system that were used in the thermoeconomic diagnosis. The scheme of the plant under study is shown in Fig.1. The plant consists of a gas turbine (GT1) with a net capacity of 225 MW. The turbine exhaust gases are used in a heat recovery steam generator (HRSG), which is composed by an evaporator (EVAP1), a superheater (SPHT1) and an economizer (ECON1). The HRSG can produce steam at 82,737 bar and 556°C. This steam is expanded in a steam turbine (ST1) to a pressure of 0,134 bar. The equipments that complement the plant are the condenser (CND1) and the feed pump (PUMP1).

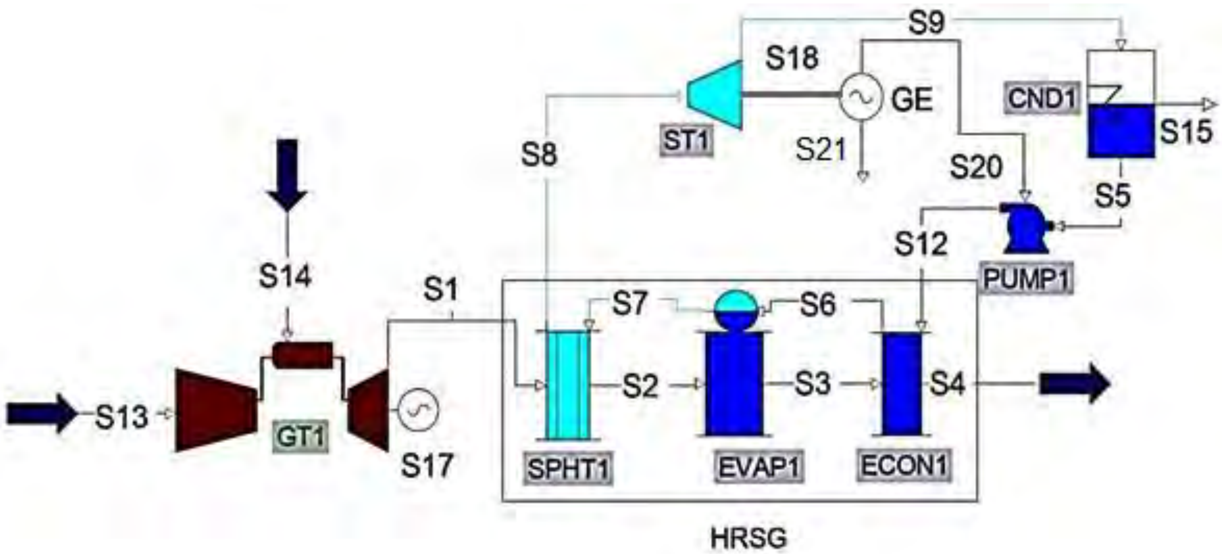

Figure 1. Configuration of Combined-Cycle Power Plant under study.

The parameters used in the simulation for the reference condition are presented in Tab.1 for each stream of the cycle. These streams are shown in Fig. (1)

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Table 1. Thermodynamic properties for the combined cycle in the reference condition

Stream	P (bar) Pressure	T (°C) Temperature	G (kg/s) Mass flow	B (KW) Exergy	Stream	P (bar) Pressure	T (°C) Temperature	G (kg/s) Mass flow	B (KW) Exergy
S1	1,038	595,4	604,751	179511,99	S9	0,134	52,3	85,042	21516,50
S2	1,038	501,3	604,751	136493,03	S12	82,737	52,9	85,042	1507,51
S3	1,038	318,2	604,751	64279,62	S14	27,579	15	13,513	666848
S4	1,038	179,5	604,751	23414,62	S15	-	-	-	20734,90
S5	0,134	52,3	85,042	781,59	S17	-	-	-	225107
S6	82,737	290,9	85,042	32559,63	S18	-	-	-	100515
S7	82,737	297,3	85,042	94025,94	S20	-	-	-	837,35
S8	82,737	556	85,042	132041,81	S21	-	-	-	97667,10

4. APPLICATION OF THE METHODOLOGY OF IMPACT ON FUEL WITH SEVERAL MALFUCTIONS

Were simulated malfunctions in the steam turbine (decreased its efficiency in 1%) and in the evaporator (about effectiveness of 90% to 83,6 %). This new condition is called testing condition and the thermodynamic properties for each stream are presented in Table 2.

Table 2. Thermodynamic properties for the Combined Cycle in the test condition.

Stream	P (bar) Pressure	T (°C) Temperature	G (kg/s) Mass flow	B (KW) Exergy	Stream	P (bar) Pressure	T (°C) Temperature	G (kg/s) Mass flow	B (KW) Exergy
S1	1,038	594,3	608,931	180230,44	S9	0,142	52,9	87,132	22274,90
S2	1,038	505,6	608,931	139329,92	S12	83,259	53,6	87,132	1577,82
S3	1,038	319,1	608,931	65037,10	S14	27,579	15	13,589	670591
S4	1,038	178,7	608,931	23386,96	S15	-	-	-	21445,80
S5	0,134	52,9	87,132	829,05	S17	-	-	-	226670
S6	83,259	290,4	87,132	33246,24	S18	-	-	-	98910,50
S7	83,259	297,8	87,132	96352,14	S20	-	-	-	863,45
S8	83,259	532,4	87,132	132079,22	S21	-	-	-	96068,80

A graphical representation of the productive structure used for the thermoeconomic diagnosis is presented in Fig. (2).

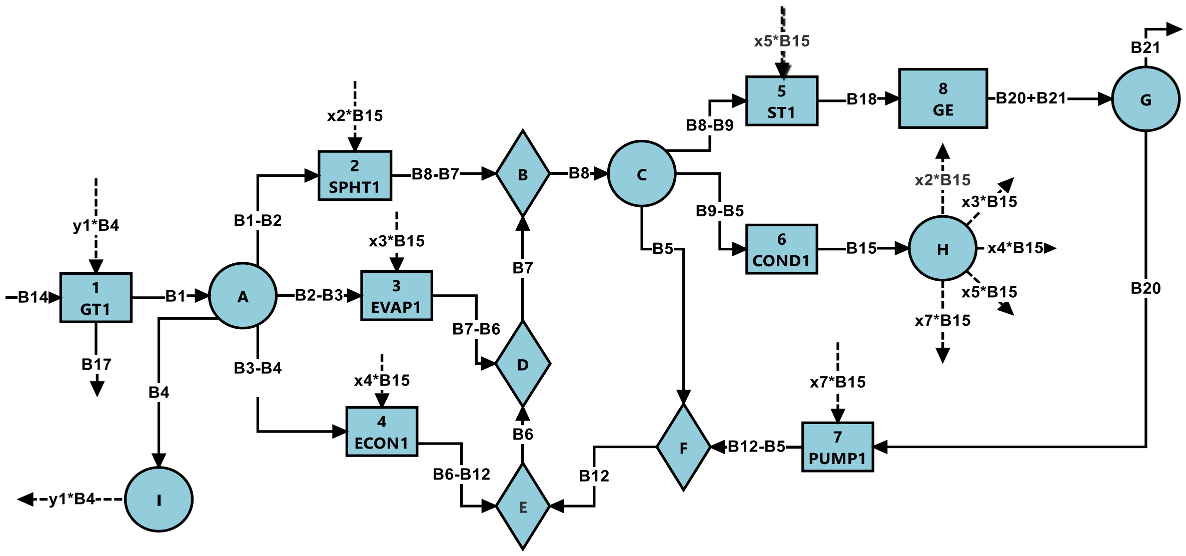

Figure 2. Productive structure of the Combined Cycle.

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With the data from Tables 1 and 2, and with the productive structure of Figure 2 is applied the Impact Fuel Methodology. The results are shown in Table 3 and Figure 3.

Table 3. Results of Termoeconomic Diagnosis.

Diagnosis			
Component	**Description**	**Malfunction [kW]**	**Dysfunction [kW]**
0	Environment		
1	GT1	-176,609	-118,871
2	SPHT1	544,210	948,996
3	EVAP1	152,717	159,499
4	ECON1	-37,428	-181,380
5	ST1	1150,149	2686,093
6	COND1	-32,559	-45,076
7	PUMP1	-0,396	-2,304
8	GE (generator)	41,291	74,234
A	Junction	0,000	0,000
B	Branch	0,000	581,220
C	Junction	0,000	0,000
D	Branch	0,000	-50,984
E	Branch	0,000	7,454
F	Branch	0,000	-12,057
G	Junction	0,000	-781,117
H	Junction	0,000	0,000
I	Junction	0,000	0,000
Total		**1641,374**	**3265,708**

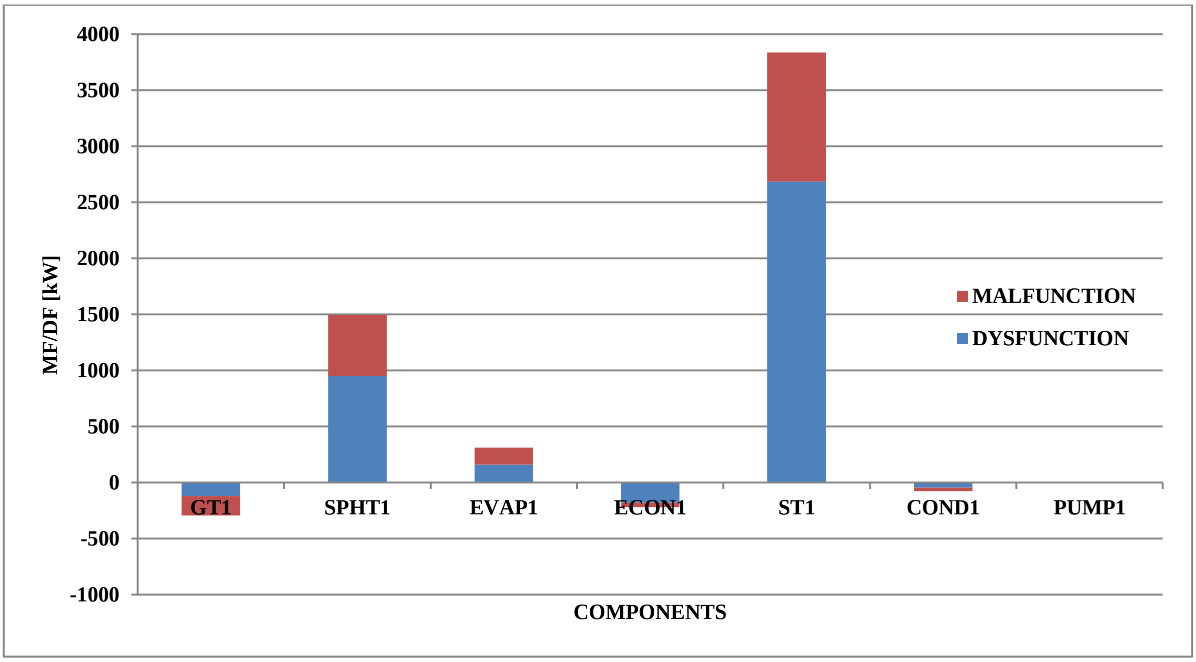

Figure 3. Malfunction (MF) and Dysfunctions (DF) in the main components of the Combined Cycle

The malfunctions were simulated in only 2 devices (ST1 and EVAP1). However, the Figure 3 shows also malfunctions in the other components. The latter are called induced malfunctions and make difficult to identify the components that have intrinsic malfunctions.

To solve this problem were created models of the individual components of the system. These models have the same characteristics as the equivalent components of the system in the reference condition. Comparing the test condition with the individual models for the same input variables is possible to identify those components with intrinsic malfunctions.

The condition for individual models is called comparative condition. Results are presented in Figure 4. The components that have intrinsic malfunctions are those with different values between the test condition and the comparative condition.

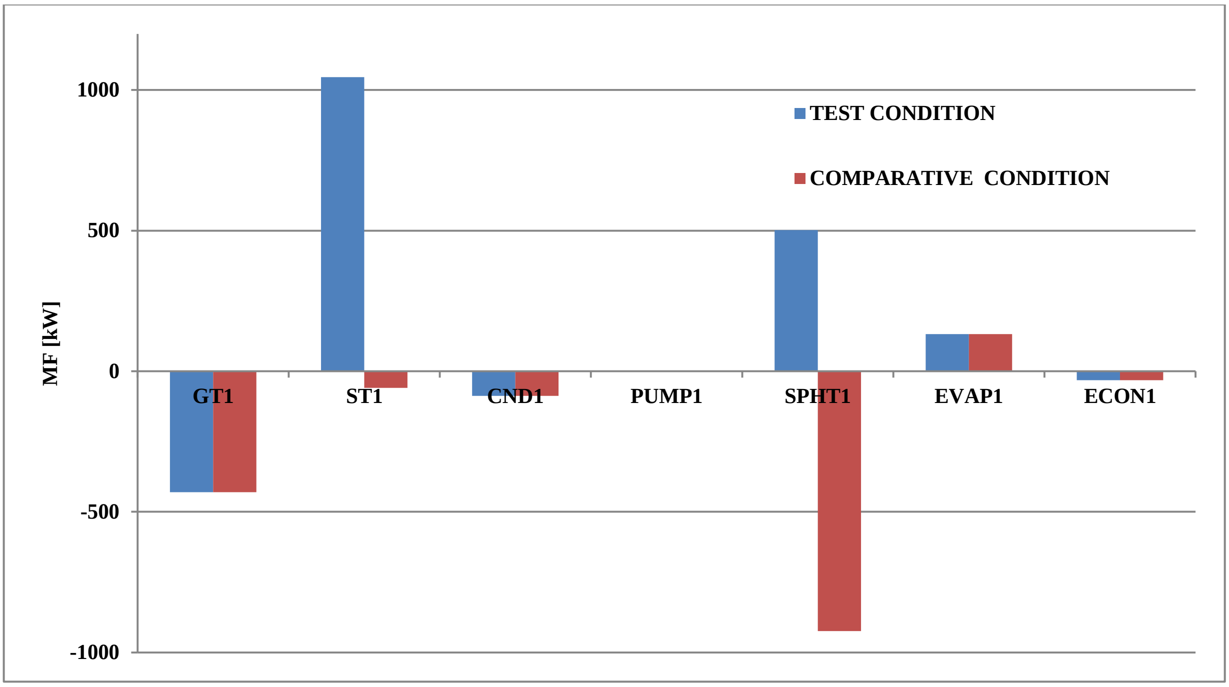

Figure 4. Comparison of malfunctions (MF) between the test condition and the comparative condition.

As can be seen, the components that have intrinsic malfunctions have different values in the two conditions. The Steam Turbine (ST1) has a malfunction with a value of 1046 kW in the test condition, whereas in the comparative condition this value is -59,6 kW (Fig. 4), meanwhile the superheater (SPHT1) shows the values of 501,7 kW and -924 kW between the test condition and the comparative condition respectively. The components that have no intrinsic malfunctions have a malfunction with the same value in the two conditions. For example, the gas turbine (GT1) has a malfunction with a value of -430 kW in the two conditions (test and comparative) (Fig. 4).

5. AVOIDABLE / UNAVOIDABLE EXERGY DESTRUCTION.

The Exergy destruction E_D can be divided into two parts: the unavoidable and avoidable exergy destruction (Tsatsaronis and Park, 2002)

$$E_D = E_D^{UN} + E_D^{AV} \tag{4}$$

The unavoidable exergy destruction E_D^{UN} is always present in a component used in a system due to technological limitations, such as availability and cost of materials (Kelly et al., 2009). For example, for a heat exchanger, its effectiveness can be increased by increasing the heat transfer area, but this would entail a higher equipment cost. The avoidable part of exergy destruction potentiates the possible efficiency improvement for a given system component (Torres and Valero, 2008).

The importance of quantifying these two types of Exergy destruction is that the thermoeconomic diagnosis should focus only on the avoidable one. For that, it is necessary to differentiate which part of the avoidable exergy destruction is due to the irreversible characteristic of the specific component (intrinsic malfunctions) and which part is due to external conditions acting over the component (induced malfunctions) (Kelly et al, 2009).

To estimate the avoidable exergy destroyed, the first thing done was to determine the extent of its counterpart: the unavoidable exergy destruction. It was used the concept of Law of Saving-Investment (Torres and Valero, 2008) together with the definition of unavoidable destroyed exergy. For its estimation it was considered that E_D^{UN} is the Exergy destruction that cannot be avoided due to factors such as technical limitations and costs of investment. Thus, it is possible to find the exergy destroyed if it is calculated for the case in which the cost (Z) tends to infinity, as shown in Eq. (5).

$$E_D^{UN} = \lim_{z \to \infty} E_D \tag{5}$$

The cost of investment for equipment is determined by several variables, but mainly to the cost of materials. For heat exchangers it has been selected as a physical parameter variation when costs tend to infinity. That parameter is the heat transfer area:

$$(\lim_{A \to \infty} Z) \to \infty \tag{6}$$

Fig. 5 shows the relationship between the exergy destroyed and the heat transfer area for SPHT1. The unavoidable exergy destroyed is the asymptote of the curve, when the heat transfer area of the heat exchanger tends to infinity. In this case the value of the destroyed exergy per unit of exergy of the product is 0,1290 kW/kW.

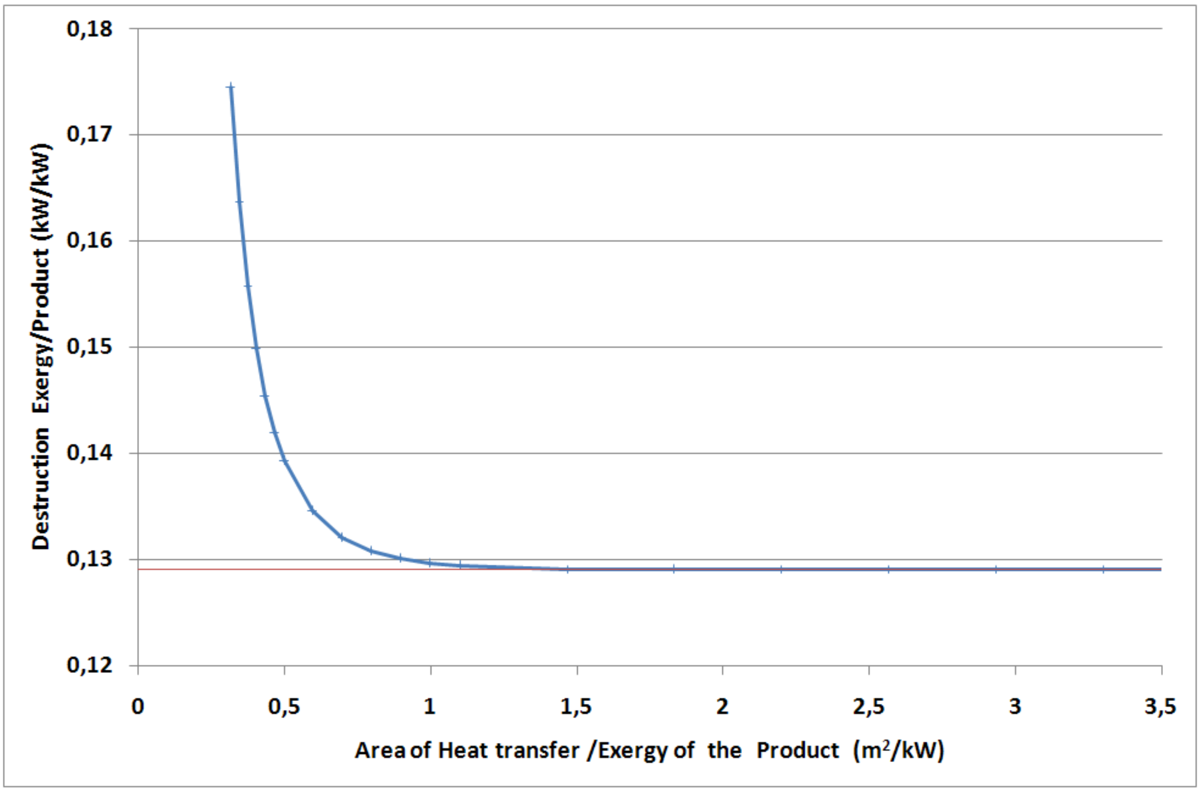

Figure 5. Relationship between Exergy destruction and the heat transfer area for the superheater (SPHT1).

The simulation shows the process and the influence of the intrinsic and the induced malfunctions, for various cases, for calculate the exogenous and the endogenous avoidable exergy destruction. Table 4 shows the exergy destruction for each component of the cycle, in terms of the malfunctions of EVAP1 and SPHT1. The malfunctions were simulated as a change in the effectiveness of these heat exchangers.

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Table 4. Exergy destroyed for each cycle component as a function of the effectiveness of the superheater (SPHT1) and the evaporator (EVAP1)

EFFECTIVENESS		EXERGY DESTRUCTION (KW)					
SPHT1	EVAP1	SPHT1	EVAP1	ECON1	CND1	ST1	PUMP1
0,850	0,850	7571,751	15463,704	11909,294	17787,598	15966,171	118,902
0,850	0,825	7523,476	15495,248	12325,878	17451,428	15824,911	116,492
0,850	0,800	7471,723	15512,441	12747,880	17107,480	15679,780	114,045
0,825	0,850	7617,230	15780,515	11900,548	17894,254	15905,499	120,016
0,825	0,825	7567,644	15722,563	12404,267	17559,101	15766,693	117,605
0,825	0,800	7513,693	15736,092	12833,244	17210,865	15620,990	115,117
0,800	0,850	7653,660	16106,741	11889,847	18001,357	15843,874	121,140
0,800	0,825	7602,999	15954,201	12484,186	17667,558	15706,908	118,727
0,800	0,800	7547,916	15965,991	12919,551	17314,647	15561,305	116,196

Figure 6 (a) shows the exergy destroyed in SPHT1, when malfunctions occur in the EVAP1 and SPHT1. It is possible to observe that a decrease in the effectiveness of SPHT1 cause an increase in the exergy destroyed. However, a decrease in the effectiveness of the evaporator causes a reducing in the SPHT1 exergy destroyed, due to a reduction in the steam produced.

Figure 6 (b) shows the relationship between the exergy destroyed and the product in the SPHT1, when malfunctions occur in the EVPA1 and the SPHT1. It becomes clear that malfunctions in SPHT1 and EVAP1 really cause inefficiency in SPHT1.

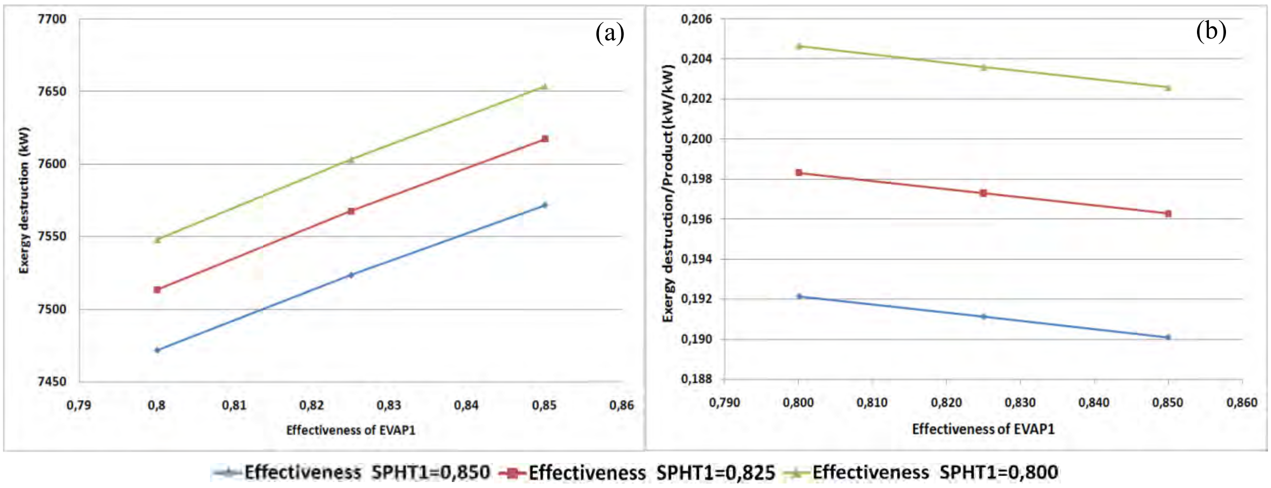

Figure 6. (a) Exergy destruction and (b) Exergy destruction/ exergy of product at the superheater (SPHT1) depending of the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1)

Figure 7 (a) shows the exergy destroyed in EVAP1, when malfunctions occur in the EVAP1 and SPHT1. It is possible to observe that a decrease in the effectiveness of SPHT1 cause an increase on the exergy destroyed in the EVAP1.

Figure 7 (b) shows the relationship between the exergy destroyed and the product in the EVAP1, when malfunctions occur in the EVPA1 and the SPHT1. It becomes clear that the malfunctions in SPHT1 and EVAP1 in fact also cause inefficiency in EVAP1.

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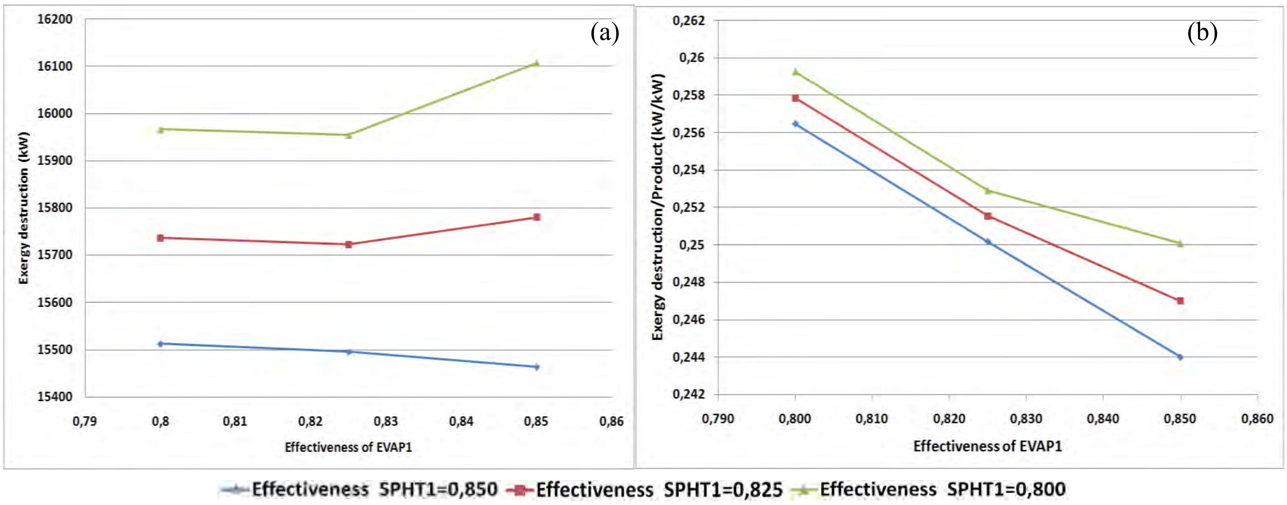

Figure 7. (a) Exergy destruction and (b) Exergy destruction/ exergy of product at the evaporator (EVAP1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1)

Figure 8 shows that a malfunction in the evaporator causes a considerable increase in the exergy destroyed on the ECON1, while its influence of the SPHT1 can be considered small.

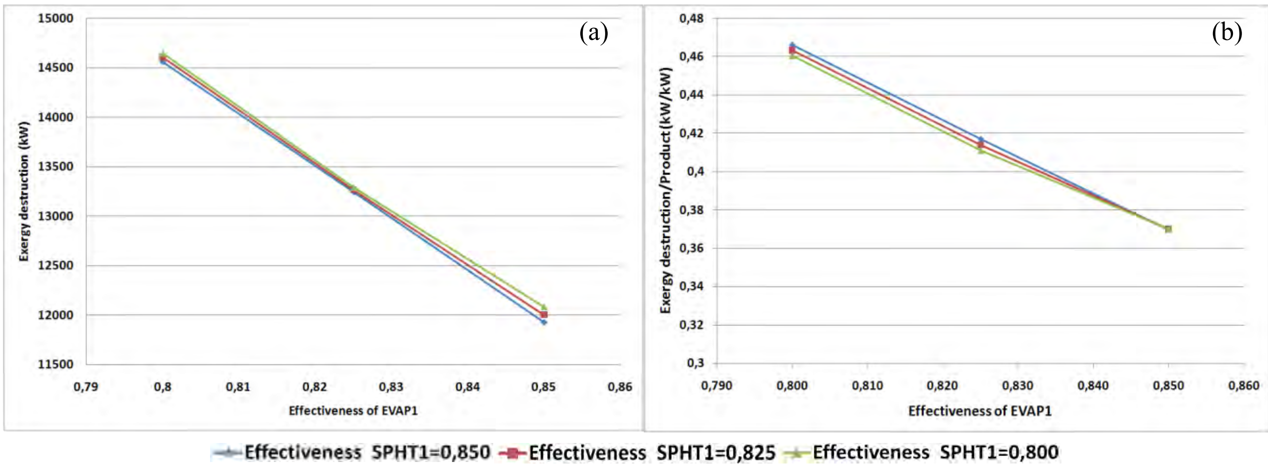

Figure 8. (a) Exergy destruction and (b) Exergy destruction/ exergy of product at the Economizer (ECON1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1)

Figure 9 shows the relationship between the exergy destroyed in the condenser and malfunctions in the evaporator and superheater. It is possible to observe that a malfunction in the SPHT1 causes an increase in the overall destroyed exergy in the condenser, while a malfunction in the evaporator contributes to a reduction in the exergy destroyed in the condenser.

The interrelation between components behavior highlights the difficulties to conduct a thermoeconomic diagnosis, since the effects of induced malfunctions can be positive or negative.

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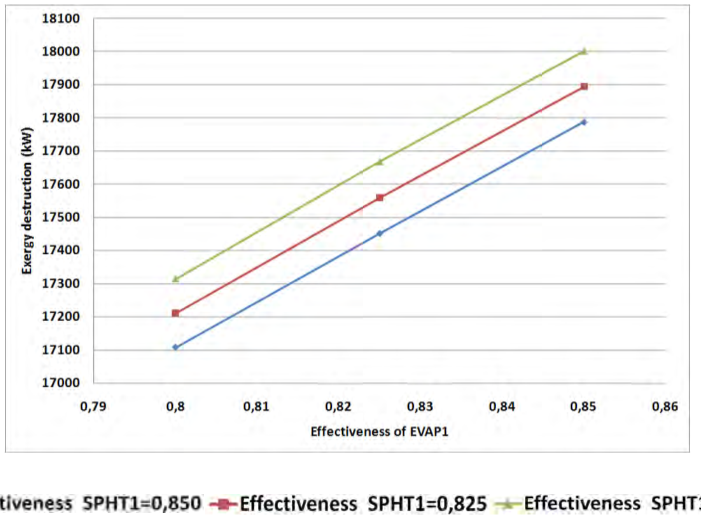

Figure 9. Exergy destruction at the Condenser (CND1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1)

Similar considerations can be make from Figures 10 and 11, which shows the exergy destroyed for ST1 and PUMP1 due to the presence of malfunctions in SPHT1 and EVAP1.

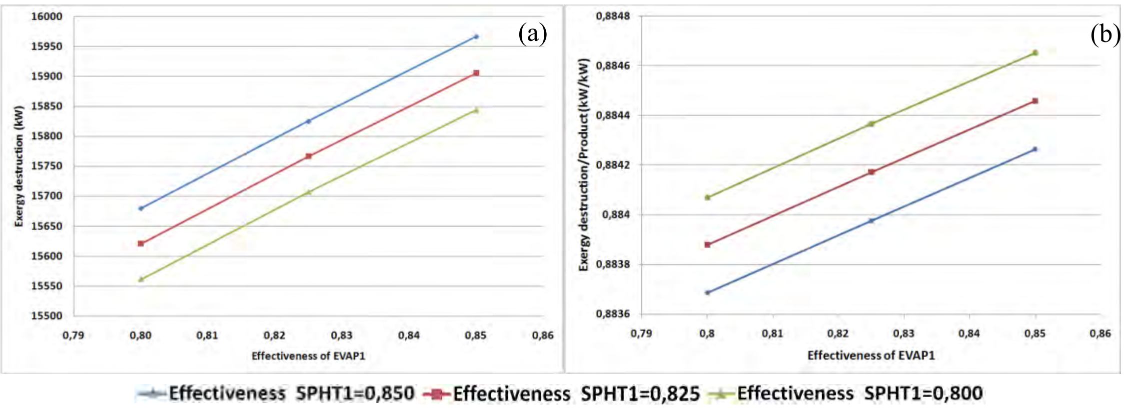

Figure 10. (a) Exergy destruction and (b) Exergy destruction/ exergy of product at the Steam Turbine (ST1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1).

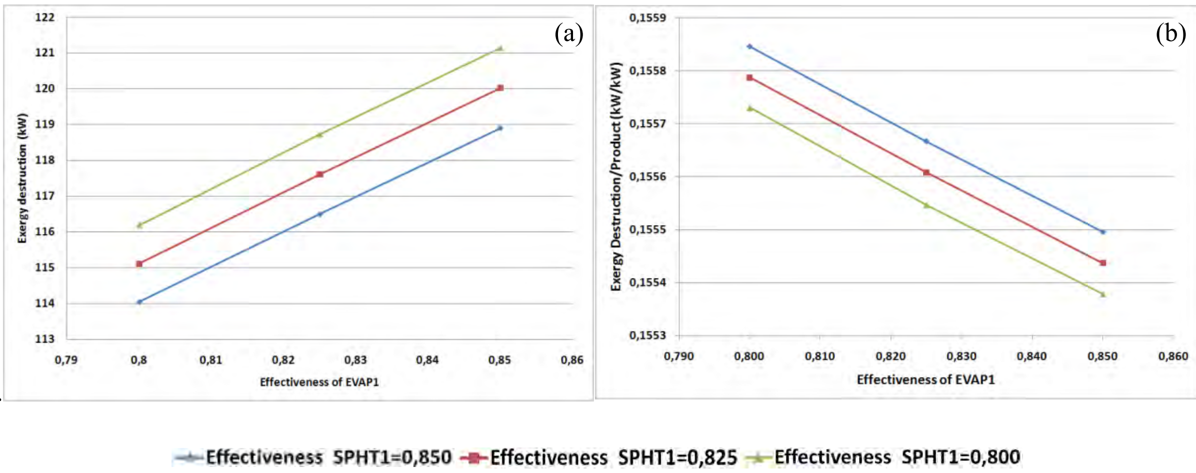

Figure 11. (a) Exergy destruction and (b) Exergy destruction/ exergy of product at the feed pump (PUMP1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1).

From Figure 12, considering the reference condition (EVAP1 and SPHT1 effectiveness equal to 85%) for the SPHT1, it is possible to observe that 84,41% of the exergy destroyed corresponds to unavoidable exergy destruction and only 19,59% corresponds to avoidable one.

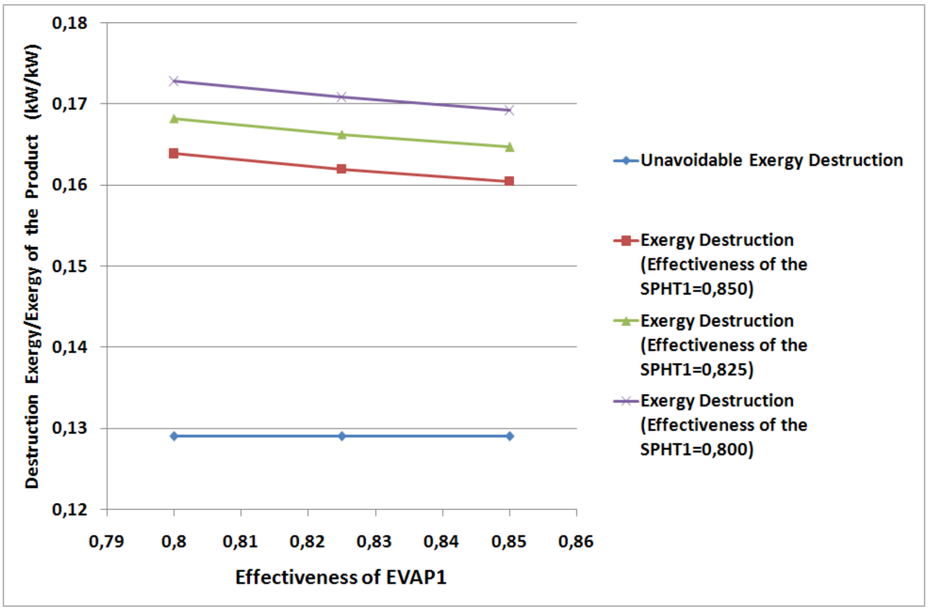

Figure 12. Destruction exergy/exergy of product at the Superheater (SPHT1) depending on the evaporator effectiveness (EVAP1) and the superheater effectiveness (SPHT1).

Considering the presence of malfunctions in the two devices: Superheated, whose effectiveness was reduced from its nominal value (85,0%) to 82,5% in order to simulate a malfunction, and Evaporator, whose effectiveness (due to a malfunction) was reduced from its nominal value (85,0%) to 80,0%, it can be observed that the exergy destroyed for the Superheater is increased by 4,825% due to the intrinsic and induced malfunctions. The distribution of exergy destruction of the Superheater under these conditions is presented in figure 13.

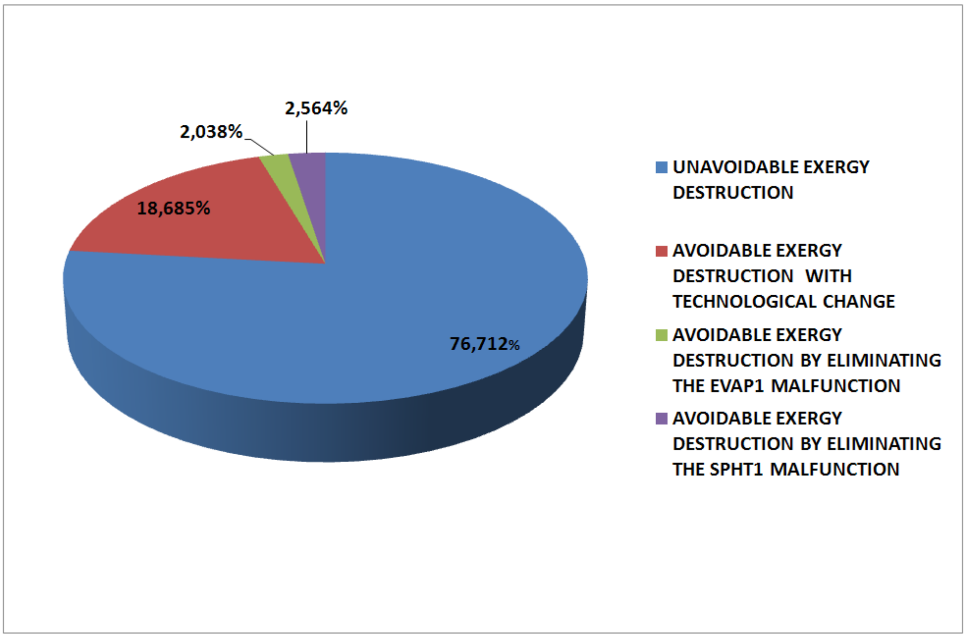

Figure 12. Percentage of the distribution of exergy destruction of the SPHT1 for EVAP1 Effectiveness = 80,0% and Effectiveness of the SPHT1=82,5%

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6. CONCLUSIONS

The deficiency that presents the method of thermoeconomic diagnosis using the fuel impact formula can be solved with the creation of individual model for components of the system using a simulator, to identify devices with intrinsic malfunctions.

To calculate the exergy destroyed of a component of a thermal cycle, it should be considered the influence of other components of the cycle, as is evident from the results obtained for the induced exergy destroyed.

The model developed replicates the operating conditions of the real thermal cycle, and can be used when comparing the deviations in fuel consumption caused by each component of the system.

It is possible to calculate the unavoidable exergy destruction in each component using parameters, such as dimensions, maximum or minimum allowable temperature, steam quality allowed, etc. This will introduce the concept of maximum avoidable exergy destroyed.

Considering the conditions analyzed, the evaporator is the component that produce the higher major impact on the exergy destruction on the others elements of the system.

For the superheater over 76% of its irreversibilities cannot be avoided by any means, and only 4,6% of the irreversibility can be avoided by corrective maintenance routines for the given case.

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