H&S APPROACH: A SYSTEMATIC AND DIRECT LINK BETWEEN THE EFFICIENCY AND THE RELATED COST IN THERMOECONOMICS

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Abstract. *The inclusion of the negentropy in thermoeconomics represented a great advance in the discipline, since it allowed one to quantify the condenser product in a steam cycle plant and to allocate explicitly the cost of the residues to the final products of the system, which was not possible before, once that the condenser is a dissipative component, whose product cannot be expressed in terms of exergy. However, by using the negentropy joined up with the exergy, the product of the condenser (negentropy) is always greater than its fuel (exergy), which seems that the condenser efficiency is greater than 100 percent by using the product/fuel efficiency index. Therefore, this paper presents a new methodology for calculating efficiencies and the related costs in thermal systems. In this new methodology, called H&S Model, the fuels and the products of each component are systematiically defined by taking into account all enthalpy, entropy and also chemical exergy additions to and removals from all the streams. Consequently, a direct link between the efficiency and the related cost in thermoeconomics is established. In particular, this paper shows that by using the H&S Model, the efficiency (the ratio between products and fuels) of each component (including the dissipative ones, such as the condenser) ranges from zero (for a totally irreversible process) to 100% (for a totally reversible process).*

Keywords: *Efficiency, Cost, Exergy Components, H&S Approach, Thermoeconomics.*

1. INTRODUCTION

The thermoeconomic methodologies have been searching for productive structures that represent the process of cost formation in the thermal systems. Generally, the productive structures defines the productive propose of the subsystems (products and fuels), using thermodynamic magnitudes. The way in which we define the productive structure is a key point of the thermoeconomic analysis (Lozano and Valero, 1993).

The product and the fuel are defined by considering the desired result produced by the component and the resources expended to generate this result. Thus the efficiency of a component is defined as the ratio between product and fuel.

Most analysts agree that exergy, instead of enthalpy only, is the most adequate thermodynamic property to define the fuels and products of the subsystems since it contains information from the second law of thermodynamics and accounts for energy quality.

Sometimes, under a thermoeconomic analysis point of view, it is necessary to consider a mass or an energy flow rate consisting of several components, for example thermal, mechanical or chemical exergy, or even to include fictitious flows such as negentropy (Torres *et al.*, 1996).

The inclusion of the negentropy in thermoeconomics represented, indeed, a great advance in the discipline, since it allowed one to quantify the condenser product in a steam cycle plant, which was not possible before, once that it is a dissipative component, whose product cannot be expressed in terms of exergy. Although the use of the negentropy concept to define the productive structure is good in order to apportion the cost of the condenser and residues to the productive components of the system, the product of the condenser (negentropy) is always greater than its fuel (exergy), which seems that the condenser efficiency is greater than 100 percent.

Therefore, this paper presents a new and general methodology for calculating efficiencies and related costs in thermal systems, by systematically defining a productive structure in which the efficiency (the ratio between products and fuels) of all components (including the dissipative one) ranges from zero (for a totally irreversible process) to 100 percent (for a totally reversible process). In this new methodology, the fuels and products used in the functional diagram in order to calculate costs coincide with the fuels and product which can be used for calculating efficiency for both productive and dissipative units. Consequently, a systematic and direct link between the efficiency and the related costs is established in thermoeconomics.

By using a combined cycle power plant, this new methodology is applied in order to demonstrate its easily and systematic applications to any thermodynamic cycle whose processes can be represented in the h-s plane.

2. THE H&S APPROACH

This methodology is called H&S Model because it is based on the disaggregation of physical exergy into enthalpy ($H=m.\Delta h$) and syntropy ($S=m.T_0.\Delta s$). Consequently, in the productive structure of the H&S Model, the fuels and products of each component are defined by taking into account all enthalpy, entropy and also chemical exergy additions to and removals from all the streams. Syntropy and negentropy are the same magnitude ($m.T_0.\Delta s$) with essentially the same meaning (negative entropy). However, the negentropy is used as a fictitious flow together with exergy (Frangopoulos, 1987 and Lozano *et al.*, 1993) and the syntropy is a physical exergy component, which must be used together with the enthalpy. Other authors (Tsatsaronis and Pisa, 1994; Frangopoulos, 1994) define productive structure by disaggregating the physical exergy into thermal and mechanical components. But the H&S Model was the first that proposes the productive diagram by disaggregating the physical exergy into enthalpic and syntropic components (Santos *et al.*, 2006). In previous works (Santos *et al.*, 2006, 2008a, 2008b and 2009a), the word negentropy was used to describe this exergy component ($m.T_0.\Delta s$). In order to avoid misunderstanding, in last works (Santos *et al.*, 2009b and 2009c) the word syntropy has been used for this therm. The H&S approach consist of the following steps:

- Representation of the thermodynamic cycle in the h,s plane or in the H&S plane.
- Definition and representation of the productive structure using the functional diagram.
- Calculation of the productive flow values.
- Formulation of the cost equations.

Is very important to say that the two first steps are not necessary to apply the H&S Model but they are recommended in order to understand and represent graphically all the process of cost formation in the plant.

The solution of the set of cost equations allows the attainment of the unit cost of each internal flow and final product. The efficiency of the overall system and of each subsystem is obtained by calculating the ratio between their products and fuels, for both productive and dissipative component.

2.1. The H&S Plane

In agreement with Valero and Royo (1992), efficiency, cost and behaviour of the system are based in the trajectory in the h,s plane any flow performs when it works for the specific purpose of the plant.

Therefore, in order to apply the H&S Model, the representation of the plant in the H,S plane is recommended because it can be useful in order to help us to identify the fuel and the product of the components of the plant. However, this step is not mandatory. The products and the fuels of each equipment, in terms of enthalpic and chemical exergy component, are defined based on the quantity of these magnitudes added to and removed from the working fluid, respectively. Because the syntropy is the negative entropy, the subsystems that decrease the working fluid entropy are syntropy producers, and the others that increase the entropy of the working fluid are syntropy consumers.

2.2. Productive Structure

According to Lozano and Valero (1993), perhaps the fundamental limitation of the Theory of Exergetic Cost, as it was originally formulated, is defining the productive structure in relation to the same flows and components present in the physical structure, because the resulting difficulties lie mainly in the adequate treatment of the dissipative units and of the residues. Therefore, the H&S Model have been applied by using the productive structure.

In order to carry out a thermoeconomic analysis, the H&S Model defines the productive purpose of the subsystems (fuels and products), as well as the distribution of the external resources and internal products throughout the system. The productive structure could be represented by means of a functional diagram, as proposed by Frangopoulos (1987) and used by Lozano and Valero (1993) and Lozano *et al.* (1993).

The functional diagram represents graphically the cost formation process of the system. The rectangles are the real units (or subsystems) that represent the actual equipments of the system. The rhombus and the circles are fictitious units called junction and bifurcations, respectively. Each productive units has inlet and outlet arrows, that represent its fuel (or resource) and products, respectively. There are productive units that have small junction to indicate that they have more than one fuels, and/or a small bifurcation to indicate that they have more than one product.

2.3. The Productive Flow Values

The flows of the functional diagram are productive flows. The only limitation which must be imposed is that it must be possible to evaluate all these flows in relation to the state of the plant as defined by the physical structure.

The productive flows that represent power and external fuel are the same flows present in the physical structure. These flows are total exergy. The remaining productive flows are the variation of an exergy component between two different states of the physical structure. For example, the productive flows expressed in terms of physical exergy ($E_{j:k}$) are the variation of physical exergy between two state (j and k) of the physical structure, as explained in Eq. (1).

$$E_{j:k} = m \cdot [h_j - h_k - T_0 \cdot (s_j - s_k)] \tag{1}$$

The productive flows representing the enthalpic ($H_{j:k}$) and the syntropic ($S_{j:k}$) components of the physical exergy are calculated using, respectively, Eq. (2) and Eq. (3), for water, steam and refrigerants, or Eq. (4) and Eq. (5) for fluids considered as ideal gas. The variables that define the Eqs. (1)-(3) are: mass flow (m), enthalpy (h) and entropy (s) of the stream at the physical states (j and k) and temperature (T) of water at the conditions of thermodynamic environment 0 (= 25°C). The new variables that appear in Eq. (4) and Eq. (5) are: universal gas constant (R), specific heat (Cp) of each element, temperature (T) and pressure (p) of the stream at the physical states (j and k).

$$H_{j:k} = m \cdot (h_j - h_k) \tag{2}$$

$$S_{j:k} = m \cdot T_0 \cdot (s_j - s_k) \tag{3}$$

$$H_{j:k} = m \cdot \int_{T_k}^{T_j} Cp \cdot dT \tag{4}$$

$$S_{j:k} = m \cdot T_0 \cdot \left[\int_{T_k}^{T_j} \frac{Cp}{T} \cdot dT - R \cdot \ln\left(\frac{p_j}{p_k}\right) \right] \tag{5}$$

The chemical exergy ($CH_{j:k}$) is considered as fuels and/or product of subsystems when the working fluid changes its chemical composition between the inlet and the outlet (j and k), as shown in Eq. (6).

$$CH_{j:k} = CH_j - CH_k \tag{6}$$

The complete procedures to calculate the chemical exergy of the streams (CH_j and CH_k) can be found in Moran and Shapiro (2006), Bejan *et al.* (1996) and Kotas (1985).

The streams representing gases are considered as composed with the same elements presents in the air (N_2, CO_2, O_2, H_2O and Ar), but their chemical composition (quantitatively) is different from that of the air.

2.4. The Cost Equations

The mathematical model for cost allocation is obtained by formulating the cost equations balance in each actual and fictitious units of the functional diagram, as shown in Eq. (7), where c is the monetary unit cost of each flow of the productive structure (unknown variable) and Y is a generical way to represent the flows of the functional diagram, which can be power (P), external fuel (Q), enthalpy (H), syntropy (S), physical exergy (E), or chemical exergy (CH) added to and removed from the working fluid. The monetary unit cost of a flow is the amount of monetary unit required to obtain one unit of this flow. The variable Z is the hourly cost of each unit due to the capital cost, operation and maintenance. Note that the monetary unit cost of the external fuel is a known variable.

$$c_{ufd} \cdot \sum Y_{out} - \sum (c_{in} \cdot Y_{in}) = Z \tag{7}$$

As shown in Eq. (7), the H&S Model attributes the same monetary unit cost (c_{ufd}) to all of the flows leaving the same productive unit or leaving the same bifurcation (Y_{out}). Because the syntropy is used as an exergy component flow, the H&S Model does not use the by-product concept, i. e., each productive unit can have more than one product (the exergy component flows, separately). This is the common rules used (or accepted) by all thermoeconomic practitioners to formulate the auxiliary equations. This rule is applied to the bifurcation and also to the real units that have two exit flows. Once that the auxiliary equations are more or less arbitrary (Tsatsaronis and Pisa, 1994) and, they are unavoidable in thermoeconomics, the H&S Model allows reducing the arbitrariness in thermoeconomics.

By modifying Eq. (7) in order to formulate cost balance to provide the exergetic unit cost (k) of each flow of the productive structure, we obtain the Eq. (8). The exergetic unit cost of a flow is the amount of exergy required to obtain one unit of exergy of this flow. This cost is a measure of the thermodynamic efficiency of the production process generating this flow (Valero *et al.*, 2006). In this case, the cost per unit of time of the subsystem due to the capital cost, operation and maintenance must not be used ($Z = 0$) and the monetary unit cost of the external flow is replaced by the exergetic unit cost of an external resource, which is considered to be equal to 1.00 kW/kW, because its generation is external to the evaluated system.. The auxiliary equations are the same as used to obtain the monetary unit cost.

$$k_{ufd} \cdot \sum Y_{out} - \sum (k_{in} \cdot Y_{in}) = 0 \qquad (8)$$

The solution of the sets of cost equations obtained by applying Eq. (7) and Eq. (8) in each device of the productive structure allows the attainment of the monetary unit cost and the exergetic unit cost of each internal flow and final product, respectively.

3. APPLICATION OF THE H&S APPROACH

Figure 1 represents the physical structure of the combined cycle power plant, which is defined as having eight units or subsystems: air compressor (AC), combustion chamber (CC), gas turbine (GT), electric generator (EG), recovery boiler (RB), feeding pump and its motor (P), steam turbine (ST) and condenser and condensing supply works (C).

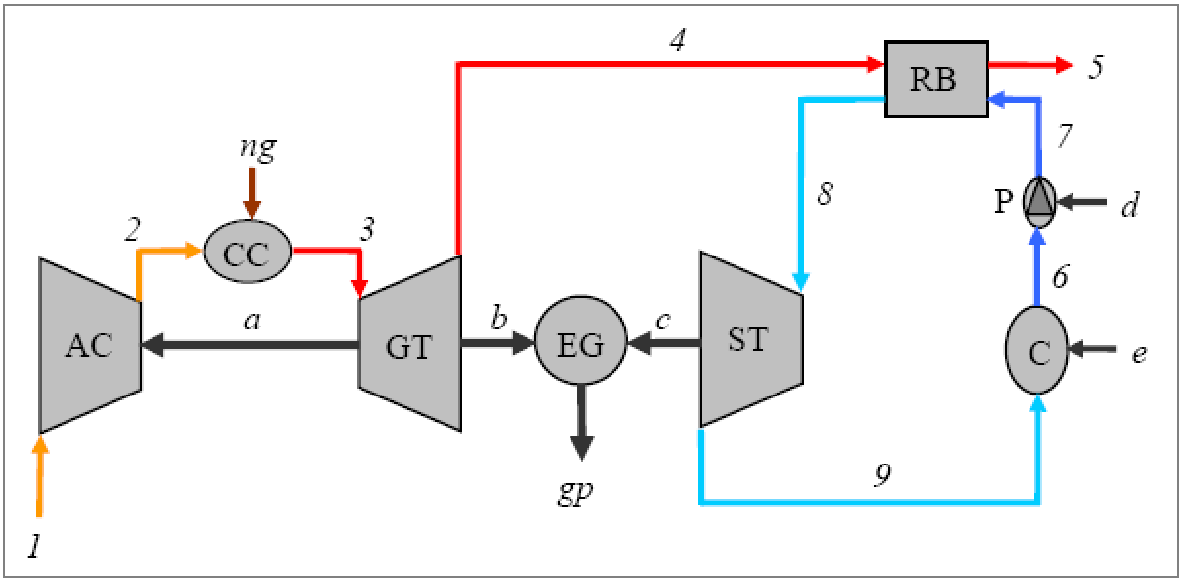

Figure 1. Physical Structure of the Combined Cycle Power Plant

The streams of the physical structure of the combined cycle power plant (Fig. 1) are: air, gases, water, steam, liquid vapor mixture, mechanical and electric power and natural gas. The description of the streams that represent the working fluids and their main parameters (mass flow, pressure and temperature) are presented in Tab. 1.

Table 1. Main Parameters of the Main Physical Flows of the Combined Cycle Power Plant

PHYSICAL FLOW		m [kg/s]	p [kPa]	T [°C]
i	Description			
1	Air	310.00	101.32	25.00
2	Air	310.00	911.90	331.78
3	Gases	314.20	902.80	870.00
4	Gases	314.20	104.33	443.05
5	Gases	314.20	101.32	180.64
6	Water	29.08	6.50	37.63
7	Water	29.08	4,080.00	38.35
8	Steam	29.08	4,000.00	417.00
9	Moisture (x = 0,89)	29.08	6.50	37.63

The mechanical net power (b) of the Brayton cycle is 58,280.05 kW and the compressor power (a) is 98,893.09 kW. The steam turbine produces 27,903.64 kW of mechanical power (c). The fuel is natural gas (ng), whose consumption in exergetic basis is 209,697.64 kW. The gross electric power (gp) produced by the electric generator is 84,415.00 kW. The electric power consumed by the feeding pump motor (d) and by the condensing supply works (e) are 205.00 kW and 210.00 kW, respectively. To model the combined cycle power plant represented in the Fig. 1, the thermodynamic model considers complete combustion with excess of air and it also considers that the air and the combustion gases are mixtures of ideal gases. The molar compositions of the air and the combustion gases streams are in Tab. 2.

Table 2. Molar Composition of Air and Gases Streams present in the Physical Structure of the Combined Cycle Plant

ELEMENT			PERCENTAGE [%]	
n	Description	Symbol	Air	Gases
1	Oxygen	O_2	20.56	15.56
2	Carbon Dioxide	CO_2	0.03	2.36
3	Water Vapor	H_2O	1.88	6.26
4	Nitrogen	N_2	76.61	74.92
5	Argon	Ar	0.92	0.90

The thermodynamic model considers that the specific heat (*Cp*) of the elements that composes the streams of air and gases varies with their temperature, according to the polynomial equation and the respective coefficients in the Table 3. The representation of the plant in the H-S plane is shown in Fig. 2. The functional diagram is shown in Fig. 3.

Table 3. Coefficients for the Specific Heat Polynomial Equation of some Ideal Gases (Lozano and Valero, 1986)

ELEMENTS			$Cp = A + B \cdot T + C \cdot T^2 + D \cdot T^3$ [kcal/kmol.K]			
n	Description	Symbol	A	$B \cdot 10^2$	$C \cdot 10^5$	$D \cdot 10^9$
1	Oxygen	O_2	6.085	0.3631	-0.1709	0.3133
2	Carbon Dioxide	CO_2	5.316	1.4285	-0.8362	1.784
3	Water Vapor	H_2O	7.7	0.04594	0.2521	-0.8587
4	Nitrogen	N_2	6.903	-0.03753	0.193	-0.6861
5**	Argon**	Ar**	4.964**	0.00	0.00	0.00

OBS: ** (Verda *et al.*, 2004)

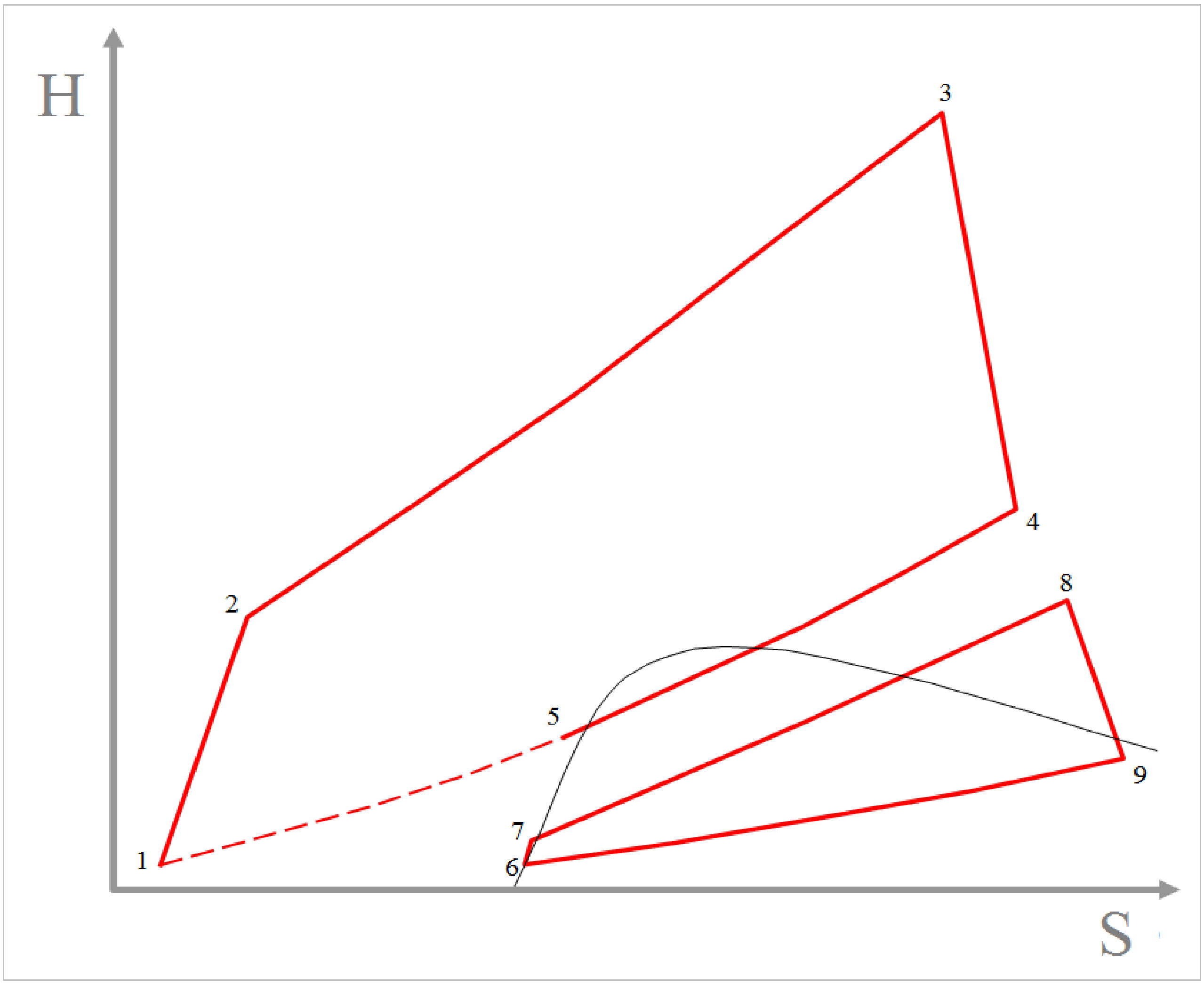

Figure 2. Representation of the Combined Cycle Power Plant in the H,S Plane

We can see in Fig 2 that in the bottom cycle (Rankine), the enthalpy of the working fluid (water-steam) is increased as much in the pump as in the recovery boiler. The turbine consumes part of this enthalpy. The operation of these productive units increases the entropy of the working fluid. The condenser consumes the remaining part of enthalpy while it decreases the entropy of the working fluid. In other words, the condenser provides the necessary syntropy (negative entropy) for the correct cyclical operation of the system. Thus, the cost associated to the condenser is charged to the units responsible for the increase of the working fluid entropy (pump, boiler and turbine), proportionally to the working fluid entropy increased by each of them.

In the topping cycle (Brayton), we have the increase of the working fluid entropy in the compressor, in the combustor and in the turbine. The recovery boiler has a negative contribution. Thus, the recovery boiler produces syntropy. The other part of syntropy is produced by the environment (E), an imaginary dissipative unit, where residual enthalpy and chemical exergy of the gases is charged. This syntropy, plus that produced by the recovery boiler are given to the units of the Brayton cycle that increase the working fluid entropy.

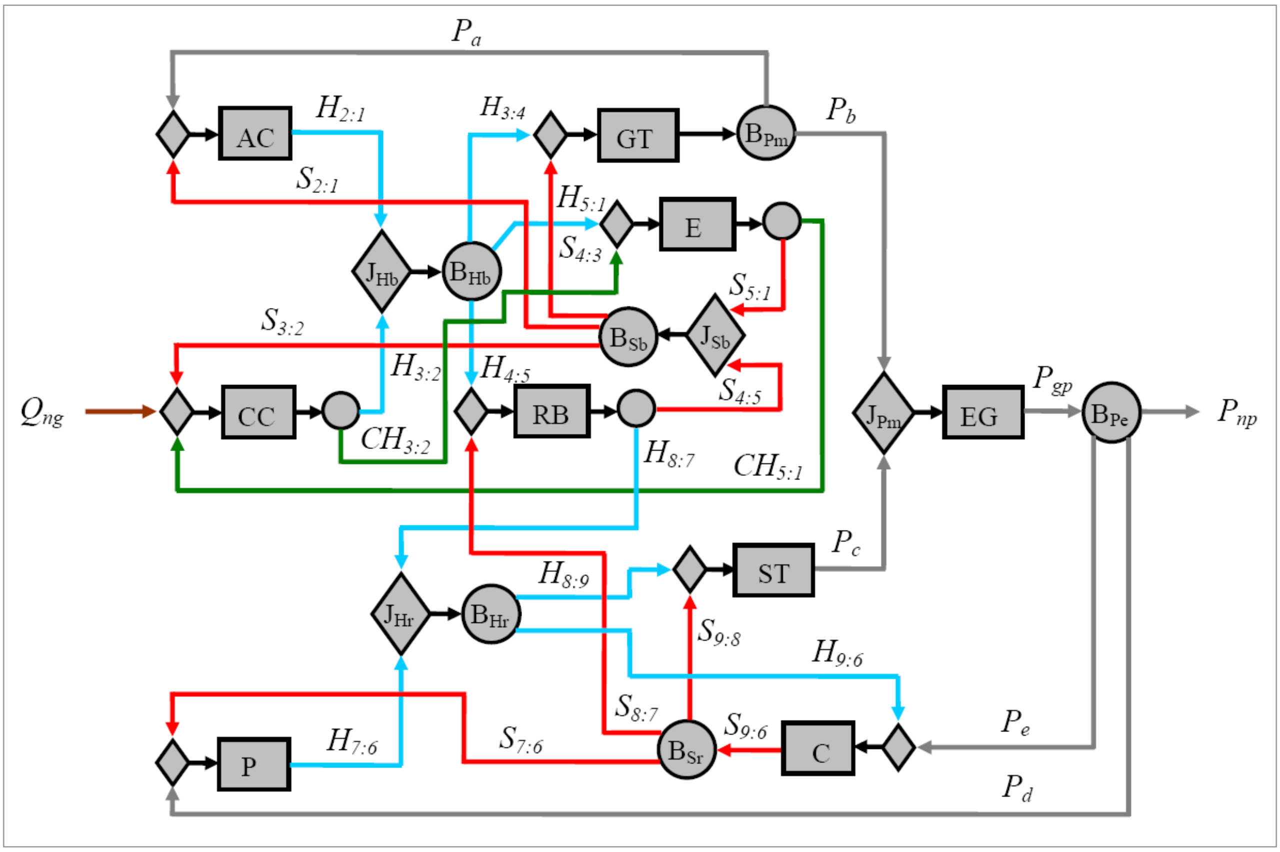

Figure 3. Productive Diagram of the Combined Cycle Power Plant according to the H&S Model

The H&S Model considers that the residue of a combined cycle power plant has two different components: (a) the chemical component that is originated in the combustion chamber, and (b) the physical (or enthalpic) component follows the working fluid entropy increase. The thermoeconomic approaches agree that the residues must be allocated where they have been originated. Thus, the chemical component of the residue is allocated to the combustion chamber, but the enthalpic component of the residue is charged to the productive units that increase de working fluid entropy.

4. COST AND EFFICIENCY

Table 4 shows the productive flows of the functional diagram of the Combined Cycle Power Plant, its values and its respective exergetic unit costs obtained by applying the H&S Approach.

According to Valero *et al.* (2006), irreversibility is the magnitude generating the costs. Consequently, in any irreversible cycle plant, the exergetic unit cost should be increased along the productive structure. Bearing this in mind, the exergetic unit costs of the internal flows and final products obtained by the H&S Model are consistent because they are greater than one, while the exergetic unit cost of the external fuel is equals one.

In H&S Model, the fuels and products used in the functional diagram in order to calculate costs coincide with the fuels and product which is used for calculating efficiency for both productive and dissipative units, as shown in Eq. (9).

$$\eta_{ufd} = \frac{\sum Y_{out}}{\sum Y_{in}} \tag{9}$$

This equation under any condition, for any subsystem, can be interpreted as, or coincide with the classical and well-known product-fuel definition of efficiency. The formula and the value of efficiency for each unit or subsystem of the functional diagram of the combined cycle power plant are shown in Tab. 5.

Table 4. Exergetic Unit Cost of the Productive Structure Flows of the Combined Cycle Power Plant

PRODUCTIVE FLOW	VALUE [kW]	EXERGETIC UNIT COST [kW/kW]
Q_{ng}	209,697.64	1.00
$E_{2:1}$	89,807.74	----
$E_{3:2}$	132,835.57	----
$E_{3:4}$ / $E_{4:5}$	164,998.07 / 44,334.68	----
$E_{5:1}$	13,310.56	----
$E_{7:6}$	122.25	----
$E_{8:7}$	35,396.38	----
$E_{8:9}$ / $E_{9:6}$	32,992.96 / 2,525.67	----
$S_{2:1}$ / $S_{3:2}$ / $S_{4:3}$	9,085.35 / 70,279.57 / 7,824.93	2.49
$S_{4:5}$	45,882.23	2.42
$S_{5:1}$	41,307.61	2.58
$S_{7:6}$ / $S_{8:7}$ / $S_{9:8}$	70.06 / 54,440.00 / 5,089.32	2.53
$S_{9:6}$	59,599.38	2.53
$H_{2:1}$	98,893.09	2.46
$H_{3:2}$	199,884.45	1.94
$H_{3:4}$ / $H_{4:5}$ / $H_{5:1}$	157,173.15 / 90,216.91 / 51,387.49	2.11
$H_{7:6}$	192.31	3.58
$H_{8:7}$	89,836.39	2.42
$H_{8:9}$ / $H_{9:6}$	27,903.64 / 62,125.05	2.42
$CH_{3:2}$	3,230.69	1.94
$CH_{5:1}$	3,230.69	2.58
P_a / P_b	98,893.09 / 58,280.05	2.24
P_c	27,903.64	2.88
P_{gp} / P_e / P_d	84,415.00 / 210.00 / 205.00	2.50
P_{np}	84,000.00	2.50

We can see in Tab. 5 that the efficiency of each unit (subsystem or component) is lower than 100%, including that of the dissipative one. By considering the chemical component of the residues entering in the combustion chamber ($CH_{5:1}$) as a fuel (Tab. 2) its efficiency is 71.72%. A very small difference in the efficiency (72.55%) of the combustion chamber is verified when this flow ($CH_{5:1}$) is neglected. The efficiency of the condenser and cooling water pump (Tab. 2) is 95.61% and the efficiency of the condenser alone is 95.93%. By using the H&S Model, the condenser efficiency in an actual steam power cycle will always be less than 100%, and this efficiency would only be 100% in case it were possible to transfer heat in the condenser at the same temperature, i. e., if the condensation temperature and the reference temperature were the same (in a reversible steam power cycle). Santos *et al.* (2009b) show that, by using the H&S Model in a reversible steam power cycle the condenser efficiency is 100%. In other words, by using the H&S Model, the efficiency of each component (including the dissipative one, such as the condenser) ranges from zero (for a totally irreversible process) to 100 percent (for a totally reversible process).

5. CLOSURE

This paper presented the H&S Model, which is a new and general methodology for calculating efficiency and cost in thermoeconomics, in which a direct link between the definition of fuel and product, the corresponding costing equations and the efficiency calculation is established.

The H&S Model is a new methodology since it is the first disaggregating the physical exergy into enthalpy and syntropy, in which the fuels and the products of each component are defined by taking into account all enthalpy, entropy and chemical exergy additions to and removals from all streams.

The H&S is a general methodology because it can be applied to any component, unit or subsystem, including the dissipative ones. Furthermore, it can be applicable to any thermodynamic cycle whose processes can be represented in the h-s plane, including to a reversible steam power cycle (Santos *et al.*, 2009b).

Table 5. Efficiency of the Device of the Productive Structure of the Combined Cycle Power Plant

DEVICE	EFFICIENCY	
	Formula	Value [%]
Air Compressor (AC)	$\frac{H_{2:1}}{S_{2:1}+P_a}$	91.59
Combustion Chamber (CC)	$\frac{H_{3:2}+CH_{3:2}}{Q_{ng}+S_{3:2}+CH_{5:1}}$	71.72
Gas Turbine (GT)	$\frac{P_a+P_b}{H_{3:4}+S_{4:3}}$	95.26
Recovery Boiler (RB)	$\frac{S_{4:5}+H_{8:7}}{H_{4:5}+S_{8:7}}$	93.82
Environment (E)	$\frac{S_{5:1}+CH_{5:1}}{H_{5:1}+CH_{3:2}}$	81.54
Pump and Motor (P)	$\frac{H_{7:6}}{S_{7:6}+P_d}$	69.91
Steam Turbine (ST)	$\frac{P_c}{H_{8:9}+S_{9:8}}$	84.57
Condenser and Pump (C)	$\frac{S_{9:6}}{H_{9:6}+P_e}$	95.61
Electric Generator (T-G)	$\frac{P_{gp}}{P_b+P_c}$	97.95
Combined Cycle Power Plant (CCPP)	$\frac{P_{np}}{Q_{ng}}$	40.06

The H&S Model establishes a direct link between the definition of fuel and product, the costing equations and the efficiency calculation once that the fuels and the products used in the functional diagram to calculate costs coincide with the fuels and product which is used for calculating the efficiency of both productive and dissipative units.

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