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Thermoeconomic Philosophy Applied to the Operating Analysis and Diagnosis of Energy Utility Systems

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Abstract

In this paper, the objectives of thermoeconomic diagnosis are presented. The paper is part of a project, started in 2001 and named TADEUS (Thermoeconomic Approach to the Diagnosis of Energy Utility Systems), aimed at integrating various experiences accumulated by a group of researchers working on thermoeconomic diagnostics, a field of research started by Antonio Valero and co-workers in 1990 and followed by various researchers all over the world. It is shown how, starting from the same basic set of ideas, researchers developed different approaches, each one having particular characteristics that are, nonetheless, complementary to each other.

Keywords: Thermoeconomic diagnosis, TADEUS problem.

1. Thermoeconomic Diagnosis

The word "diagnosis" applied to energy systems means the art of discovering anomalies by monitoring the operating condition through hands-on measures. While the aim of techniques adopted in power plants usually consists of predicting possible failures through measurements of thermo-mechanical quantities (e.g., rotor vibrations, pressures and temperatures of lubrication and cooling circuits, metal temperatures, etc.), thermoeconomic diagnosis is focused on the analysis of system performance in terms of efficiency.

The objective of such a discipline consists in the detection of an efficiency deviation, the location of its main causes, and the quantification of its effects in terms of additional fuel consumption or economic impact. Exergy and thermoeconomic analysis are the main tools on which this discipline is based and can be applied to any type of energy system typology. Together with this type of generality comes another important characteristic which is its inductive nature, i.e. the search for the causes of anomalous behavior is done without knowledge of the effects provoked by all the possible anomalies. Other widely adopted methodologies for the diagnosis of efficiency reductions, such as gas path analysis (Stamatis, Mathioudakis, and Papailiou, 1990) or the fault matrix method (Saravanamuttoo and MacIsaac, 1983) are deductive.

The thermoeconomic approach to diagnosis is a fairly new approach or philosophy. Its cradle was the University of Zaragoza in the eighties. The first work on diagnosis was made with the GAUDEAMO project for Endesa coal power plants. It was begun in 1981 and lasted until 1986, and its aim was to formulate and apply a procedure for computer-assisted analysis of performance tests using systematic exergy audits (Valero et al., 1986). In the same years, the theoretical seeds for diagnosis were also sowed. Illustrations of that work are some papers by Valero, Lozano and co-workers on “A general theory of exergy saving” (Valero, Lozano, and Muñoz, 1986) and “Application of the exergetic costs theory to a steam boiler in a thermal generating station” (Lozano and Valero, 1987) .The first paper states the definition and the theory for calculating exergetic costs; and the second applies this concept to the diagnose of a steam boiler, formulating and first resolving the question of *“what is the additional fuel consumption of the total plant due to a discrepancy in the normal functioning of the boiler as compared to that of the same boiler at design conditions?”*. Both papers were recognized with the ASME Edward F. Obert award in 1986 and 1987. In a letter to ASME Performance Tests Committee (PTC) by A. Valero in January of 1988, Valero states: *"…with very little more assessment effort than is needed at present,…, it would be possible to increase the quality of the diagnosis of the plant´s behavior as many times as the number of independent measures which would have been taken…. In what remains in this century, and of course in the next, we will see that performance tests will become a common practice, and in general the instrumentation in plants will become both more accurate and cheaper, thus increasing the amount of data available. For this reason it is desirable that the PTC of ASME should start a conscientious study in order to propose additional codes and/or methodologies based on Second Law analyses".* The paper "On causality in organized energy systems: III. Theory of perturbations" Valero et al. (1990) presented for the first time the concepts of exergy malfunctions and dysfunctions and analytically demonstrated their relationship with the impact on raw material consumption of a component in an organized energy system no matter how complex. This paper separated the causation of exergy losses from their localization and quantification in conventional Second Law analyses. The paper "Theory of the exergetic cost" (Lozano and Valero, 1993) divulged those findings to a broader audience and showed itself to be a true milestone in the field of applied thermodynamics.

In the nineties, the seeds grew and Zaragoza played the role of the "academia" for thermoeconomic diagnosis. Many master and Ph.D. degree students were educated in this philosophy, leading to its continued development and contributing to the export of this knowledge. This topic became in these years one of the most studied topics in thermoeconomics and many papers were published.

Some of the results that were achieved in these years are: the mathematical formulation of the fuel impact formula (Lozano et al., 1994; Reini, Lazzaretto, and Macor, 1995), the definition of the indicators for the localization of anomalies (Stoppato and Lazzaretto, 1996), and the definition of concepts such as intrinsic malfunctions, induced malfunctions, and dysfunctions (Torres et al., 1999; Valero, Torres, and Lerch, 1999). The key idea for thermoeconomic diagnosis is to find the causes and evaluate the impact on fuel, ΔF_T, of a given additional irreversibility. From an exergy balance it is known that

$$\Delta F_T = \Delta P_T + \sum_{j=1}^{n} I_j \tag{1}$$

Thus, an additional fuel consumption is the sum of additional irreversibilities in the components and any additional production. However, location of the irreversibilities is not the same as causation.

A first solution to the problem of causation was to relate it with the exergetic cost (Valero, Lozano, and Muñoz, 1986), i.e.

$$\Delta F_T \cong k_{P,j}^{*} \Delta I_j \tag{2}$$

This formula was approximate but predictive nonetheless. A more precise formula describing the malfunction of the component was (Lozano and Valero, 1987; Valero et al., 1990)

$$\Delta F_T \cong k_{F,i}^{*} P_i \Delta\kappa_i \tag{3}$$

This expression only takes into account the irreversibility increase due to the variation in exergy efficiency (malfunction).

Based on these ideas, Reini, Lazzaretto, and Macor (1995) developed a formula on fuel impact such that

$$\begin{aligned}\Delta F_T \cong & \sum_{i=1}^{n}\left(\sum_{j=0}^{n} k_{P,j}^{*}(x_0)\Delta\kappa_{ji}\right) P_i(x_0) \\ & + \sum_{i=1}^{n} k_{P,i}^{*}(x_0)\, \Delta P_{s,i}\end{aligned} \tag{4}$$

This was an important contribution because it allowed one to assess the impact on fuel as a sum of contributions of each component, $\Delta\kappa$, to the variation of final resources. This equation considers the exergetic cost and the product for the reference conditions. It allows one to know the contribution to the impact on fuel of each component and to determine the irreversibilities due to malfunctions. Nonetheless, it too is not exact, since in fact an error of 1% in $\Delta\kappa$ will produce an error of 1% in ΔF_T.

A few years after this contribution, Torres et al. (1999) refined this expression to the following:

$$\begin{aligned}\Delta F_T = & \sum_{i=1}^{n}\left(\sum_{j=0}^{n} k_{P,j}^{*}(x_1)\Delta\kappa_{ji}\right) P_i(x_0) \\ & + \sum_{i=1}^{n} k_{P,i}^{*}(x_1)\Delta P_{s,i}\end{aligned} \tag{5}$$

This is an exact formula quite close to the previous one but now the unit exergetic costs are taken at the actual conditions. Thus, all the exergies of the system for both the reference and actual state must be known in order to diagnose.

This expression can substituted into equation (1) and allows one to exactly quantify the impact of malfuntions on a given system.

With the theory established and several applications of diagnosis to actual power plants made, different research groups began making important contributions. This important activity also had the consequence of generating non-thermodynamic entropy, in particular in the specific nomenclature. For this reason, in 2001, on the occasion of the ECOS conference in Istanbul, some of the researchers interested in this topic decided to define a test case. The idea was to apply the different procedures to the same plant, as already done for thermoeconomic optimization in 1992 (Valero et al., 1994) with the CGAM problem. The aim of this new effort was to compare the results and highlight the main characteristics of each approach. The objective was also to share this background of knowledge and experiences with other research groups interested in thermoeconomic diagnosis, enlarging the community.

This test has been called the TADEUS problem (*T*hermoeconomic *A*nalysis and *D*iagnosis of *E*nergy *U*tility *S*ystems) in honor of Prof. Tadeus Kotas. It is consists of a combined cycle and a couple of operating conditions: the operating condition to be analyzed and a reference condition without anomalies.

The TADEUS problem is a significant test for a number of reasons: 1) most of the components, in particular in the gas turbine section, are characterized by efficiencies strongly dependent on the operating condition; this means that an intrinsic malfunction is often accompanied by induced malfunctions; 2) the components are closely interconnected, which results in a propagation of the induced effects throughout the system.

The combined cycle considered for the TADEUS problem is comprised of two gas turbines (125 MWe each), two heat recovery steam generators, and a steam turbine (about 100 MWe). A schematic of this plant is shown in *Figure 1*. TABLE I provides a legend for the various streams in *Figure 1*.

A diagnosis procedure is always based on a comparison between two plant operating conditions: the *actual* one, which is the one to be analyzed in order to detect and locate possible anomalies, and the *reference* one, which is an opportune condition during which the plant is operating without anomalies.

TABLE I. MAIN POINT OF THE COMBINED CYCLE PLANT.

Point	Description
gt0	Ambient
gt1	Inlet compressor
gt2	Outlet compressor
gt3	Inlet turbine
gt4	Outlet turbine
gt5	Outlet HRSG
gt6	Refrigeration 4° stage turbine
gt7	Refrigeration 3° stage turbine
gt8	Refrigeration 2° stage turbine
gt9	Refrigeration of the rotor
gt10	Fuel
gt11	Mechanical power compressor
gt12	Mechanical power turbine
gt13	Electric power
st1	Inlet high pressure turbine
st2	Outlet high pressure turbine
st3	Low pressure steam
st4	Inlet low pressure turbine
st5	Outlet low pressure turbine
st6	Outlet condenser
st7	Outlet extraction pump
st8	Mechanical power HP turbine
st9	Total mechanical power turbine
st10	Electric power steam turbine
st11	Electric power extraction pump
g1	Inlet low pressure economizer
g2	Outlet low pressure economizer
g3	Inlet low pressure evaporator
g4	Outlet low pressure evaporator
g5	Inlet circulation pump
g6	Inlet high pressure economizer
g7	Outlet high pressure economizer
g8	Inlet high pressure evaporator
g9	Outlet high pressure evaporator
g9b	Inlet high pressure super-heater
g10	Outlet high pressure super-heater
g11	Outlet low pressure super-heater
g12	Inlet low pressure super-heater
g13	Gas inlet high pressure super-heater
g14	Gas inlet high pressure evaporator
g15	Gas inlet low pressure super-heater
g16	Gas inlet high pressure economizer
g17	Gas inlet low pressure evaporator
g18	Gas inlet low pressure economizer
g19	Gas outlet heat recovery steam generator
g20	Electric power circulation pump

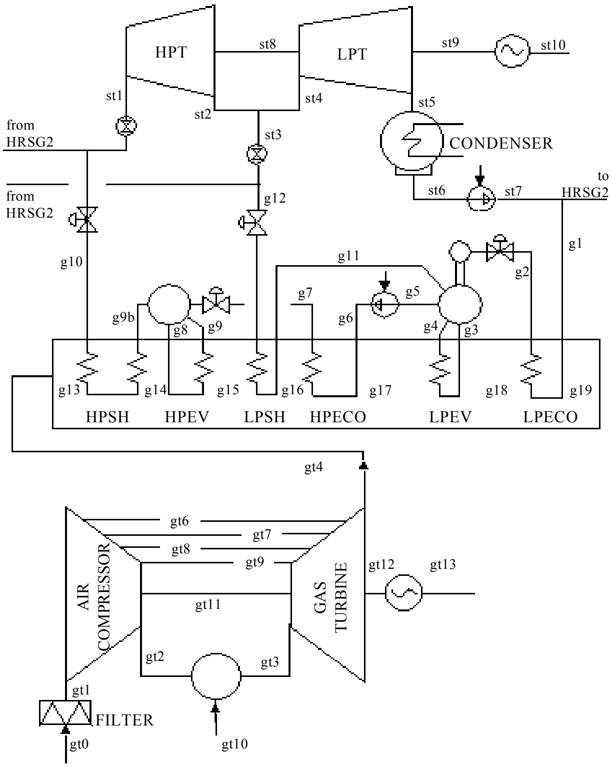

Figure 1. Schematic of the combined cycle power plant proposed for the TADEUS.

2. The TADEUS Problem

The *actual* operating condition proposed for the TADEUS problem is shown in TABLES IIA, IIB, and IIC. This condition was obtained by using a plant simulator which plays the role of a real power plant. As in an actual plant, the diagnosis must be conducted without knowing in advance if and where anomalies took place. Moreover, the model is not used to locate the anomalies detected. It is only used to generate reliable *actual* operating conditions.

The model requires the specification of ambient conditions (temperature, pressure and relative humidity), the lower heating value of the fuel, and the total electric power to be produced. Moreover, several anomalies can be produced by modifying component design parameters. The model determines the system state according to the off-design behavior of the components and the control system constraints.

The operating condition considered is characterized by three anomalies in the first gas turbine and in the first HRSG: 1) filter fouling, 2) erosion of the gas turbine, and 3) high pressure super-heater fouling. These are obtained 1) by increasing the design pressure drop (+25%); 2) by modifying the design values of the flow coefficient (+2.5%) and the polytropic efficiency (-1%) (Diakunchak, 1992); and 3) by increasing the design approach point temperature (+10%).

The choice of a reference condition is a crucial part of the diagnosis. In fact, deviations of some thermodynamic quantities between the actual operating and reference operating conditions can be due to external causes, which can be eliminated by simply selecting a different reference condition. These external causes can be due to, for instance, 1) plant production: the efficiency of a plant at its nominal power is different than at partial load; 2) ambient conditions: the behavior of components is generally sensitive to ambient temperature, pressure and relative humidity; and 3) fuel quality: a different lower heating value produces an impact on the combustion products since, for instance, the same fuel mass flow rate produces a different temperature. An additional aspect which impacts the diagnosis result is constituted by the set-points: if the plant operates with a different set-point, the whole thermodynamic picture changes.

TABLE IIA. THERMODYNAMIC VARIABLE VALUES OF THE GAS TURBINES AT THE ACTUAL OPERATING CONDITION.

TGA	G	T	p	h	s
	kg/s	°C	bar	kJ/kg	kJ/kgK
gt0	434.5	15	0.987	-101	6.87
gt1	434.5	15	0.9759	-101	6.873
gt2	380	386.7	12.94	283.3	6.981
gt3	388.1	1145	12.81	109.9	8.248
gt4	430.7	511.5	1.007	-560.6	8.236
gt5	430.7	117.3	0.987	-994	7.461
gt6	1.763	103.3	2.207	-11.77	6.908
gt7	6.707	195.9	4.358	82.96	6.937
gt8	16.35	261	6.555	150.4	6.954
gt9	17.75	386.7	12.94	283.3	6.981

TGB	G	T	p	h	s
	kg/s	°C	bar	kJ/kg	kJ/kgK
gt0	432.4	15	0.987	-101	6.87
gt1	432.4	15	0.9781	-101	6.873
gt2	378.1	389.6	13.23	286.5	6.98
gt3	386.2	1151	13.1	112.2	8.248
gt4	428.6	506.6	1.007	-570.8	8.229
gt5	428.6	118	0.987	-998	7.464
gt6	1.754	103.9	2.227	-11.19	6.907
gt7	6.674	197.2	4.419	84.29	6.936
gt8	16.27	262.8	6.668	152.3	6.953
gt9	17.67	389.6	13.23	286.5	6.98

kW	gt10	gt11	gt12	gt13
TGA	368494	162959	123837	122599
TGB	368494	163508	127262	125989

TABLE IIB. THERMODYNAMIC VARIABLE VALUES OF THE HRSG'S AT THE ACTUAL OPERATING CONDITION.

HRSG 1	G kg/s	T °C	p bar	h kJ/kg	s kJ/kgK
g1	60.260	53.68	7.867	225.4	0.751
g2	60.260	161.70	6.608	682.8	1.959
g3	241.000	162.70	6.608	687.2	1.969
g4	241.000	162.70	6.608	768.8	2.157
g5	50.900	162.70	6.608	687.2	1.969
g6	50.900	163.60	64.770	694.6	1.972
g7	50.900	268.30	54.400	1176.0	2.959
g8	203.600	269.30	54.400	1181.0	2.969
g9	203.600	269.30	54.400	1584.0	3.713
g9b	50.900	269.30	54.400	2790.0	5.934
g10	50.900	484.20	52.770	3394.0	6.899
g11	9.366	162.70	6.608	2761.0	6.728
g12	9.366	261.30	6.410	2979.0	7.193
g13	430.700	511.50	1.007	-560.6	8.236
g14	430.700	449.00	1.005	-631.9	8.141
g15	430.700	277.30	1.000	-822.6	7.842
g16	430.700	272.90	0.999	-827.4	7.833
g17	430.700	220.30	0.996	-884.3	7.724
g18	430.700	177.70	0.991	-930.0	7.629
g19	430.700	117.30	0.987	-994.0	7.461

HRSG 2	G kg/s	T °C	p bar	h kJ/kg	s kJ/kgK
g1	59.260	53.68	7.867	225.4	0.751
g2	59.260	161.70	6.608	682.8	1.959
g3	237.000	162.70	6.608	687.2	1.969
g4	237.000	162.70	6.608	771.5	2.163
g5	49.740	162.70	6.608	687.2	1.969
g6	49.740	163.60	64.770	694.6	1.972
g7	49.740	268.30	54.400	1176.0	2.959
g8	199.000	269.30	54.400	1181.0	2.969
g9	199.000	269.30	54.400	1584.0	3.713
g9b	49.740	269.30	54.400	2790.0	5.934
g10	49.740	481.40	52.770	3387.0	6.891
g11	9.518	162.70	6.608	2761.0	6.728
g12	9.518	261.30	6.410	2979.0	7.193
g13	428.600	506.60	1.007	-570.8	8.229
g14	428.600	445.90	1.005	-640.1	8.138
g15	428.600	277.30	1.000	-827.4	7.843
g16	428.600	272.90	0.999	-832.3	7.834
g17	428.600	221.20	0.996	-888.1	7.727
g18	428.600	177.70	0.991	-934.8	7.630
g19	428.600	118.00	0.987	-998.0	7.464

All these cause of deviations can be eliminated by considering a reference operating condition characterized by the same load, the same ambient conditions, the same fuel quality, and the same set-points.

The definition and use of the reference case varies considerably among the various approaches and is based on the different types of information that the authors intend to provide together with the localization of the anomalies. In particular, the definition of load is a delicate part of this procedure. As an example, it can be assumed to be the "same plant production" or the "same fuel rate" or the "same mass flow rate of the process fluid". In TABLES IIIA, IIIB, and IIIC a reference operating condition characterized by the same electricity production as in the actual operating condition is provided.

TABLE IIC. THERMODYNAMIC VARIABLE VALUES OF THE STEAM TURBINE AT THE ACTUAL OPERATING CONDITION.

ST	G kg/s	T °C	p bar	h kJ/kg	s kJ/kgK
st1	100.6	482.8	52.77	3390	6.895
st2	100.6	190.4	4.211	2839	7.101
st3	18.88	257.8	4.211	2979	7.384
st4	119.5	200.9	4.211	2861	7.148
st5	119.5	53.62	0.1476	2424	7.481
st6	119.5	53.62	0.1476	224.5	0.7503
st7	119.5	53.68	7.867	225.4	0.7507

st8	55499 kW
st9	52254 kW
st10	105598 kW
st11	112.1 kW

For defining the reference condition, a reliable plant simulator is very useful, since it can be used to determine the most useful reference condition. Once this reference condition has been determined, the only cause of deviation between the actual and reference conditions is a result of the presence of anomalies in the plant.

TABLE IIIA. THERMODYNAMIC VARIABLE VALUES OF THE GAS TURBINES AT THE REFERENCE OPERATING CONDITION.

TGA TGB	G kg/s	T °C	p bar	h kJ/kg	s kJ/kgK
gt0	425.9	15	0.987	-101	6.87
gt1	425.9	15	0.9781	-101	6.873
gt2	372.4	385.4	13.04	281.9	6.977
gt3	380.5	1152	12.91	106.6	8.255
gt4	422.2	509.8	1.007	-573.9	8.236
gt5	422.2	117.2	0.987	-1006	7.463
gt6	1.727	103.1	2.216	-12.02	6.906
gt7	6.573	195.4	4.382	82.4	6.934
gt8	16.03	260.2	6.596	149.6	6.951
gt9	17.4	385.4	13.04	281.9	6.977

kW	gt10	gt11	gt12	gt13
TGA-TGB	365450	159148	126263	125000

TABLE IIIB. THERMODYNAMIC VARIABLE VALUES OF THE HRSG'S AT THE REFERENCE OPERATING CONDITION.

HRSG 1	G	T	p	h	s
HRSG2	kg/s	°C	bar	kJ/kg	kJ/kgK
g1	58.800	53.28	7.779	223.7	0.746
g2	58.800	161.20	6.535	680.9	1.955
g3	235.200	162.20	6.535	685.3	1.965
g4	235.200	162.20	6.535	767.7	2.154
g5	49.580	162.20	6.535	685.3	1.965
g6	49.580	163.10	63.940	692.5	1.967
g7	49.580	267.50	53.710	1172.0	2.952
g8	198.300	268.50	53.710	1177.0	2.961
g9	198.300	268.50	53.710	1582.0	3.708
g9b	49.580	268.50	53.710	2790.0	5.940
g10	49.580	484.90	52.100	3396.0	6.908
g11	9.223	162.20	6.535	2760.0	6.731
g12	9.223	260.50	6.338	2977.0	7.195
g13	422.200	509.80	1.007	-573.9	8.236
g14	422.200	447.60	1.005	-645.0	8.141
g15	422.200	276.50	1.000	-835.1	7.842
g16	422.200	272.10	0.999	-839.8	7.834
g17	422.200	220.10	0.996	-896.1	7.726
g18	422.200	177.20	0.991	-942.1	7.630
g19	422.200	117.20	0.987	-1006.0	7.463

TABLE IIIC. THERMODYNAMIC VARIABLE VALUES OF THE STEAM TURBINE AT THE REFERENCE OPERATING CONDITION.

ST	G	T	p	h	s
	kg/s	°C	bar	kJ/kg	kJ/kgK
st1	99.15	484.9	52.1	3396	6.908
st2	99.15	191.8	4.149	2842	7.115
st3	18.45	257	4.149	2977	7.388
st4	117.6	201.9	4.149	2863	7.16
st5	117.6	53.22	0.1448	2425	7.493
st6	117.6	53.22	0.1448	222.8	0.7452
st7	117.6	53.28	7.779	223.7	0.7456
st8	54927 kW				
st9	51538 kW				
st10	104335 kW				
st11	109.1 kW				

4. Conclusions

In the papers which appear in this issue, some of the latest developments in thermoeconomic diagnosis are shown. Applications to the TADEUS problem are presented in order to clarify the different features of some of the principal thermoeconomic approaches presently in the literature. The authors' hope that other research groups may be able to contribute to the development of diagnosis by applying their approaches to this very same system and comparing their results with those shown in this issue.

Nomenclature

I_j	Irreversibility in the jth component [kW]
k_{ij}	Unit exergy consumption
$k_{p,j}*$	Unit exergy cost of the jth component product
$k_{F,i}*$	Unit exergy cost of the jth component fuel
MF	Malfunction [kW]
P_i	Product of the ith component [kW]
(x_o)	Reference operating condition
(x_1)	Actual operating condition
ΔF_T	Fuel impact [kW]
ΔI_j	Variation in component irreversibility [kW]
$\Delta \kappa_i$	Variation in the component's total unit exergy consumption
$\Delta \kappa_{ji}$	Variation in the unit consumption of the jth resource of the ith component
ΔP_T	Variation in total plant production [kW]
$\Delta P_{S,i}$	Contribution of the jth component to the variation in plant production [kW]

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