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Thermoeconomic Diagnosis Theory Based on Thermo-Characterization*

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Abstract

In this paper, the axioms and procedures to define a thermoeconomic diagnosis theory, based on thermo-characterization, are presented. This theory can be applied for advanced energy systems. The thermo-characterization set for each component allows evaluating all the effects when environmental variation, internal or control malfunction occurs. Furthermore, it should allow real-time monitoring in actual operating process, by determining a **matrix of malfunctions** and its **global thermoeconomic assessment**. Results are validated with respect to an analytical simulator and high accuracy is obtained.

Keywords: *Diagnosis; malfunctions, thermoeconomic diagnosis; thermo-characterization.*

1. Introduction

The main objective of the thermoeconomic diagnosis consists basically in the evaluation of the additional consumption of resources, which can be interpreted by the effects on efficiency, heat rate and production when anomalies or malfunction are present in the components of a system, hence the diagnosis must identify the component wherein they are taking place and estimate their impact either economic or energetic.

In advanced power systems, the only way to have an effective program of both energy saving and predictive maintenance is through a reliable on-line performance monitoring and diagnosis system.

Previous theories based on analytical models or exergoeconomic analyses are quite complex when applied in real-time applications and cost allocations for malfunctions are typically loosely calculated.

As one evolution of several theories, Valero, Torres, Serra & Lozano (1992) proposed the Exergy Cost Theory as a method for thermoeconomic diagnosis and other issues such as optimization. Then Lozano & Valero (1993) used the Exergetic Cost concept to evaluate the fuel consumption due to local irreversibilities. Another method of thermoeconomic diagnosis is the Fuel-Impact proposed by Lozano, Bartolome, Valero & Reini (1994), which relates the individual variation of the specific consumptions of resources in each one of the components to the total variation of resources in the system. This method has also been used to analyze different types of systems like those presented by Reini (1994) and Reini, Lazzaretto & Macor (1995). The philosophy of these methods consists mainly in comparing real operating conditions with reference operating conditions, while maintaining the product (power) of the system constant as well as the environmental conditions. The TADEUS paper series presented by Valero et. al. (2004) compiles the evolution of the different tendencies of the diagnosis methods. As to diagnosis using energy indicators, Zaleta, Gallegos, Rangel & Valero (2004) proposed an interpretation, from a global point of view, of the power plant. This method of thermodynamic diagnosis is called Reconciliation of Heat Rate and Power, and is essentially based on the comparison between two operating conditions at the same mass flow rate, one concerning the Test Operation Condition (TOC), and the other regarding the Reference Operation Condition (ROC). This method of diagnosis has already been installed in actual power plants, where different malfunctions and external variations are detected in real time. Pacheco, Rangel, Zaleta & Valero (2010) have proposed a method based on the concepts of the fuel impact formula and the analytical reconciliation method with a modification of the reference state, the integration of a modified fuel impact formula and the introduction of a filtering technique for the effects induced by the control and regulation system.

The disadvantages of these methods are: they demand a high capacity of both hardware and software; they need a global instrumentation of the process (they are truncated when the energy balance is not obtained); the mathematical complexity; and, finally the low precision in results.

A thermoeconomic analysis applying quantitative causality analysis to quantify intrinsic and induced effects in the application of the fuel impact formula was developed by Usón & Valero (2007). This method was successfully applied to a coal-fired power plant (Usón & Valero, 2009) where a systematic decomposition of effects, both intrinsic and induced, fuel quality and set points were achieved.

The thermo-characterization theory proposed in this paper permits to diagnose in an isolated form each one of the components or subsystems with respect to the causes of one or some of the overall anomalies' impact and to determine by means of formulas its global effect in the process, without the necessity of having highly accurate instrumentation, hardware and software. This method is validated with regard to a simulator and results have provided a low relative percentage of error.

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2. Diagnosis theory based on thermo-characterization

The thermo-characterization diagnosis is based fundamentally on seven premises.

Premise 1. Disaggregation. Any energy system can be disaggregated into ***n*** subsystems or components, each one delimited by a control volume and defined strategically by **p** points which should be located preferably over the border of the instrumentation and process sections, etc., as shown in Figure 1. Each control volume must fulfill both the overall energy and mass balance.

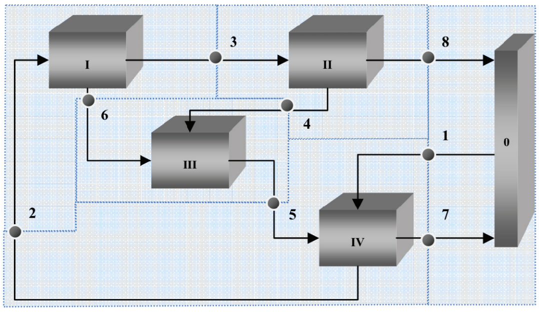

Figure 1. Generic system with subsystems (n=4) and strategic points (p=8).

Premise 2. Local processes. The operating state of the $\mathbf{i^{th}}$-component can be ***thermo-characterized*** from inlet and outlet conditions by parameters

a) Enthalpy changes ($\boldsymbol{\omega}_i$)
b) Entropy changes ($\boldsymbol{\sigma}_i$,)
c) Mass (or Volumetric) Flow Rate (**FR**)

The productive objective of the component (heating, cooling, shaft work, reaction, etc.), can be characterized by the parameters ($\boldsymbol{\omega_i}$, $\boldsymbol{\sigma_i}$, $\mathbf{FR_i}$) in accordance to a defined $\mathbf{i^{th}}$-component (control volume), as shown in Figure 2. In this regard, Eqs. (1) and (5) evaluate changes in the parameters $\boldsymbol{\omega_j}$ and $\boldsymbol{\sigma_j}$, respectively, whereas Eq. (6) defines the mass Flow Ratio, **FR**.

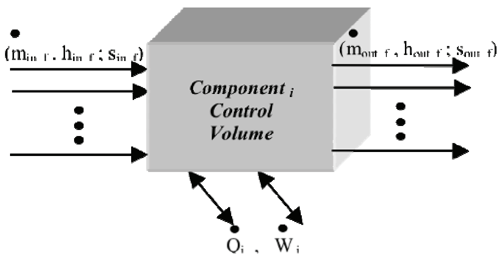

Figure 2. Control volume of a **i**-component.

$$\omega_i\left[\frac{kJ}{kg}\right] = h_{in} - h_{out} = \sum_{i=1}^{n}\dot{x}_{in,i}h_{in,i} - \sum_{j=1}^{m}\dot{y}_{out,j}h_{out,j} \quad (1)$$

where:

$$h_{total} = h_{static} + \frac{c^2}{2} + gz + \mu x + ... \quad (2)$$

$$\dot{x}_i = \frac{\dot{m}_{in,i}}{\sum \dot{m}_{in}} \quad (3)$$

$$\dot{y}_j = \frac{\dot{m}_{out,j}}{\sum \dot{m}_{out}} \quad (4)$$

$$\sigma_i\left[\frac{kJ}{kg\cdot K}\right] = s_{in} - s_{out} = \sum_{i=1}^{n}\dot{x}_{in,i}s_{in,i} - \sum_{j=1}^{m}\dot{y}_{out,j}s_{out,j} \quad (5)$$

$$FR = \frac{\dot{m}_{actual-load}}{\dot{m}_{design-load}} \; or \; \frac{\dot{V}_{actual-load}}{\dot{V}_{design-load}} \quad (6)$$

Premise 3. Reference state at different loads and operation modes. Energy systems are designed to work at different loads from design to partial loads or operation modes (off-design). This is achieved by controlling the mass or volumetric flows of some components (i.e. IGV, control valves, etc.) or establishing set-points for certain properties of control (i.e. T, P, etc.). It is well known, in terms of fluid mechanics, that a change in the mass flow rate at any point in a process causes changes in the up-stream pressures and indirect effects on the temperatures of the fluids, even though malfunctions are not present (i.e. Ellipse of Stodola).

Thus each $\mathbf{i^{th}}$-component keeps a path for its reference state according to its point of integration in the process, loads and operation modes, without anomalies. Such reference states can be represented in a three-dimensional ***thermo-characterized*** parameter ($\boldsymbol{\omega_{i,ref}}$, $\boldsymbol{\sigma_{i,ref}}$, **FR**) as shown in Figure 3. And it can be obtained by an acceptance test (i.e. ASME-PTC) or by a plant simulator. The parameters can be characterized (i.e. by using polynomial regressions, etc.) as a function of **FR**: $\boldsymbol{\omega_{i,ref} = \omega(FR)}$, and $\boldsymbol{\sigma_{i,ref} = \sigma(FR)}$.

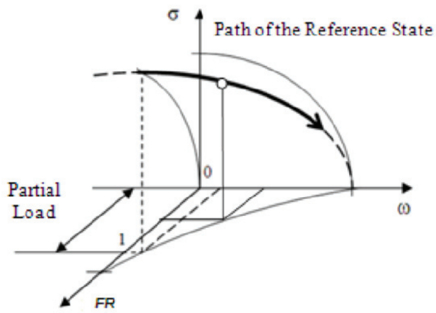

Figure 3. Three-dimensional space (ω, σ, FR) of the reference state of a $\boldsymbol{i^{th}}$*-component.*

Premise 4. Effect of the Malfunctions or Anomalies (matrix of malfunctions). Every energy system will have a specific number of free variables: **FR** and (***m***). They can be entirely identified by the criterion of the designers, operators or by the free variables of a thermodynamic plant simulator as Zaleta et. al. (2003) proposed. These variables can be classified as load **FR** (flow rate) and three categories of (***m***) variables:

a) **Environmental** (*i.e.* P_0, T_0, Hum, HHV, etc)
b) **Control** and **Set Point** *(i. e.* IGV, T, $\dot{m}$, etc)
c) **Internal Indicators** *(i.e.* η_{iso}, ϕ, UA, etc).

Each m variable has a specific reference value(s) defined as $malf_j$, some can be constant, and others are a function of the process load.

$$malf_{j,ref} = const \text{ or } malf_j \, (FR) \tag{7}$$

When the magnitude of these variables during actual operation ($malf_{j,actual} \neq malf_{j,ref}$) are different from the reference value, they are considered as malfunctions, represented as in Eq. (8):

$$\delta malf_j = (malf_{j,actual} - malf_{j,ref}) \tag{8}$$

In an actual process, any $\delta malf_j$ can affect the performance of an i^{th}-component. In this way, the ***thermo-characterized*** parameters ω_i and σ_i, will be affected as Figure 4 shows.

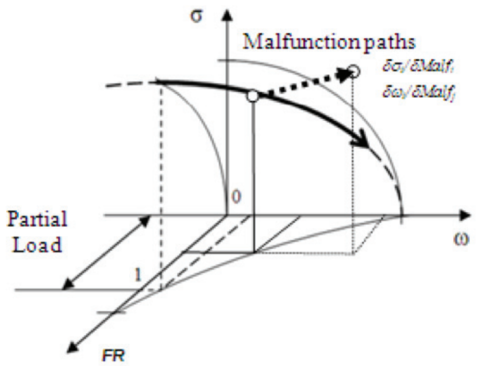

Figure 4. Effect of malfunction on the trajectory of ω, σ (at same FR).

When the effects are analyzed at the same **FR**, the impact by load can be isolated, as described in **premise 3**. Once the m malfunctions and the n component have been identified, a matrix of sensibility can be identified [**n x m**].

Table 1. Sensibility Matrix (n x m) of the components with respect to malfunction variables.

δmalf	Components 1	…i…	n
1	(1,1)	(i,1)	(n,1)
…j…	(1,j)	(i,j)	(n,j)
m	(1,m)	(i,m)	(n,m)

Two matrices are to be constructed as provided in Eqs. (9): $MALF_\omega$[**n x m**] and $MALF_\sigma$[**n x m**]. These matrices are obtained by means of an <u>overall process simulator,</u> by changing only one $malf_j$, maintaining constant load **FR**, and charactering the function of $\frac{\partial \omega_i}{\partial malf_j}$ and $\frac{\partial \sigma_i}{\partial malf_j}$ for each i^{th}-component.

$$MALF_\omega\left[n \times m\right]\Big\|_{FR} = \begin{pmatrix} \frac{\partial \omega_1}{\partial malf_1} & \cdots & \frac{\partial \omega_n}{\partial malf_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \omega_1}{\partial malf_m} & \cdots & \frac{\partial \omega_n}{\partial malf_m} \end{pmatrix} \tag{9a}$$

$$MALF_\sigma\left[n \times m\right]\Big\|_{FR} = \begin{pmatrix} \frac{\partial \sigma_1}{\partial malf_1} & \cdots & \frac{\partial \sigma_n}{\partial malf_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial \sigma_1}{\partial malf_m} & \cdots & \frac{\partial \sigma_n}{\partial malf_m} \end{pmatrix} \tag{9b}$$

These operators can be simulated under a wide range of loads **FR**, and $malf_j$, and can be characterized numerically as

$$\frac{\partial \omega_i}{\partial malf_j} = f(\mathrm{FR}, \mathrm{malf}_j) \tag{10a}$$

$$\frac{\partial \sigma_i}{\partial malf_j} = f(\mathrm{FR}, \mathrm{malf}_j) \tag{10b}$$

Premise 5. Performance Test. By real-time measurement from local instrumentation installed strategically at important points (***p***) of the process, it can be tested in terms of their basic thermodynamic properties, such as (**P**, **T**, $\dot{m}$, $\dot{v}$, etc.); in addition, these procedures (such as ASME Performance Test Code PTC's) allow one to determine the mass and energy balances in components or in a global process. The main objectives of the Performance Test are to obtain the actual present values of:

a) FR
b) $malf_{j,actual}$ and $malf_{j,ref} = malf(FR)$
c) $\Delta malf_j = (malf_{j,actual} - malf_{j,ref})$
d) $\omega_{i,\,actual}$ and $\sigma_{i,actual}$
e) $\omega_{i,\,ref} = \omega\,(FR)$ and $\sigma_{i,ref} = \sigma\,(FR)$
f) $\Delta\omega_i = \omega_{i,actual} - \omega_{i,ref}$ and $\Delta\sigma_i = \sigma_{i,actual} - \sigma_{i,ref}$
g) $F_{ref} = F\,(FR)$, $P_{ref} = P\,(FR)$ and $\eta_{ref} = P\,(FR)$
h) $\Delta F = F_{actual} - F_{ref}$, $\Delta P = P_{actual} - P_{ref}$ and $\eta_{ref} = \eta_{ref}\eta_{actual}$

Premise 6. Local reconciliation of malfunctions. The deviations found at one specific performance test in the thermo-characterized parameter $\Delta\omega_i$ and $\Delta\sigma_i$ can be disaggregated by the effect of the **m** malfunctions $\Delta malf_j$. This effect can be taken into account by reconciliation of the total impact, as shown in Eqs. (11) and (12). Figure 5 shows for an i^{th}-component the reconciliation of malfunctions as a summatory function.

$$\Delta\omega_i = \Delta\omega_{i,1} + \cdots + \Delta\omega_{i,m} = \sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial \omega_i}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{11a}$$

$$\Delta\sigma_i = \Delta\sigma_{i,1} + \cdots + \Delta\sigma_{i,m} = \sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial \sigma_i}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{11b}$$

For n components, a matrix representation is:

$$\Delta\omega\left[n \times 1\right] = \int MALF_\omega\left[n \times m\right] \times dmalf\left[m \times 1\right] \tag{12a}$$

$$\Delta\sigma\left[n \times 1\right] = \int MALF_\sigma\left[n \times m\right] \times dmalf\left[m \times 1\right] \tag{12b}$$

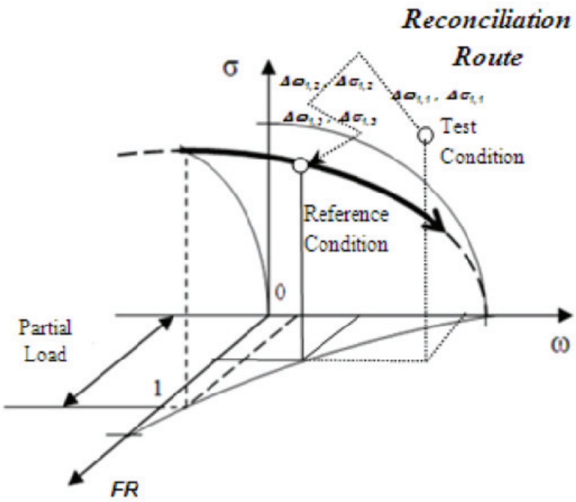

Figure 5. Graphical representation of the local reconciliation of malfunctions as a summatory term.

Premise 7: Global impact. From a plant simulator the total Fuel **(F),** total Product **(P)** and Efficiency **(η)** in a process depends of the value of the **m** free variables (**malf$_j$**) as well as the load **FR**.

$$F = f\left(malf_1, \ldots malf_j, \ldots malf_m, FR\right) \tag{13a}$$

$$P = f\left(malf_1, \ldots malf_j, \ldots malf_m, FR\right) \tag{13b}$$

$$\eta = f\left(malf_1, \ldots malf_j, \ldots malf_m, FR\right) \tag{13c}$$

Any j-malfunction can be characterized for its impact on **F, P** and η and be represented in a matrix (m x 1) as shown in Eqs. (14):

$$\frac{\partial F}{\partial\, malf} = \left[\left.\frac{\partial F}{\partial\, malf_1}\right|_{FR}, \ldots \left.\frac{\partial F}{\partial\, malf_j}\right|_{FR} \ldots, \left.\frac{\partial F}{\partial\, malf_m}\right|_{FR} \right] \tag{14a}$$

$$\frac{\partial P}{\partial\, malf} = \left[\left.\frac{\partial P}{\partial\, malf_1}\right|_{FR}, \ldots \left.\frac{\partial P}{\partial\, malf_j}\right|_{FR} \ldots, \left.\frac{\partial P}{\partial\, malf_m}\right|_{FR} \right] \tag{14b}$$

$$\frac{\partial \eta}{\partial\, malf} = \left[\left.\frac{\partial \eta}{\partial\, malf_1}\right|_{FR}, \ldots \left.\frac{\partial \eta}{\partial\, malf_j}\right|_{FR} \ldots, \left.\frac{\partial \eta}{\partial\, malf_m}\right|_{FR} \right] \tag{14c}$$

From a performance test, the information obtained (premise 5) is the detected deviation in the overall indicator **F**, **P** and η, but the first question is always: *What is the impact on the overall indicator by the malfunction?* The answer to this question can be solved by applying a reconciliation method (Zaleta et. al. 2004), and then the effect spreads over ΔF, ΔP as indicated by Eqs. (15).

$$\Delta F = \sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial F_T}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{15a}$$

$$\Delta P = \sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial P_T}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{15b}$$

$$\Delta \eta = \sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial \eta_T}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{15c}$$

However, the second question is: *What is the impact on the overall indicator by a component when a malfunctions occurs?*

The solution is to develop formulations of **F, P** and η in terms of the parameters **ω** and **σ**, considering the n components, and by using First Law. Eq. (16).

$$F = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, FR\right) \tag{16a}$$

$$P = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, FR\right) \tag{16b}$$

$$\eta = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, FR\right) \tag{16c}$$

Or by Second Law or exergy analysis:

$$F = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, \sigma_1, \ldots \sigma_i, \ldots \sigma_n, FR\right) \tag{17a}$$

$$P = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, \sigma_1, \ldots \sigma_i, \ldots \sigma_n, FR\right) \tag{17b}$$

$$\eta = f\left(\omega_1, \ldots \omega_i, \ldots \omega_n, \sigma_1, \ldots \sigma_i, \ldots \sigma_n, FR\right) \tag{17c}$$

Once Eqs. (16) or Eqs. (17) are defined, the answer to the second question is in Eqs. (15), which can be modified *by the chain rule* to determine impact on the overall plant parameters by **n** components and by **m** malfunction as described in Eqs. (18).

$$\Delta F = \sum_{i=1}^{n}\sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial F_T}{\partial\, \omega_i}\frac{\partial \omega_i}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{18a}$$

$$\Delta P = \sum_{i=1}^{n}\sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial P_T}{\partial\, \omega_i}\frac{\partial \omega_i}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{18b}$$

$$\Delta \eta = \sum_{i=1}^{n}\sum_{j=1}^{m} \int_{malf_{j,ref}}^{malf_{j,actual}} \left.\frac{\partial \eta_T}{\partial\, \omega_i}\frac{\partial \omega_i}{\partial\, malf_j}\right|_{FR} dmalf_j \tag{18c}$$

Moreover Eqs. (15), can be extended in terms of **σ** or exergy definitions.

The impacts on global parameters (ΔF, ΔP or Δη) can be converted into economical effects as

a) ΔF into Fuel Cost [$/sec],
b) ΔP into Utility Change [$/sec],
c) Δη into Unitary Cost [$/kWh],

3. Case study

A combined cycle power plant is proposed in order to illustrate the diagnosis approach and demonstrate the practical feasibility of the theory through the development of the seven premises presented. Fig. 6 shows the steps for developing the theory, and it is described in two main blocks: a) previous thermo-characterization; and, b) actual operation diagnosis. Within these blocks the steps for applying the premises are described.

3.1 Premise 1. Disaggregation

An energy system can be dividied into **n** sub-systems or components. In the case study, there are nine sub-systems (n=9), each one is delimited by a control volume as shown in Figure 6, and there are also eighteen points (p=18) which are strategically defined. Each control volume fulfills energy and mass balances. Table 2 shows the design parameters (FR=1) for each of the 18 points defined in the cycle.

3.2 Premise 2. Local processes

According to premise 2, any component or sub-system can be characterized by its parameters $\boldsymbol{\omega_i}$, $\boldsymbol{\sigma_i}$ and its mass flow rate **FR** applied according to the defined control volume, and Eqs. (1) and (5) describes changes in the parameters $\boldsymbol{\omega_j}$ and $\boldsymbol{\sigma_j}$.

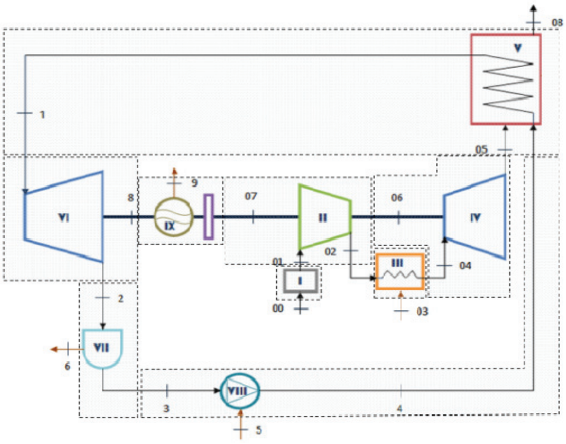

Figure 6. General description of the combined cycle and its disaggregation.

The intention of this article is not to show all the analytical models of simulators of advanced power systems, but in this case within the simulator are included the necessary models to reproduce the operating conditions and anomalies of the proposed system.

3.3 Premise 3. Reference state at different loads and operation modes

The energy systems are designed to work at different loads from design to partial loads or operation modes, even overload conditions. This is obtained by controlling the mass or volumetric flows of some components (i.e. **IGV** is used in this case as a control variable to determine **FR**) and to establish set-points for certain properties of control (i.e. **T, P,** etc.). By using analytical simulators, the reference state can be represented in a three-dimensional space ($\boldsymbol{\omega_i}$, $\boldsymbol{\sigma_i}$, **FR**) as shown in Figure 8, in which a graphical representation of the component ***i=2*** is presented, a mass flow rate was used from **FR=1** to **FR=0.411** and the values for **ω** and **σ** were characterized. Table 3 shows the characterization of the parameters $\boldsymbol{\omega_i}$ and $\boldsymbol{\sigma_i}$ for each component without any malfunctions or anomalies at different mass flow rates (**FR**).

3.4 Premise 4. Effect of the Malfunctions or Anomalies

In order to understand the perturbation and effects of the anomalies and malfunctions over the reference state of the **n**$^{\text{th}}$ component, it is necessary to develop two steps:

a) A definition of malfunctions or anomalies;
b) A perturbation analysis of the effects on the reference state of the **n** sub-systems.

3.4.1 Definition of malfunctions or anomalies in the system

A definition of ***m*** free variables of the system is strictly necessary. These ***m*** parameters ***[malf$_j$]*** are going to be identified in the proper simulator, through the free variables of the mathematical model, and can be classified into three types: environmental; control; or, internal. Table 4 identifies the variables [malf$_j$], its normal reference value and the abnormal range of typical variation (at **FR**=1) expected to occur during the system life. It is important to note that these values can change with respect to the load (**FR**).

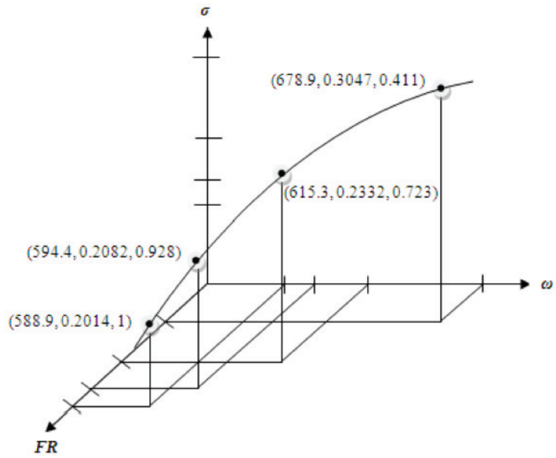

Figure 8. Dynamic reference state of the compressor (component i=2) represented in ω, σ and FR.

3.4.2 Perturbation Analysis of the Effects on the Reference State of the n Sub-systems

Once the malfunctions or anomalies in the overall system are identified, the next step is to make tables such as Table 5. Here the malfunction value can be manipulated in the simulator by varying the upper/lower percentage of a controlled variation of the malfunction, then a simulator program is run, causing variations in all components, in order to obtain the values of Eqs. (1) and (5). Also, the malfunctions effects are analyzed at constant **FR**, and the impact by load can be isolated, as is described in premise 3. Any malfunction will have a variation effect on the characteristics parameters $\boldsymbol{\omega_i}$ and $\boldsymbol{\sigma_i}$ of some components, thus, two matrices will be obtained, which represent the effect of the overall malfunctions in each component or sub-system.

The information produced will allow knowing in a predictive manner the malfunction impact in regard to **Δω** and **Δσ** in an upper/lower percentage of a controlled variation of the malfunction, and it is prepared to be used during an on-line monitoring evaluation. By this means it is possible to obtain the coefficients like those presented in Eqs. (19) and (20).

$$\frac{\partial \omega_2}{\partial malf_2} = \frac{\partial \omega_{compressor}}{\partial T_0}$$
$$= \begin{Bmatrix} \left(1.31341135 - 0.0008907 \cdot T_{00}\right)\big|_{FR=1} \\ \left(1.23132488 - 0.001038 \cdot T_{00}\right)\big|_{FR=0.75} \\ \left(1.04182962 - 0.001028 \cdot T_{00}\right)\big|_{FR=0.5} \end{Bmatrix}$$
$$= \left(0.34059285 + 1.8321149 \cdot \mathrm{FR} - 0.8592964 \cdot \mathrm{FR}^2\right)$$
$$- \left(-0.0050151 + 0.0145658 \cdot \mathrm{FR} - 0.00866 \cdot \mathrm{FR}^2\right) \cdot \mathrm{T}_{00} \qquad (19)$$

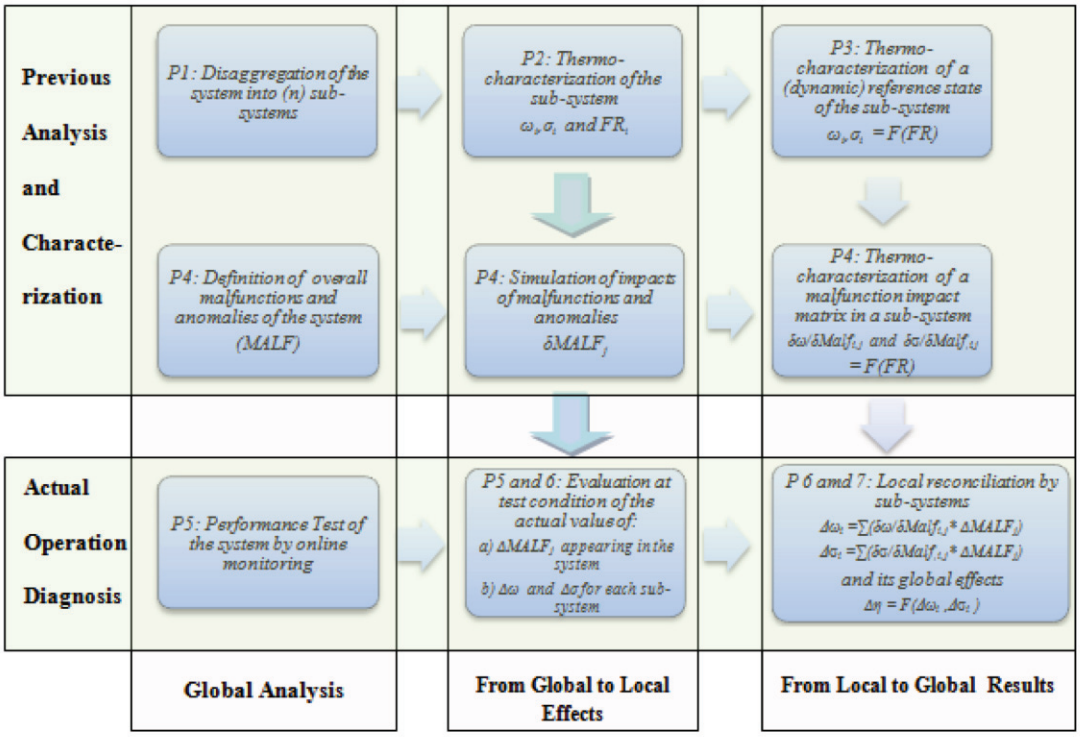

Figure 7. Diagram of steps and premises for a thermo-characterization of an energy system.

Table 2. Design parameters for the power plant.

Code	#	Description	T(°C)	P(bar)	$\dot{m}$(kg/s)	h(kJ/kg)	s(kJ/kgK)	W(MW)	Q(MW)
00	1	Inlet Air	26.85	1.013	10.7	300.4	5.702		
01	2	Compressor Inlet	26.85	0.993	10.7	300.4	5.707		
02	3	Compressor Outlet	460.2	22.47	10.7	749.3	5.733		
03	4	Fuel			0.1975	48000			9.479
04	5	Turbine Inlet	1227	22.47	10.7	1635	6.554		
05	6	Turbine Outlet	615.6	1.013	10.7	920.4	6.834		
06	7	Turbine Power						7.649	
07	8	Compressor Power input						4.802	
08	9	Exhaust Gases	146.9	1.013	10.7	421.5	6.041		
1	10	Main Steam	400	100	1.679	3096	6.211		
2	11	Exhaust Steam	53.96	0.15	1.679	1925	5.95		
3	12	Pump Inlet	53.96	0.15	1.679	225.9	0.7546		
4	13	Condensed Water	54.34	100	1.679	236	0.7547		
5	14	Power Pump						0.017	
6	15	Heat Waste							2.854
7	16	Heat HRSG							5.337
8	17	ST Power output						1.966	
9	18	Net Power						4.798	

$$\frac{\partial\sigma_{21}}{\partial malf_2} = \frac{\partial\sigma_{compressor}}{\partial T_0}$$

$$= \begin{Bmatrix} \left(0.000274875 - 7.5972x10^{-7} \cdot T_{00}\right)\Big|_{FR=1} \\ \left(0.00027022 - 1.01839x10^{-6} \cdot T_{00}\right)\Big|_{FR=0.75} \\ \left(0.000194931707 - 7.756x10^{-7} \cdot T_{00}\right)\Big|_{FR=0.5} \end{Bmatrix}$$

$$= -\,0.000167559758 + 0.0010075361 \cdot \mathrm{FR}$$

$$-\,0.000565106344 \cdot \mathrm{FR}^2$$

$$-\left(-12.1436 + 59.8576 \cdot \mathrm{FR} - 40.1168 \cdot \mathrm{FR}^2\right) \cdot \mathrm{T}_{00} \qquad (20)$$

It is possible to obtain all the coefficients of the matrix $\frac{\partial\omega_i}{\partial malf_j}$ and $\frac{\partial\sigma_i}{\partial malf_j}$ in the same way.

3.5 Premise 5. Performance test

A Performance test of a process will require instrumentation and measurements at specific points in the process, as described in Table 2. In this example, Performance test data are provided from the simulator.

A specific case of operating condition was simulated, where three anomalies were developed simultaneously. They were abnormal conditions values in:

- Environmental Temperature;
- Compressor Efficiency; and,
- TAT.

The data obtained from Table 5 are provided in order to illustrate a typical scenario, which is presented during a performance test and compared in regards to a reference state, and the results are as follows.

a) In the overall system, three malfunctions are present:

$$\Delta malf_2 = \Delta T_{00} = 15\left[K\right]$$

$$\Delta malf_5 = \Delta \eta_{compressor} = -5\left[\%\right]$$

$$\Delta malf_8 = \Delta TAT = 20\left[K\right]$$

b) For all n components, their parameters **ω_i**, **σ_i**, and **FR** were obtained and compared with regard to its respective reference state at the same **FR** value in order to know if the deviations **$\Delta\omega_i$** and **$\Delta\sigma_i$**, do exist.

In the case of the compressor, the isolated effect due to ΔT_{00} is determinate according to Eqs. (21) and (22):

$$\Delta\omega_{2,2}\Big|_{FR=0.998} = \int_{T_{00,ref}}^{T_{00,test}} \frac{\partial \omega_{compressor}}{\partial T_0} dT_{00} = 52.9\left[\frac{kJ}{kg}\right] \tag{21}$$

$$\Delta\sigma_{2,2}\Big|_{FR=0.998} = \int_{T_{00,ref}}^{T_{00,test}} \frac{\partial \sigma_{compressor}}{\partial T_0} dT_{00} = 0.0488\left[\frac{kJ}{kg\cdot K}\right] \tag{22}$$

The question at this point is: *What is the impact of the three causes developed during the performance test on the parameters **$\Delta\omega_i$** and **$\Delta\sigma_i$** for each component?* It is shown as follows.

3.6 Premise 6. Local reconciliation of malfunctions

The deviations found, when comparing the **test** with the **reference** condition of the characteristic parameters (**$\Delta\omega_i$** and **$\Delta\sigma_i$**) are known to be influenced by the effect of one or several of the **m** malfunctions (environmental, control or internal) detected in the performance test, **$\Delta MALF_j$** or a matrix **ΔMalf[m x 1]** (which are independents variables and were thermo-characterized previously, according with **premise 4**) can be released in terms that represent the effect of each malfunction and in sum reconcile the total impact, such as shown in Eq. (9). By applying the reconciliation concepts of Eq. (11) in the case of the compressor effected by $malf_2$, $malf_5$ and $malf_8$, the following are obtained:

$$\Delta\omega_{2,FR=0.998} = 52.9\left[\frac{kJ}{kg}\right]$$

$$= \Delta\omega_{2,2} + \Delta\omega_{2,5} + \Delta\omega_{2,8}$$

$$= 20.6\left[\frac{kJ}{kg}\right] + 30.1\left[\frac{kJ}{kg}\right] + 2.2\left[\frac{kJ}{kg}\right]$$

$$\Delta\sigma_{2,FR=0.998} = 0.0488\left[\frac{kJ}{kg\cdot K}\right]$$

$$= \Delta\sigma_{2,2} + \Delta\sigma_{2,5} + \Delta\sigma_{2,8}$$

$$= \left(0.00371 + 0.04014 + 0.00499\right)\left[\frac{kJ}{kg\cdot K}\right]$$

The results of the local reconciliation provide information about the impact of overall anomalies $\Delta MALF_j$ in terms of enthalpy and entropy changes of the **n** components. In the case of the compressor (Component ***i=2***) at this point it is known that the higher impact is from the efficiency change, and the lower effect is from TAT changes. By this same manner the quality and quantity of the impact of these three anomalies can be known in the remaining **n** components of the case study.

3.7 Premise 7: Global impact.

The typical global indicators of a system (objective functions) are: power (P), Fuel (F), efficiency (η), effectiveness, cost of generation, heat rate (HR), etc. The diagnosis requires an objective function to analyze, and for this article efficiency is chosen, which is the inverse of the heat rate (HR), which is a parameter commonly used in the power stations, since it allows to quantify the amount of heat provided by the fuel to produce a kilowatt-hour of energy.

The objective consists in finding a general expression that represents accurately the variation of the objective function with respect to the behavior of a sub-system and the global impact of a parameter of the system in general, defined previously in Eqs. (16) and (17).

The definition of efficiency as an objective function was analyzed to calculate the impact of the malfunctions present in the cycle. In agreement with Thermoeconomics, for a productive process to exist it must be provided with fuels (F), which when the process is completed are transformed into products (P).

$$\eta = \frac{P}{F} \tag{23}$$

In all energy systems it is possible to define the total fuel (F_T) and the total product (P_T) in terms of the characteristic parameters. In the case of the Gas Turbine, by First Law analysis:

$$P = \dot{m}_{01}\left(\omega_4 - \omega_2\right) \tag{24}$$

$$F = \dot{m}_{01}\Delta\omega_3 \tag{25}$$

And by Second Law analysis:

$$P = \dot{m}_{01}\left(\omega_4 - \omega_2\right) \tag{26}$$

$$F = \dot{m}_{01}\left(1 - \frac{T_0}{T_{III}}\right)\omega_3 \tag{27}$$

In the case study when an abnormal value of malfunction occurs in the gas cycle, a change of fuel and product can be expressed as Eqs. (28) and (29):

$$dP = \dot{m}_{01}\left(\Delta\omega_4 - \Delta\omega_2\right) \tag{28}$$

$$dF = \dot{m}_{01}\Delta\omega_3 \tag{29}$$

And the Impact on the efficiency of the gas cycle can be expressed as Eq. (30):

$$\frac{\Delta\eta_{CG}}{\eta_{CG}} = \left[\frac{\left(\Delta\omega_4 - \Delta\omega_2\right)}{\omega_4 + \omega_2} - \frac{\Delta\omega_3}{\omega_3}\right] \tag{30}$$

It is important to note that by First Law or Exergetic analysis, Eq. (30) is the same and does not matter which analysis is used (by energy balance or exergy balance). Therefore Eq. (30) is "universal" for the evaluation of malfunctions or anomalies with respect to the objective function.

By applying this theory to the case study, three anomalies were presented which affected all components, therefore the following was obtained:

$$\Delta\eta_{CG} = -4.37\% \\ = (-1.23\%)\big|_{\Delta Malf_2} + (-1.84\%)\big|_{\Delta Malf_5} + (-1.3\%)\big|_{\Delta Malf_8}$$

The method allows disaggregating the terms of the impact by components even further according to Eq. (14).

3.7.1 Economic Impact

Once the impact of the malfunction in the objective function is obtained, it can be converted to Heat Rate terms (where HR=1/η). This impact can then be transformed into an economic value by means of Eq. (31).

$$\Delta\$\big|_{malfunction}\left[\frac{\$}{hr}\right] = \Delta HR \cdot FC\left[\frac{\$}{kJ}\right]\cdot\left(\frac{3600s}{1hr}\right)\cdot \dot{W}_R\left[kW\right] \quad (31)$$

Where *FC* stands for the fuel cost provided in [$/kJ] units.

3.8 Methodology validation

This methodology was validated using a simulator developed in EES (Engineering Equation Solver), and the diagnostic methodology considered is the Reconciliation Method proposed by Zaleta et al. (2004).

The results shows high accuracy as is seen in Table 6, where the analyzed variable is the environmental temperature at FR=1 with a 10% induced variation. This malfunction was evaluated and compared by applying the analytical formula obtained with the methodology proposed in this work and using the simulator program.

Table 6. Methodology and simulator results.

Malfunction	Analytical formula	Simulator	% error
+10%	-2.848	-2.779	2.494
- 10%	2.452	2.43	0.9041

The thermoeconomic diagnosis method used to compare this methodology needs a simulator program which includes complex mathematical models with large PC processing requirements, up to 2218 MBpm (i.e. Uniscort, a simulator program that was developed using the Reconciliation Method proposed by Zaleta et al., 2004). Therefore by using the proposed methodology which does not need a simulator, the processing charge decreases allowing online monitoring to be realized in shorter times.

4. Conclusions and Perspectives

The theory proposed herein contributes to the field of diagnosis with a formulation that describes the local impacts of the malfunctions occurring in the components or subsystems. This Theory can be correctly adjusted to any energy process, namely, power generation, petrochemical, refrigeration systems and others.

However, a good knowledge of the components and an initial simulator is required to obtain a thermo-characterization of the reference state and of the malfunction effects, but once obtained, it comes to define the characteristic equations, without using a simulator during a performance test or real-time diagnosis processes. In fact, there is a reduction in time and load of the numerical processing because the use of a simulator is eliminated.

In general, the advantages of thermo-characterization is that it allows to compare the reference and test operation conditions, which means that it helps to find any deviations with regards to the reference conditions, under the following statements:

a) The time and effort of simulation is a heavy load at first, due to the fact that it obtains a large number of tables, graphics and characteristics equations.
b) Once obtained, the mathematical models are lighter from the point of view of PC processors, being of great use for real time monitoring.
c) The models offer excellent precision in the prediction of the impact to the objective function, and
d) It allows realizing a thermoeconomic diagnosis by components without the necessity to evaluate the entire process.

In this article an analytical formulation was developed using the efficiency as an objective function, which was defined based on products and resources of the system to make an analysis based on the First and Second Law of Thermodynamics as well as the respective analysis cause-effect of the anomalies. Since both analyses arrived at the same formulas, it was demonstrated that it is the same to use the energy formulation by First or Second Law of Thermodynamics. Moreover, the thermocharacterization in terms of $\boldsymbol{\omega}$ and $\boldsymbol{\sigma}$ can be used for exergy analysis, since it is possible to apply to any i-component the exergy balance, Eq. (32).

$$\Delta b_i = \omega_i - T_0\sigma_i = q_i\left(1-\frac{T_0}{T}\right) - w_i + I_i \quad (32)$$

When a malfunction appears it can be expressed as shown in Eq. (33).

$$\frac{\partial \Delta b_i}{\partial malf_j} = \frac{\partial \omega_i}{\partial malf_j} - T_0\frac{\partial \sigma_i}{\partial malf_j} \quad (33)$$

In conclusion, it is possible to say that with a single magnitude for the allocation of impact in the objective function due to a malfunction present in the power systems, as well as without taking into account the energy or exergy base by which it is analyzed, the results will be the same. Therefore, the energy diagnosis will be the same independently of the thermodynamic base that is being considered.

Table 3. Characterization of the parameters ω_i and σ_i with respect to mass Flow Rate (FR).

	Design Condition		**Partial Loads**					
	***FR*=1**		***FR*=0.928**		***FR*=0.723**		***FR*=0.411**	
SUB-SYSTEMS	ω [kJ/kg]	σ [kJ/kg K]	ω [kJ/kg]	σ [kJ/kg K]	ω [kJ/kg]	σ [kJ/kg K]	ω [kJ/kg]	σ [kJ/kg K]
I	589	0.2014	573.6	0.2051	524	0.2178	422.3	0.2467
II	588.9	0.2014	594.4	0.2082	615.3	0.2332	678.9	0.3047
III	746	0.6456	761.4	0.6636	811	0.7237	912.7	0.8586
IV	941.9	0.005182	928.4	0.007348	879.5	0.01185	745.5	0.007839
V	272.5	0.5031	285.9	0.5226	334.9	0.5909	469	0.7586
VI	892.4	0.5896	883.6	0.6166	852	0.7132	769.8	0.9645
VII	1978	6.046	1987	6.073	2018	6.17	2100	6.421
VIII	10.13	0.0000648	10.13	0.0000648	10.13	0.0000648	10.13	0.0000648

Table 4. Free variables defined to the case study (m=19) with normal and abnormal (malfunctions or anomalies) values at FR=1.

	SUB-SYSTEM	**MALF$_j$**	**TYPE**	**NORMAL VALUE**	**ABNORMAL LOWER VALUE**	**ABNORMAL UPPER VALUE**
I	FILTERS	1. Admission pressure	Environmental	1.013 bar	0.9	1.1
		2. Admission temperature	Environmental	300 K	270	330
		3. Relative Humidity	Environmental	35%	0	100
		4. Pressure Drop	Internal	0.02 bar	0	1
II	COMPRESSOR	5. Efficiency	Internal	80 %	50	95
		6. Admission Coefficient	Internal	186.6	170	200
III	COMBUSTION CHAMBER	7. Pressure Drop	Internal	0.05 bar	0	1
		8. TIT (Turbine Inlet Temp)	Control	1500 K	1000	1600
IV	GAS TURBINE	9. Efficiency	Internal	80 %	50	95
		10.Admission Coefficient	Internal	18.43	15	20
V	HRSG	11.Efficiency	Internal	90 %	50	95
		12.Drop pressure (steam side)	Internal	10 bar	0	30
		13.Drop pressure (gas side)	Internal	0.05 bar	0	1
		14.Main steam temperature	Control	673 K	500	700
VI	STEAM TURBINE	15.Main Steam pressure	Control	100 bar	50	
		16.Efficiency	Internal	90 %	50	95
VII	CONDENSER	17.Vacuum pressure	Control	0.15 bar	0.02	1
		18.Sub cooling Temperature	Internal/ Control	0 K	0	5
VIII	PUMP	19.Efficiency	Internal	90%	50	95

Table 5. Example of the effect of an anomaly (environmental temperature, j=2) on a component (compressor, i=2). The units of ω and Δω are (kJ/kg) whereas for σ and Δσ are (kJ/kg·K).

Environmental Temperature											
		T_{01}=300 K		T_{01}=330 *K*				T_{01}=270 *K*			
		Reference State		*upper* 10%				*lower* 10%			
						Differences				Differences	
IGV	***FR***	***ω***	***σ***	***ω***	***σ***	***Δω***	***Δσ***	***ω***	***σ***	***Δω***	***Δσ***
0	1	589	0.2014	635.4	0.2047	46.4	0.0033	541.2	0.1979	-47.8	-0.0035
22	0.928	573.6	0.2051	618.8	0.2085	45.2	0.0034	527.1	0.2015	-46.5	-0.0036
44	0.723	524	0.2178	565.3	0.2212	41.3	0.0034	481.5	0.2142	-42.5	-0.0036
66	0.411	422.3	0.2467	455.1	0.2498	32.8	0.0031	388.5	0.2433	-33.8	-0.0034
86	0.071	111.6	0.1856	111.4	0.1737	-0.2	-0.0119	110.6	0.1974	-1	0.0118

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NOMENCLATURE

Acronyms

FR	Mass Flow Ratio
GT	Gas Turbine
HRSG	Heat Recover Steam Generator
IGV	Inlet Guide Vanes
Malf/MALF	Malfunction
ROC	Reference Operation Condition
ST	Steam Turbine
TAT	Turbine outlet Temperature
TIT	Turbine Inlet Temperature
TOC	Test Operation Condition

Symbols

B,b	Exergy
F	Fuel
H, h	Enthalpy
I	Irreversibilities
$\dot{m}$	Mass Flow
P	Pressure/Product
$\dot{Q}$, q	Heat
s	Entropy
T	Temperature
$\dot{W}$	Power
Δ	Change
η	Efficiency
Φ	Coefficient of mass flow admission
Σ	Summation operator
ω	Difference of enthalpy
σ	Difference of entropy

Subscripts

00/0	Environmental Conditions
i	Number of component
j	Number of Malfunction
D,d	Design Condition
R, ref	Reference Condition
actual	Test Condition

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