APPLICATION OF THERMOECONOMICS TO OPERATION DIAGNOSIS OF ENERGY PLANTS

Antonio Valero and César Torres Cuadra
Center of Research for Energy Resources and Consumption, Centro Politécnico Superior, Universidad de Zaragoza, Spain.

Keywords: Thermoeconomics, Operation Diagnosis, Structural Theory of Thermoeconomics, Irreversibility, Malfunction.

Contents

1. Introduction
2. Thermoeconomic Operation Diagnosis
2.1. Malfunction and Dysfunction Analysis
2.2. Malfunction Causes Analysis
3. Concluding Remarks
Glossary
Bibliography
Biographical Sketches

Summary

The paper introduces a methodology, based on the Structural Theory of Thermoeconomics (see *Structural Theory of Thermoeconomics*) and Symbolic Thermoeconomics (see *Symbolic Thermoeconomic Analysis of Energy Systems*), to the operation diagnosis of energy systems. It provides the theoretical basis and practical procedures to identify the causes of the degradation of the efficiency of a thermal plant in operation, and the assessment of its effects in terms of additional fuel consumption.

1. Introduction

According to the ASME guide PTC-PM, a diagnosis procedure must have a deductive nature based on the observed symptoms. It must be flexible enough, and must recommend new tests to isolate causes and inform whether these tests are cost-effective or not. The methodology should have the following steps:

- Identification of components and degradation symptoms.
- Clear description of the symptoms to allow a simple problem recognition.
- Evaluation of the deterioration mechanisms and the root causes.
- Validation and conclusions.

As a result, a diagnostic procedure should yield those specific recommendations to change operating strategies, maintenance actions and components replacement.

The objective of a monitoring system is the efficiency improvement or in other words detection of efficiency deviations. A 3% deviation of efficiency with respect to a reference conditions, is quite easily detected by the operator, therefore a monitoring system must detect losses in the range of 0.25–0.5%. Values under this range become difficult to identify because of the instrumentation accuracy. Moreover it is very difficult to locate and to find the real causes of all effects that can simultaneously occur. This is due to the high complexity of interrelations among components in a power cycle. A successful interpretative procedure will reduce the non-accountable losses to a minimum, and will put forward the ultimate causes of component degradation.

According with these ideas a diagnosis methodology will require:

- **Data Acquisition System:** to monitoring the power plant, including data filtering, consistence checking and historical storage.
- **Performance Tests:** a procedure, normally based on performance test codes, that determines the actual state of the plant with the higher attainable accuracy, with regard to the available instrumentation.
- **State of Reference:** a validated model of the plant which represents the state of reference for any operation mode, environmental conditions or feedstock compositions.

Thermoeconomic Diagnosis Model: that allocates and assesses the increase of resources consumption compared to the one foreseen by the state of reference and explains the underlying causes.

This paper focuses on the last point, the description of theoretical basis and the practical procedures of a thermoeconomic methodology for operation diagnosis.

In order to clarify the concepts introduced in the paper, we will use the example of a cogeneration gas turbine described in the article (see *The Thermodynamic Process of Cost Formation*). The control parameter values and fuel – product values for reference and operation conditions, used in the example – are shown in Tables 1 and 2.

N#	***Description***		$\mathbf{x^0}$	$\mathbf{x}$
pcb	Combustor pressure losses	ΔP_1	0.05	0.052
ncp	Compressor isentropic efficiency	η_{cp}	0.85	0.84
ntg	Turbine isentropic efficiency	η_{tg}	0.87	0.86
TGT	Inlet turbine gases temperature	T_3	850 ºC	855 ºC
rcp	Compression ratio	P_2/P_0	5	5
ncb	Combustor 1st law efficiency	η_{cb}	0.98	0.975

Table 1. Model operational variables.

	Design			Operation		
	P (kW)	**I (kW)**	k_P^*	**P (kW)**	**I (kW)**	k_P^*
Combustor	6630.9	5150.1	1.7767	6815.2	5472.4	1.8030
Compressor	2594.8	382.2	2.3464	2662.7	449.0	2.4641
Turbine	5477	306	2.0451	5611.8	338.1	2.1085
HRSG	2355	1087.7	2.8315	2355	1173.0	2.9793

Table 2. Design and Operation values

2. Thermoeconomic Operation Diagnosis

Thermoeconomic diagnosis is a Second Law based technique oriented to operation analysis. The exergy balance of an installation allows us to allocate and calculate irreversibilities in the production process and to identify the equipment which affect overall efficiency and the reasons thereof. This information, although useful, has proved not to be enough. In practice, when attempting to achieve energy savings in an installation, we must consider that not all irreversibility can be avoided. The potential exergy saving is limited by technical and economic constraints. Thus, the technical possibilities for exergy savings, which is called technical exergy saving, are always lower than the theoretical limit of thermodynamic exergy losses. From this perspective, in the plant of our example, we can see in Table 2 that only 506 kW, out of the 7.432 MW of the total irreversibilities of the plant, can be saved with respect to reference conditions.

Therefore, the additional fuel consumption can be expressed as the difference between the resources consumption of the plant in operation and the resources consumption for a reference or design condition, with the same production objectives, i.e. with the same total plant product.

$$\Delta F_T = F_T(x) - F_T(x_0) \tag{1}$$

It can be broken up into the sum of the irreversibilities of each component:

$$\Delta F_T = \Delta I_T = \sum_{j=1}^{n} \left(I_j(x) - I_j(x_0) \right) = \sum_{j=1}^{n} \Delta I_j \tag{2}$$

However, the local exergy savings which can be achieved in the different units or processes of an installation are not equivalent. The same decrease in the local irreversibility of two different components leads, in general, to different variations of the total plant energy consumption. It is shown in the **fuel impact formula,** presented in the article *Symbolic Thermoeconomic Analysis of Energy Systems* that expresses the increase of resources consumption in the plant, as a function of the marginal exergy consumption of each individual component of the plant:

$$\Delta F_T = \sum_{i=1}^{n} \left(\sum_{j=0}^{n} k^{*}_{\mathrm{P},j}(x) \Delta\kappa_{ji} \right) P_i(x_0) \qquad (3)$$

The variation of the marginal exergy consumption of each component increases its resources consumption and then its irreversibilities in a quantity $\Delta\kappa_{ji} P_i^0$, which is called, *malfunction*. Consequently, it implies an additional consumption of the external resources given by $k^{*}_{\mathrm{P},j} \Delta\kappa_{ji} P_i^0$, which is called the **malfunction cost.** Therefore, the total fuel impact can be written as the sum of the fuel impact or malfunction cost of each component, as shown in Eq. (3).

In order to analyze the impact on resource consumption of a plant, we need to know the design and operation values of the irreversibilities, product, unit exergy cost for design and operation, and the increase of the marginal exergy consumption of each component of the plant. A performance test or a simulator model together with the fuel-product model of the plant defined in article *The Thermodynamic Process of Cost Formation*, provide the values shown in Table 3.

	0.02629	0	0	0
	0	0	0.00348	0.02652
$\Delta\langle \mathbf{KP} \rangle$	0	0	0.00089	0.00972
	0	0.02135	0	0
	0	0	0	0

Table 3. Increase of unit consumption matrix.

Figure 1 compares in a bar graph the malfunction cost and the irreversibility increase or technical saving of each component. It shows that the irreversibility increase and the malfunction are mainly located in combustor, meanwhile malfunction cost appears in all components.

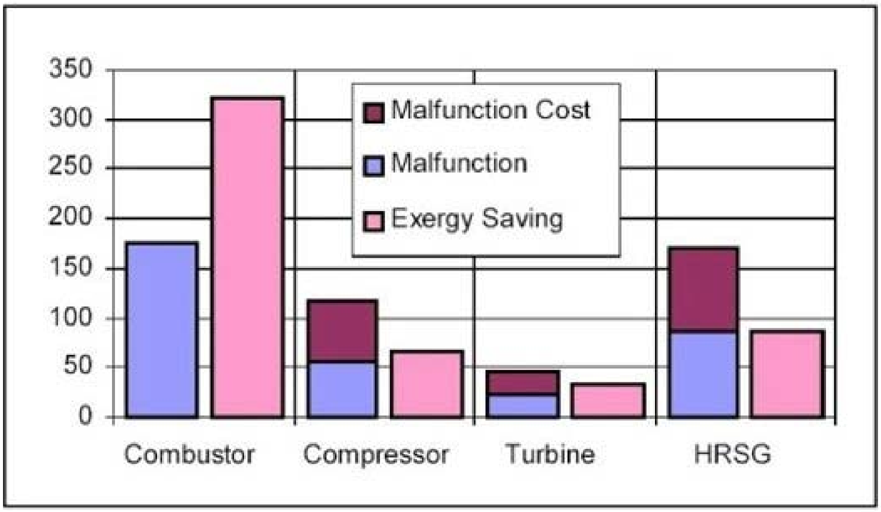

Figure 1. Malfunction cost and exergy saving.

-
-
-

Bibliography

ASME, (1993). *ASME Performance Test Codes: Plant Monitorization, PTC PM,* The American Society of Mechanical Engineers.

Lozano M. A., Bartolome J. L., Valero A., and Reini M. (1994). Thermoeconomic Diagnosis of Energy Systems. *Flowers 94: Florence World Energy Research Symposium*. Florence. Italy. [It is the first paper in which the thermoeconomic diagnosis methodology is presented. It is described the application to a coal fired power plant sited in Teruel, Spain.]

Lozano M. A., Valero A., and Serra L. (1996). Local optimization of energy system: AES Vol. 36. *Proceedings of the ASME Advanced Energy System Division*, Atlanta, Georgia. [A local optimization method, based on the minimization of the thermoeconomic cost the product of each component, is presented in this paper. This method allows the separate optimization of the plant devices without dealing with the whole plant model.].

Schwarz P., Lozano M. A., Von Spakovsky M. R., and Valero A. (1997). Diagnostic analysis of a PFBC power plant using a thermoeconomic methodology. *TAIES'97 Proceedings of Intl. Conference*, Beijing, China. [Application of the thermoeconomic diagnosis to an actual power plant fired with Pressurized Fluidized Bed Combustion boiler, sited in Escatrón, Spain.]

Torres C, Valero A., and Serra L. (2001). Structural theory and thermoeconomic diagnosis, Part 1: on malfunction and dysfunction analysis. To be published in *Energy Conversion and Management Journal*. [Detailed description of malfunction and dysfuntion analysis is presented in this paper.]

Valero A., Correas L., and Serra L. (1999). On-line thermoeconomic diagnosis of thermal power plants, in *Thermodynamics and Optimization of Complex Energy Systems*, Kluver Academic Publishers (Bejan and Mamut eds.), pp. 117–136. [Description of the On Line Thermoeconomic Diagnosis System designed and implemented in the IGCC power plant sited in Puertollano, Spain. This system is general enough to be implemented in whatever complex energy system.]

Valero A., Lozano M. A., Serra L., and Torres C. (1994). Application of the exergy cost theory to the CGAM problem, *Energy*, **19**(3). Pergamon Press Ltd. pp. 365, 381. [This paper shows the application of ECT to the optimization of energy systems. This issue of Energy is a monograph in which the same problem, i.e. the CGAM problem, is solved applying different thermoeconomic methodologies. Each paper of the referred issue presents the solution of each thermoeconomic method.]

Verda V. (2001). *Thermoeconomic Diagnosis of an Urban District Heating System Based on Cogenerative Steam and Gas Turbines.* Ph.D. Thesis, Politecnico di Torino and University of Zaragoza. [Detailed description and formalization about the procedure of implementing the control system of a complex energy system in the thermoeconomic diagnosis methodology.]

Verda V., Serra L., and Valero A. (2001). The effects of the regulation system on the thermoeconomic diagnosis of a power plant, Part I: The diagnosis procedure; Part II: Application to a gas turbine based cogeneration plant. To be presented in *International Conference ECOS 2001*, Istambul, Turkey. [Brief description of the procedure of implementing the control system in the thermoeconomic diagnosis methodology and its application to a cogeneration plant.]

Biographical Sketches

Antonio Valero, Chair in Thermal Systems at the University of Zaragoza, Spain. Since 1982, Dr. Valero has been involved in the fundamentals of thermoeconomics relating the idea of irreversibility with that of cost. He has searched the physical roots of the process of cost formation. He has applied thermoeconomics to the optimization, design, diagnostics and operation of conventional and advanced power plants, cogeneration systems, bio-mass plants, sugar factories, and dual power and water production plants. Dr. Valero is also involved in the applications of Second Law of Thermodynamics to environmental problems and global resources assessments. Second Law outcomes of the greenhouse effect, Second Law assessment of the Earth's mineral reserves, fresh water and fossil fuels are some of his relevant contributions. He currently serves as a director of CIRCE, a research institute for Energy Resources and Consumption comprised of 60 researches. Circe is devoted to developing and disseminating the rational use of energy through the integration and extensive use of renewable energies and cost efficient measures. Dr. Valero received the James Harry Potter Gold Medal (1996) established by the American Society of Mechanical Engineers in recognition of an eminent achievement in the application of the science of thermodynamics in mechanical engineering. He also received three Edward F. Obert Awards for the Best Paper in ASME Advanced Energy Systems. He is honorary professor of the North China University of Electric Power , China, and several other universities worldwide. He is the Vice-president of the ISGWES, the International Study Group for Water and Energy Systems, and he holds memberships in the American Association for the Advancement of Sciences, the American Society of Mechanical Engineers and the International Association for Hydrogen Energy, among other distinctions.

César Torres Cuadra is research contributor at the CIRCE foundation – Center of Research for Energy Resources and Consumption, Zaragoza, Spain. He received the Bachelor Diploma in Mathematics from the University of Zaragoza in 1984. He worked as researcher in the ITA (Technological Institute of Aragon) and he performed graduate studies in Mechanical Engineering with mayor in Energy Optimization in the University of Zaragoza, lading to the Ph.D. degree in 1991. He works in ENDESA, one of the main Spanish utilities, at the Telecommunications and Control System division, as software engineer on electric network and generation control systems projects. His research activity is related to the development of thermoeconomic analysis of energy systems methodologies. He has an extensive number of publications in journals and international conferences.