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ξ-ε Analysis for the Thermoeconomic Diagnosis of Energy Systems*

Sergio Usón[1**] and Antonio Valero
CIRCE. Centre of Research for Energy Resources and Consumptions.
Department of Mechanical Engineering. University of Zaragoza.
María de Luna 3, Campus Río Ebro, 50018, Zaragoza (Spain)
E-mail: [1]suson@unizar.es

Abstract

Thermoeconomic diagnosis is aimed at the detection of malfunctioning components in energy systems and the quantification of additional fuel consumption caused by each malfunction. A formulation is proposed based on: i) the use of enthalpy, entropy and flow rate for the characterization of flows within a system; ii) the linearization of restrictions; and, iii) the application of standardized indicators for variations in components behavior, set-points and system product. The approach allows one to introduce the concepts of thermoeconomic analysis (irreversibility and cost) to describe the process of fuel impact formation, without losing the capability of describing accurately the physical behavior of the system. A simple example is developed to illustrate the ideas presented.

Keywords: Thermoeconomic diagnosis, quantitative causality analysis, irreversibility, cost.

1. Introduction

Thermoeconomic diagnosis comprises the activities aimed at the detection of anomalies in energy systems and the quantification of the additional fuel impact caused by each one of them. The TADEUS (Thermoeconomic Approach for the Diagnosis of Energy Utility Systems) initiative was aimed at serving as a common forum for scientists and researchers interested in this topic. In the first paper (Valero et al., 2004a) the problem is defined and an example is proposed as a common test-bench. In a second paper (Valero et al., 2004b), the main concepts and tools provided by Thermoeconomics for the diagnosis problem are summarized.

One of the most important tools provided by Thermoeconomics for the diagnosis problem is the *fuel impact formula*. It relates the behavior of the different components to the fuel consumption. It was suggested by Valero et al. (1990, 1999) and developed by Reini (1994), Lozano et al. (1994) and Torres et al. (1999).

The main problem in the practical application of thermoeconomic analysis to the diagnosis problem is the presence of induced effects, which sometimes makes the detection of the malfunctioning components difficult. In the framework of the TADEUS problem, several authors have proposed different techniques to minimize these undesirable effects.

The methodology proposed by Verda (2004) is based on the filtration of effects induced by the control system, while Reini and Taccani (2004) propose to filter the variation of the product of the different components.

Lazzaretto and Toffolo (2006) have made a critical review of thermoeconomic diagnosis methodologies and consider that thermoeconomic variables are not enough to eliminate induced effects. These authors propose to identify the malfunctioning components through the movements of their characteristic curves measured by the irreversibility variation (Toffolo and Lazzaretto, 2004).

Due to the difficulties appearing in the application of thermoeconomic tools, some authors more interested in the applicability of the diagnosis methods to real examples propose to avoid the use of Thermoeconomics and apply directly a thermodynamic representation of the system. For the diagnosis of the TADEUS problem, Zaleta and Muñoz (2004) use a simulator and Correas (2004) applies a *diagnosis algorithm* which does not need a fine tuned simulator. This algorithm has also been used to diagnose a combined cycle (García-Peña et al., 2001) and a coal fired power plant (Usón et al., 2006). It is the origin of the *quantitative causality analysis* (Usón et al., 2007).

The combination of thermodynamic and thermoeconomic models has also been explored. Valero et al. (1999) proposed to use a simulator to determine the effect of the variation of an operating parameter x_r on unit exergy consumptions. Usón and Valero (2007) apply *quantitative causality analysis* to quantify intrinsic and induced effects in the application of the *fuel impact formula*. Another line of research is related to the representation of malfunctions in the h-s (enthalpy-entropy) plane. Zaleta et al. (1997, 2004) propose a thermo-characterization of power system components based on the representation in the ω, σ, *MFR* space. ω is the enthalpy increment, σ is the entropy increment and *MFR* is the mass flow ratio.

In this paper, thermodynamic-based approaches (such as quantitative causality analysis) are connected with thermoeconomic concepts such as cost and with the movements of the points in the enthalpy-entropy (*h-s*) plane. The goal is to achieve the conceptual elegance and rigor of Thermoeconomics without losing the information contained in a thermodynamic model.

The formulation proposed allows one to relate directly how variations in components' efficiencies, set-points and plant product impact fuel consumption, which is the goal in practical applications. Furthermore, it is possible to apply a

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**Corresponding Author

detailed analysis which comprises the whole *process of impact formation*, by introducing the concepts of irreversibility increment and cost. Although this extended procedure requires the calculation of more parameters, it is interesting, at least from the theoretical point of view, because thermoeconomic parameters are calculated without losing the capability of describing the physical behavior of the system.

2. Standardized Formulation of Quantitative Causality Analysis

The idea presented in this paper is that if the linearized equations of the thermodynamic model are expressed under certain conditions (using enthalpy and entropy as intensive properties and defining suitable indicators for degradation in components and variation in set-points), it is possible to develop a formulation which combines the ability to reproduce real behavior (like methods based on the thermodynamic description of the system) and the conceptual rigor of Thermoeconomics.

Afterwards, equations to define the physical behavior of the components and expressions to calculate increments in irreversibility and in fuel consumptions are written. Finally, the idea of cost is introduced. These points are developed below.

2.1 Standardized Formulation for Common Equations of Thermal Systems

The aim of this section is to present how equations describing restrictions for thermal systems can be expressed in a homogeneous way by considering enthalpies, entropies and flow rates as thermodynamic variables to represent the system.

A flow undergoing a process from 1 to 2 is considered. These points are characterized by h_1, h_2, s_1 and s_2. The flow rate for both points is $\dot{m}$. This set of variables comprising enthalpies, entropies and flow rates can be represented as $\boldsymbol{\chi}$. There is also an indicator of the process (e.g. isentropic efficiency) which, in general, depends on these five parameters.

$$\eta_{1,2} = \eta_{1,2}\left(h_1, s_1, h_2, s_2, \dot{m}\right) = \eta_{1,2}\left(\boldsymbol{\chi}\right) \tag{1}$$

If the previous equation is linearized around a point $\boldsymbol{\chi}^0$, it is possible to write:

$$\Delta\eta_{1,2} \cong \left.\frac{\partial\eta_{1,2}}{\partial h_1}\right|_{\chi^0} \cdot \Delta h_1 + \left.\frac{\partial\eta_{1,2}}{\partial s_1}\right|_{\chi^0} \cdot \Delta s_1 + \left.\frac{\partial\eta_{1,2}}{\partial h_2}\right|_{\chi^0} \cdot \Delta h_2 + \left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0} \cdot \Delta s_2 + \left.\frac{\partial\eta_{1,2}}{\partial \dot{m}}\right|_{\chi^0} \cdot \Delta\dot{m} \tag{2}$$

This relation can be rearranged:

$$\frac{\Delta\eta_{1,2}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \cong \frac{\left.\frac{\partial\eta_{1,2}}{\partial h_1}\right|_{\chi^0}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \cdot \Delta h_1 + \frac{\left.\frac{\partial\eta_{1,2}}{\partial s_1}\right|_{\chi^0}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \cdot \Delta s_1 + \frac{\left.\frac{\partial\eta_{1,2}}{\partial h_2}\right|_{\chi^0}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \cdot \Delta h_2 + \Delta s_2 + \frac{\left.\frac{\partial\eta_{1,2}}{\partial \dot{m}}\right|_{\chi^0}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \cdot \Delta\dot{m} \tag{3}$$

It has the following structure:

$$\Delta\xi_{\eta_{1,2}} \cong \xi_{\eta_{1,2},h1} \cdot \Delta h_1 + \xi_{\eta_{1,2},s1} \cdot \Delta s_1 + \xi_{\eta_{1,2},h2} \cdot \Delta h_2 + \Delta s_2 + \xi_{\eta_{1,2},\dot{m}} \cdot \Delta\dot{m} \tag{4}$$

where ξ is a variable which has dimensions of specific entropy and represents the increment of entropy in the output (Δs_2) when the other variables remain constant. It can be named *standardized degradation indicator*, and is related with the efficiency indicator of the process with the following relation:

$$\Delta\xi_{\eta_{1,2}} = \frac{\Delta\eta_{1,2}}{\left.\frac{\partial\eta_{1,2}}{\partial s_2}\right|_{\chi^0}} \tag{5}$$

There are other restrictions which do not relate several points, but only refer to a parameter (φ) related to a single point. φ can be a property (temperature, pressure…) or other indicator (e.g. flow coefficient) and, in general, depends on enthalpy, entropy and flow rate. This relation can be linearized:

$$\Delta\varphi \cong \left.\frac{\partial\varphi}{\partial h_1}\right|_{\chi^0} \cdot \Delta h_1 + \left.\frac{\partial\varphi}{\partial s_1}\right|_{\chi^0} \cdot \Delta s_1 + \left.\frac{\partial\varphi}{\partial \dot{m}}\right|_{\chi^0} \cdot \Delta\dot{m} \tag{6}$$

which can be rearranged as:

$$\frac{\Delta\varphi}{\left.\frac{\partial\varphi}{\partial h_1}\right|_{\chi^0}} \cong \Delta h_1 + \frac{\left.\frac{\partial\varphi}{\partial s_1}\right|_{\chi^0}}{\left.\frac{\partial\varphi}{\partial h_1}\right|_{\chi^0}} \cdot \Delta s_1 + \frac{\left.\frac{\partial\varphi}{\partial \dot{m}}\right|_{\chi^0}}{\left.\frac{\partial\varphi}{\partial h_1}\right|_{\chi^0}} \cdot \Delta\dot{m} \tag{7}$$

It has the following structure:

$$\Delta\varepsilon_{\varphi_1} \cong \Delta h_1 + \varepsilon_{\varphi_1,s1} \cdot \Delta s_1 + \varepsilon_{\varphi_1,\dot{m}} \cdot \Delta\dot{m} \tag{8}$$

where ε is a variable with dimensions of specific enthalpy, which can be named *standardized set-point indicator*.

Another type of restriction is related to the product provided by the system. For example, if one product is the power produced by a turbine with inlet flow 1 and outlet flow 2, its linearized equation can be expressed as:

$$\Delta\omega_{1,2} \cong \dot{m} \cdot \Delta h_1 - \dot{m} \cdot \Delta h_2 + \left(h_1 - h_2\right) \cdot \Delta\dot{m} \tag{9}$$

where $\omega_{1,2}$ is the power produced by the turbine.

Finally, it is possible to have other restrictions, which do not include a degree of freedom for the system. For example, a mass balance of a bifurcation where a flow 1 is divided into two flows, 2 and 3, has the following equation:

$$\Delta\dot{m}_1 - \Delta\dot{m}_2 - \Delta\dot{m}_3 = 0 \tag{10}$$

All linearized equations can be summarized in a system:

$$\mathbf{A} \cdot \Delta\chi \cong \Delta\psi \tag{11}$$

where $\boldsymbol{A}$ is the matrix of coefficients and $\boldsymbol{\Delta\chi}$ and $\boldsymbol{\Delta\psi}$ are respectively the vectors containing the variations of enthalpies, entropies and flow rates, and the variations of standardized indicators:

$$\Delta\chi = \begin{bmatrix} \Delta\mathbf{h} \\ \Delta\mathbf{s} \\ \Delta\dot{\mathbf{m}} \end{bmatrix} \tag{12}$$

$$\Delta\psi = \begin{bmatrix} \Delta\xi \\ \Delta\varepsilon \\ \Delta\omega \\ \mathbf{0} \end{bmatrix} \tag{13}$$

Finally, $\boldsymbol{\Delta\chi}$ can be calculated from $\boldsymbol{\Delta\psi}$ by inverting $\boldsymbol{A}$.

$$\Delta\chi \cong \mathbf{A}^{-1} \cdot \Delta\psi \tag{14}$$

The procedure is based on the linearization of equations describing the thermal system, like the *quantitative causality analysis* (Usón et al., 2007). However, the standardized indicators are used for component's degradation and set-point variation, and enthalpy and entropy are used as intensive properties for flow characterization. This is very convenient for the calculation of other parameters such as increment in irreversibility and impact on fuel, as is explained below. Additionally, $\boldsymbol{A^{-1}}$ contains the information of the evolution of all the points in the *h-s-m* space, which connects with other diagnosis approaches (Zaleta, 1997, Zaleta et al., 2004).

2.2 Calculation of Fuel Impacts

To calculate the fuel impact, a vector $\boldsymbol{F\chi}$ containing the partial derivatives of F related to χ is needed:

$$\Delta F \cong \mathbf{F\chi} \cdot \Delta\chi \tag{15}$$

Again, the calculation of elements of $\boldsymbol{F\chi}$ is direct, due to the use of enthalpies, entropies and flow rates as variables for describing the thermal system. If Eq (14) and (15) are combined, it is possible to calculate the impact of standardized indicators of processes and set points and plant product on plant fuel consumption:

$$\Delta F \cong \mathbf{F\chi} \cdot \mathbf{A}^{-1} \cdot \Delta\psi = \mathbf{F\psi} \cdot \Delta\psi \tag{16}$$

The previous equations connect the variation of the independent variables with the fuel impact, so that the diagnosis problem is solved. However, it is more interesting to look inside the process formation of the impacts, which is the aim of the following sections. First, irreversibility variations are calculated and then, the concept of cost is introduced.

2.3 Calculation of Irreversibility Variation

The increment of irreversibility can be easily related to the variation of the vector of thermodynamic variables $\boldsymbol{\Delta\chi}$ by using a matrix $\boldsymbol{I\chi}$.

$$\Delta\mathbf{I} \cong \mathbf{I\chi} \cdot \Delta\chi \tag{17}$$

Each element $I\chi_{ij}$ represents the partial derivatives of the irreversibility in element i related to the variable j of χ, evaluated at χ^0. Since χ contains enthalpies, entropies and flow rates, these derivatives are usually very simple.

It is interesting to relate the variation of a *standardized degradation indicator* of a component with the increment of the irreversibility that it causes in the same component. For this purpose, the *malfunction coefficient* can be defined as:

$$\mu_i = \frac{\Delta I_{i,\xi_j}}{\dot{m}_i\big|_{\chi^0} \cdot T_0 \cdot \Delta\xi_j} \tag{18}$$

where T_0 is the temperature of the environment, and ξ_j is a standardized degradation indicator associated with component i. With the previous definition, the coefficient μ is dimensionless and, due to the presence of the flow rate, the dependence on the load is avoided.

2.4 Calculation of Costs

Once both fuel impacts and irreversibility increments have been calculated, it is possible to relate them. If the fuel impact caused by a variation of a degradation indicator ξ_j is divided by the increment of the irreversibility caused in the component i <u>associated with this degradation</u> the *unit cost* of this irreversibility increment is obtained:

$$k^*_{\xi_i} = \frac{\Delta F_{\xi_i}}{\Delta I_{\xi_i}} \tag{19}$$

The unit cost of a plant product is calculated by dividing the corresponding fuel impact by the increment of product:

$$k^*_{\omega_i} = \frac{\Delta F_{\omega_i}}{\Delta\omega_i} \tag{20}$$

Finally, it is possible to make a similar definition associated with a variation of a standardized set-point indicator:

$$\tilde{k}^*_{\varepsilon_i} = \frac{\Delta F_{\varepsilon_i}}{\dot{m}_i\big|_{\chi^0} \cdot \Delta\varepsilon_i} \tag{21}$$

where the flow rate has been introduced in order to filter out the dependence on the load and to obtain a dimensionless parameter. This pseudo-cost is different from the previous costs because it can have any value (it might also be negative). The tilda notation is used to distinguish the pseudo-cost from the 'true' costs calculated by Eqs. (19) and (20).

Unit costs presented in this section have two characteristics. First, they have been derived from the thermodynamic model of the system, instead of using a more or less accurate productive structure. This means that their calculation is a bit more complex but they represent the physical behavior of the components. Additionally, they are marginal costs because they relate increments.

2.5 Summary of the Procedure

The formulation presented allows one to determine the increment of fuel consumption caused by each one of the variations of the parameters characterizing the system analyzed. Although it is possible to connect directly the variation of parameters with the corresponding fuel impact (Eq. 16), the theory developed allows one to see the process of impact formation by introducing concepts of thermoeconomic analysis, such as irreversibility and cost.

A variation in a process indicator causes a variation in a standardized degradation indicator, which causes an increment in the component irreversibility (through its malfunction coefficient) which, in turn, originates a fuel increment (through its corresponding unit cost):

$$\Delta\eta_{1,2} \rightarrow \Delta\xi_{1,2} \rightarrow \Delta I_{\xi_{1,2}} \rightarrow \Delta F_{\xi_{1,2}} \quad (22)$$

If a set point indicator varies, its corresponding standardized set-point indicator also does, which causes a fuel increment (through its corresponding unit pseudo-cost):

$$\Delta\varphi_1 \rightarrow \Delta\varepsilon_1 \rightarrow \Delta F_{\varepsilon_1} \quad (23)$$

Finally, an increment in the demand of one of the plant products causes an increment in the fuel demand of the system:

$$\Delta\omega_1 \rightarrow \Delta F_{\omega_1} \quad (24)$$

3. Example of Application

3.1 Definition of the System

To illustrate and to clarify the ideas presented in the previous section, a simple example is developed. A steam turbine is considered, in which steam is expanded from 1 to 2. The characteristics of the system are summarized in Table 1:

Table 1. Properties of points.

Point	T (ºC)	p (bar)	x	h (J/kg)	s (J/kg·K)
1	450	40		$3.33\cdot10^6$	6936
2	39	0.07	0.9	$2.33\cdot10^6$	7502

The power produced is 50 MW due to a flow rate of 50.0 kg/s. The turbine has an isentropic efficiency of 0.85. The reference state chosen for the calculation of exergy is 1 bar and 20 ºC.

3.2. Formulation of standardized equations

For simplicity, conditions at point 1 are considered as constant; accordingly, the system has only three degrees of freedom: isentropic efficiency (process indicator), pressure at point 2 (point indicator) and power produced (plant product). The variables considered in the standardized model are enthalpy and entropy at point 2, and flow rate.

In this situation, the standardized set of equations which describes the system behavior can be expressed as:

$$\left.\begin{pmatrix} \xi_{\eta,h_2} & 1 & 0 \\ 1 & \varepsilon_{p_2,s_2} & 0 \\ -\dot{m} & 0 & (h_2-h_1) \end{pmatrix}\right|_{\chi^0} \cdot \begin{pmatrix} \Delta h_2 \\ \Delta s_2 \\ \Delta\dot{m} \end{pmatrix} \cong \begin{pmatrix} \Delta\xi_\eta \\ \Delta\varepsilon_{p_2} \\ \Delta\omega \end{pmatrix} \quad (25)$$

where the value of the derivatives are:

$$\left.\xi_{\eta,h_2}\right|_{\chi^0} = 0.0008996\,\mathrm{K}^{-1} \quad (26)$$

$$\left.\varepsilon_{p_2,s_2}\right|_{\chi^0} = -311.6\,\mathrm{K} \quad (27)$$

The standardized and conventional parameters are related by the following relations:

$$\frac{\Delta\xi_\eta}{\Delta\eta} = -4828\frac{\mathrm{J}}{\mathrm{kg\cdot K}} \quad (28)$$

$$\frac{\Delta\varepsilon_{p_2}}{\Delta p_2} = 1.846\cdot10^6\frac{\mathrm{J}}{\mathrm{kg\cdot bar}} \quad (29)$$

$$\Delta\omega = \Delta\dot{W} \quad (30)$$

3.3. Calculation of Fuel Impacts

The vector $\boldsymbol{F\chi}$ which connects ΔF and $\boldsymbol{\Delta\chi}$ is:

$$\mathbf{F\chi}^t = \left.\begin{pmatrix} 0 & 0 & \left(h_1 - h_0 - T_0\cdot(s_1 - s_0)\right)\end{pmatrix}\right|_{\chi^0} \quad (31)$$

With the previous vector and the information presented in Section 3.2, it is possible to decompose the fuel impact into a summation of terms corresponding to the standardized parameters:

$$\Delta F \cong 15823\cdot\Delta\xi_\eta + 50.78\cdot\Delta\varepsilon_{p_2} + 1.30\cdot\Delta\omega \quad (32)$$

where ΔF and $\Delta\omega$ are expressed in W, $\Delta\xi_\eta$ in J/kg and $\Delta\varepsilon_{p_2}$ in J/(kg•K).

A similar expression can be obtained for the non-standardized variables:

$$\Delta F \cong -7.639\cdot10^7\cdot\Delta\eta + 9.372\cdot10^7\cdot\Delta p_2 + 1.30\cdot\Delta\dot{W} \quad (33)$$

where ΔF and $\Delta\dot{W}$ are expressed in W, Δp_2 in bar and $\Delta\eta$ is dimensionless.

3.4. Calculation of Irreversibility Increments

Since there is only one component, the matrix $\boldsymbol{I\chi}$ has only one row:

$$\mathbf{I\chi} = \left.\begin{pmatrix} 0 & \dot{m}\cdot T_0 & s_2\cdot T_0\end{pmatrix}\right|_{\chi^0} \quad (34)$$

The malfunction coefficient associated with the turbine isentropic efficiency has the following value:

$$\mu_\eta = \frac{\Delta I_\eta}{\left.\dot{m}\right|_{\chi^0}\cdot T_0\cdot\Delta\xi_\eta} = 0.9187 \quad (35)$$

As it can be seen, the value of this dimensionless parameter is quite close to 1, which indicates that it is a suitable method to normalize the irreversibility increment.

3.5. Calculation of Costs

The unit cost of plant product is given directly by the last component of Eq. (32):

$$k^*_\omega = 1.30 \quad (36)$$

The unit cost associated with the turbine isentropic efficiency is:

$$k^*_\eta = 1.175 \quad (37)$$

By using this cost, it is possible to relate the variation of the standardized indicator and the fuel impact:

$$\Delta F_\eta = k^*_\eta \cdot \Delta I_\eta = k^*_\eta \cdot \mu_\eta \cdot \dot{m}\Big|_{\chi^0} \cdot T_0 \cdot \Delta\xi_\mu = 15823 \cdot \Delta\xi_\eta \quad (38)$$

Finally, the pseudo-cost associated with the standardized indicator of outlet pressure is:

$$\tilde{k}^*_{p_2} = 1.015 \quad (39)$$

which allows one to calculate its fuel impact:

$$\Delta F_{p_2} = \tilde{k}^*_{p_2} \cdot \dot{m}\Big|_{\chi^0} \cdot \Delta\varepsilon_{p_2} = 50.78 \cdot \Delta\varepsilon_{p_2} \quad (40)$$

As can be seen, these results are the same as those expressed by Eq. (32) and are the final goal of the diagnosis procedure. However, Eqs. (32) and (33) are opaque and do not give information on the *process formation of the impact*. The development of the detailed procedure calculates intermediate parameters which introduce the concept of irreversibility and cost; thus the method is connected with thermoeconomic analysis without losing information on the physical behavior of the system.

4. Conclusion

A formulation has been developed that is based on a convenient expression of the linearized equations describing the thermal system, which uses enthalpy and entropy as intensive properties and standardized indicators for components' degradation, set-points and variation of plant product.

Since the approach is based on the physical description of the system, it is very useful for practical applications, because induced effects are minimized. Furthermore, it is possible to develop a detailed *analysis of fuel impact formation*, which quantifies not only the impact but other important intermediate parameters: increments in irreversibility and cost. Accordingly, this formulation for thermoeconomic diagnosis combines the ability to reproduce the physical behavior of the systems (like thermodynamic-model based approaches), with formal rigor, homogeneity, and direct interpretation of coefficients (like in Thermoeconomics).

Costs calculated within this detailed analysis correspond exactly with the physical behavior of the thermal system; in fact, the simplified and the detailed approach provide exactly the same results. This opens a promising research line on the assessment of thermoeconomic models for the diagnosis problem.

The formulation has been applied to a simple example, in order to clarify concepts. It is only a first step, and the application to complex systems is under development.

Nomenclature

F	Plant fuel [W]
h	Enthalpy [J/kg]
k^*	Unit cost
$\tilde{k}^*$	Unit pseudo-cost
$\dot{m}$	Flow rate [kg/s]
MFR	Mass flow ratio
p	Pressure [bar]
s	Entropy [J/(kg·K)]
T	Temperature [ºC]
x	Vapour mass fraction
$\dot{W}$	Power [W]

Greek

ε	Standardized set point indicator [J/kg]
η	Isentropic efficiency
μ	Malfunction coefficient
ξ	Standardized degradation indicator [J/(kg·K)]
σ	Entropy increment [J/kg·K]
φ	Thermodynamic property
$\boldsymbol{\omega}$	Plant product [W], Enthalpy increment [J/kg·K]

Matrices and vectors

$\boldsymbol{A}$	Matrix of coefficients
$\boldsymbol{F\chi}$	Vector of partial derivatives of F related to $\boldsymbol{\chi}$
$\boldsymbol{F\psi}$	Vector of partial derivatives of F related to $\boldsymbol{\psi}$
$\boldsymbol{I}$	Vector of irreversibilities [W]
$\boldsymbol{I\chi}$	Matrix of partial derivatives of $\boldsymbol{I}$ related to $\boldsymbol{\chi}$
$\boldsymbol{\chi}$	Dependent standardized properties vector
$\boldsymbol{\psi}$	Independent standardized properties vector

Subscripts

0	Environment
1	Initial point of the process
2	Final point of a process

Superscripts

0	Reference state

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