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Thermoeconomic Evaluation and Exergy Efficiency of Dissipative Components: A New Approach

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Abstract: Thermoeconomic evaluation aims at diagnosing the malfunction of energy systems and at optimizing their structure and performance. One of the main limitations of this approach is the adequate treatment of dissipative components, i.e., components where exergy is destroyed without gaining thermodynamically useful output (condensers, throttling valves, etc.). Such components are constituents of some energy systems and influence their overall thermal efficiency. This research introduces the use of a different criterion of exergy efficiency to assess dissipative components. In this case, it is possible to define the efficiency of dissipative components without the introduction of negentropy flows. As case study, a Rankine cycle discussed in literature is selected. The different approaches to evaluate dissipative components are applied and compared with the proposed one. Results show that with the proposed approach it is possible to evaluate dissipative components in isolation avoiding the inconsistencies resulting from the use of negentropy flows in the assessment. The introduction of negentropy flows also increases the complexity of the assessment.

Key words: Dissipative components, energy efficiency, thermoeconomic assessment increases, dissipative assessmentm, approach

INTRODUCTION

Thermoeconomics, a relative new science, combines concepts of the second law of thermodynamics with concepts of economic analysis in order to save energy, providing a rational way to assess costs of production processes (de Sousa and Olivera, 2001; Santos *et al*., 2016; Jodat, 2016; Valero *et al*., 2002). Basically, the thermoeconomic model is a set of equations describing the cost formation process of a system. The basis of the thermoeconomic evaluation is the exergy efficiency, traditionally defined (Lazzaretto and Tsatsaronis, 2006; Valero, 2006; Valero *et al*., 1994) as the ratio of the obtained product (s) to the invested resources (s) (fuel supply) of a process both measured in exergy units:

$$\text{Exergy efficiency} = \frac{\text{Product (s)}}{\text{Fuel (s)}} \tag{1}$$

In fact, exergy based assessment pinpoint the location, magnitude and costs of inefficiencies (Alkan *et al*., 2013). The physical cost of the process (Valero, 2006), represents the ratio of the resource (s) consumed (fuel supply) in a process to the product (s) obtained from it, both measured in exergy units:

$$\text{Physical cost} = \frac{\text{Fuel (s)}}{\text{Product (s)}} \tag{2}$$

And is thus, the inverse of the exergy efficiency. In thermal systems components are frequently encountered where a product cannot be defined in exergy terms according to the definition of product of thermoeconomy (e.g. condensers, throttling valves, etc.) (Sharifi and Khalilarya, 2016; Farshi *et al*., 2013). In these components exergy is destroyed without gaining a thermodynamically useful output. The usefulness of the dissipative components lies in their interactions with other productive units giving service to other productive components or to the overall system, to reduce operating costs or to fulfill emissions standards (Piacentino and Cardona, 2010a, b) allowing the system to have higher productivity and efficiency (). In every dissipative component, there is a decrease of energy between the input and the output but from the thermodynamic point of

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Corresponding Author: A. Sagastume Gutierrez, Industrial Engineering Program, Engineering Faculty, Universidad de la Costa, Barranquilla, Colombia view a product cannot be defined for them. Consequently for these components it is not possible to define the exergy efficiency as stated in Eq. 1 (Lazzaretto and Tsatsaronis, 2006). However, dissipative components are constituents of thermal systems and influence the overall efficiency of these systems. Therefore, dissipative components performance must be evaluated when the system is evaluated. According to Lozano and Valero (1993), one of the fundamental limitations of the theory of exergetic costs is the treatment of dissipative components. Accounting for the costs of dissipative components is a critical aspect of thermoeconomics (Piacentino, 2015; Luo *et al*., 2014) and the cost allocation principle of dissipative components is an open research line (Lourenco *et al*., 2015; Yao *et al*., 2012; Piacentino and Cardona, 2010a, b; Torres *et al*., 2008). The costs allocation issues of dissipative components are related with the exergy efficiency Eq. 1 defined in the exergetic analysis which is the base of thermoeconomy. One main limitation of thermoeconomy is that it is strongly based on the concept of efficiency (Piacentino and Cardona, 2010a, b) already proposed to expand the exergetic analysis to better assess dissipative components like condensers.

Dissipative components are usually assed by using negentropy based cost allocation which can introduce distortions in the assessment been inadequate in some cases (Piacentino and Cardona, 2010a, b). Torres *et al*. (2008) associated with exergy destruction, rather than the unit exergetic costs are determined. Although, the scope-oriented thermoeconomics avoids the introduction of fictitious exergetic products for dissipative components, the authors acknowledge the impossibility to strictly follow the cost formation process and to calculate the specific costs of each flow, been inadequate for the cost accounting of existing plants (Piacentino and Cardona, 2010a, b). The researchers point that the scope-oriented thermoeconomics is more suitable for the optimization of energy systems design.

In general, the evaluation of dissipative components represents a challenge for thermoeconomy. Researchers dealing with this topic have not reached agreement on the best way to proceed. The objective of this research is to introduce the evaluation criterion discussed by Gutierreza and Vandecasteele (2011) in the thermoeconomic assessment of dissipative components in thermal systems.

MATERIALS AND METHODS

Concept and definitions

Energy efficiency: A comprehensive evaluation of a thermal system requires an appropriate definition of the exergy efficiency and also a proper costing approach for each component of the system. Following Eq. 1, it is clear that an important step to find the exergy efficiency is the definition of the fuel and the product of the system. The product principle refers to the sum of all the exergy content to be considered in the outlet flows including the flows generated within the component ΣE_p; plus all the increases in the exergy content between the inlet and the outlet that contributes to the purpose of the component (i.e., the exergy additions to the respective material flows) (Lazzaretto and Tsatsaronis, 2006). Similarly, the fuel principle refers to all the exergy contents to be considered at the inlet of the component (including the exergy of energy flows supplied to the component); plus all the exergy decreases between the inlet and the outlet (i.e., the exergy removals from the respective material flows); minus all the exergy increases (between inlet and outlet) that does not contribute to the purpose of the component (Lazzaretto and Tsatsaronis, 2006).

In any case, regardless of the decisions made to define the product and the fuel for each component of the system, it should be stressed that, once defined they lead to unequivocally determined auxiliary equations.

Physical structure, productive structure and aggregation level : When thermoeconomics is applied to complex systems, it is necessary in order to allocate the costs, to define the aggregation level of the system, understanding as such the collection of subsystems which completely makes up the whole system. The complexity of the system (the flows representing the interactions between the components of the system) is represented in the physical structure and the interactions of the fuel and the product defined for the different components within the system are represented in the productive structure. A productive structure illustrates graphically the fuel and the product of each component and contributes in visualizing and better understanding the definitions of fuel and product and consequently the auxiliary costing equations obtained from the F- and P- principles. The way in which the productive structure is defined is a core element in the thermoeconomic analysis and the effectiveness of the costs obtained in the evaluation is strongly dependent on the definition of the productive structure. A good definition of the productive structure should describe in good depth and as simply as possible the purpose of the different components and flows described in the physical structure. In some thermoeconomic approaches the productive structure (Lazzaretto and Tsatsaronis, 2006):

- Introduces states that do not correspond to any real state of the system
- May lead to complex diagrams that often have little resemblance with the corresponding physical structure

As in a system the number of flows is larger than the number of components (m), the number of cost balances that can be formulated is insufficient to calculate all the costs of the system. Therefore, all exergy based costing approaches explicitly or implicitly require auxiliary equations for calculating the costs of flows. In order to obtain the auxiliary equations cost allocation rules (fuel-product rules) are needed (Lazzaretto and Tsatsaronis, 2006; Valero *et al.*, 1994).

The F-rule deals with the removal of exergy from an exergy flow within the considered component when for this flow the exergy difference between inlet and outlet is considered in the definition of the fuel. The P-rule refers to the supply of exergy to an exergy flow within the component (Lazzaretto and Tsatsaronis, 2006; Valero *et al.*, 1994).

F-rule: Each exergy unit removed from a fuel stream is removed at the average specific cost at which the removed exergy was supplied to the same stream in upstream components.

In this way, we obtain one auxiliary equation per each removal of exergy. Therefore, the number of auxiliary equations provided by the F principle equals the number of exiting exergy flows associated with the definition of the fuel for the different components.

P- rule: Each exergy unit supplied to any flow associated with the product is supplied at the same average cost at which the supplied exergy was removed from the same flow in upstream components.

Then, considering that each flow to which exergy is supplied corresponds to an exiting flow, the P principle provides $(n_P\text{-}1)$ auxiliary equations where (n_P) is the number of exiting exergy flows that are included in the product definition.

FP- rule: The energy of every fuel and every product is positive. In general for a given definition of fuel and product, all thermoeconomics methods result in similar auxiliary cost equations (Lazzaretto and Tsatsaronis, 2006).

RESULTS AND DISCUSSION

Evaluation of dissipative components: Kutas (1995) classified the dissipative components in three groups:

- Components which have as their primary function, heat exchange with the environment
- Components designed to accelerate otherwise spontaneous processes. The flow of matter in these components undergoes a reduction or no significant change in exergy and hence, the output cannot be expressed in terms of exergy
- Devices which are dissipative by design. These involve inherently irreversible processes such as throttling valve and stirring

Moreover, Kutas (1995) proposes to evaluate the performance of these components by using the efficiency defect:

$$1-\eta=\frac{E_D}{E_F} \tag{3}$$

This equation represents the Fraction of the Energy supply (E_F) that is lost through the Energy Destruction (E_D).

Although for dissipative components no product and thus no exergy efficiency can be defined, these components are constituents of thermal systems and influence their performance. However, the physical model is not enough to identify the cost formation process of the dissipative components. In order to deal with dissipative components within thermal systems different approaches have been developed in thermoeconomics.

Exergy model: All the costs associated with dissipative components are distributed among all other components served by it (Farshi *et al.*, 2013; Santos *et al.*, 2009; Lazzaretto and Tsatsaronis, 2006; Santos *et al.*, 2016). In this case, it is not possible to isolate the condenser and its individual influence on the overall thermal efficiency cannot be established.

Negentropy flows along with exergy flows are used: In this case, the product of the dissipative component is the negentropy $(T_O.(S\text{-}S_O))$. For example in a simple Rankine cycle the pump, the steam boiler and the turbine increase the entropy of the working fluid. This increase of entropy must be rejected to the environment through the condenser to close the cycle of the working fluid (Santos *et al.*, 2016; Santos *et al.*, 2009; Lozano *et al.*, 1993). In this case, the term defining negentropy $(T_0.\Delta S)$ is considered twice, once in the exergy flow and once in the negentropy flow. Therefore, the components where the entropy of working fluid is reduced are considered twice and their products are larger than their fuels (i.e., the exergy efficiency of these devices exceeds 100%) which can be interpreted as an inconsistency.

Enthalpy-negentropy model: This model is a modification of the energy-negentropy model combining negentropy with enthalpy flows to define the product of dissipative components (Santos *et al*., 2016; Lozano *et al*., 1993). Basically, this model research like the exergy-negentropy model, the difference being that the exergy values of the different flows are substituted by their enthalpy value. In this case as energy (a measure of quantity) rather than exergy (a measure of quantity and quality) is used the availability of the different flows to perform work remains unnoticed.

When the different methods using negentropy flows are applied to complex systems also the number of flows exceeds the number of components and it is also necessary to use cost allocation rules to obtain auxiliary equations. In this case, two criteria exist to obtain the auxiliary equations (Santos *et al*., 2016; Lozano *et al*., 1993).

Byproduct (B_p) criterion: This criterion considers that each subsystem can produce only one product and the main function of these productive units is to produce exergy. Thus, the negentropy flows exiting these subsystems are considered byproducts. Therefore, these byproducts (negentropy flows) assume the same unit cost as the product of the dissipative component which is the subsystem that only produces negentropy flows.

Equality (E_q) criterion: This criterion considers that the flows that exit the same productive unit are products which must have the same unit cost, since, they were produced under the same resources and, consequently, under the same costs. This is in accordance with one of the propositions of the exergetic cost theory, approach proposed by Valero *et al*. (1994).

In general, the inclusion of negentropy flows in the evaluation of thermal systems increases the complexity of the assessment. These models lead to complex diagrams with little resemblance with the corresponding physical structure of thermal systems. Also, additional auxiliary equations with different cost allocation rules are required.

Proposed thermoeconomic evaluation of dissipative components: The objective of this research is to apply the exergy efficiency proposed by Gutierreza and Vandecasteele (2011) to deal with the dissipative components within thermal systemswhen applying a thermoeconomic approach:

$$\eta = \frac{E_D^{UN}}{E_F} = 1 - \frac{E_D^{AV} + E^{loss}}{E_F} \tag{4}$$

In order to evaluate thermal systems Exergy Cost Accounting (ECA) (Valero *et al*., 1994) will be used. This method is based in the unit exergy consumption that is defined as the fuel required to produce a certain amount of a product and depends on the amount of exergy destroyed in the process. In thermoeconomics the exergy balance of a process is:

$$E_F - E_P = E_D \tag{5}$$

which allow to define the exergy efficiency as stated in Eq. 1. In this case, the fuel exergy required to generate one exergy unit of product is defined as the unit consumption k:

$$K = \frac{E_F}{E_P}\frac{1}{\eta} \tag{6}$$

Equation 6 does not apply for dissipative components because no product can be defined for them. Therefore, for dissipative components a different unit exergy consumption is defined. In this case, the exergy balance proposed by Gutierreza and Vandecasteele (2011) is used where the exergy supply to the process equals the sum of the avoidable and unavoidable exergy destruction plus the exergy loss to the surroundings:

$$E_F = E_D^{UN} + E_D^{AV} + E_{loss} \tag{7}$$

In Eq. 7, the purpose of the dissipative component in thermodynamics terms is to provide a service with its exergy consumption as close as possible to the value of the unavoidable exergy destruction E_D^{UN} which is irreversibly associated to the process. With this consideration the unit consumption for dissipative components is defined as:

$$K_{diss} = \frac{E_F}{E_D^{UN}} \tag{8}$$

Also from the ECA the unit exergy cost is defined as:

$$K^* = \frac{E_i^*}{E_i} \tag{9}$$

where is the exergy cost of the flow i. For dissipative components the exergetic cost E_D^{UN*} is defined as the amount of exergy per unit time required to ensure the unavoidable exergy destruction necessary to drive the dissipative process. Consequently, the unit exergy consumption for dissipative components is defined as:

$$K^{*}_{diss} = \frac{E^{UN*}_{D}}{E^{UN}_{D}} \quad (10)$$

The unit thermoeconomic cost (c*) of a physical flow is defined as the cost in monetary units of each exergy unit expended in producing that flow (Valero *et al.*, 1994). The thermoeconomic cost of a physical flow is defined as the quantity in monetary unit per second required to produce that flow (Valero *et al.*, 1994):

$$\Pi = c^{*} \cdot E^{*} = c \cdot E \quad (11)$$

The unit exergoeconomic cost is defined as the cost in monetary units per unit of exergy of the flow (Valero *et al.*, 1994):

$$c = c^{*} \cdot k^{*} \quad (12)$$

For dissipative components the Unit Thermoeconomic cost is defined as the cost in monetary units per exergy unit supplied to the dissipative component $(\Pi = c^{*}_{diss} . E^{UN*}_{D})$; the unit exergoeconomic cost is defined as the cost in monetary units per unit of unavoidable exergy irreversibly destroyed in the dissipative component $(\Pi = c_{diss} . E^{UN}_{D})$.

It is important to remark that the definitions presented in this research for the unit exergetic cost and exergy consumption and for the unit thermoeconomic cost and exergoeconomic cost are only applicable to dissipative components. For the components where it is possible to define a product we will continue to use the definitions of the exergy cost accounting methodology (Valero *et al.*, 1984).

Case study thermal power plant: The application of the proposed model is demonstrated here with the help of a thermal power plant based on a Rankine cycle analyzed by Lozano *et al.* (1993) (Fig. 1).

Figure 1 shows a simplified thermal power plant based on A rankine cycle. The plant is considered to be made up of four components: boiler, turbine-alternator, condenser-cooling water pump and boiler feed pump. In this case, the steam boiler is fed with 66815 kW of fuel producing 18.52 kg/sec of steam at 500°C and 60 bar. The steam is completely expanded in the turbogenerator to 39.04°C and 0.07 bar generating 20000 kW of net power. The pump is supplied with 138.2 kW of electric energy and increases the water pressure and temperature to 63 bar and 39.31°C. The thermodynamics properties of the complete Rankine cycle appear in Table 1.

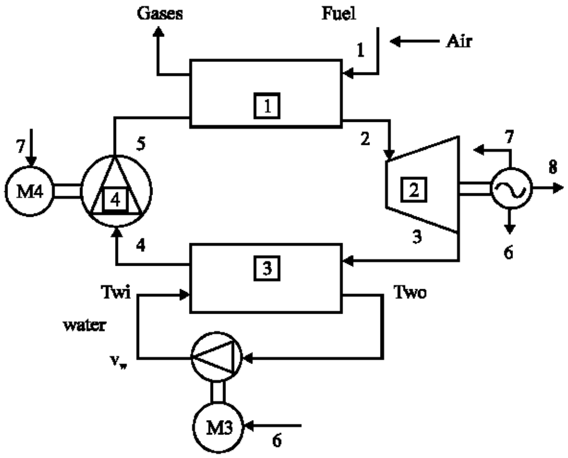

Fig. 1: Physical structure of the Rankine cycle

Table 1: Thermodynamic properties of the Rankine cycle

Flow	m (kg/sec)	T (°C)	P (bar)	E (kw)
1				66815.00
2	18.52	500.00	60.00	26074.00
3	18.52	39.04	0.07	2513.00
4	18.52	39.04	0.07	44.49
5	18.52	39.31	63.00	163.30
6				75.00
7				138.20
8				20000.00

The external economic costs of the process for the fuel amortization and maintenance is given by $c_1 \cdot E_1 + \xi \cdot (Z_1, Z_2, Z_3, Z_4)$, where the market price of the fuel energy is $c_1 = 8.93 \cdot 10^{-6}$ \$/kJ. The capital and maintenance factor is $\xi = 6.7 \cdot 10^{-9}$ and the purchase cost of the productive unit (Z_i) is (Lozano *et al.*, 1993):

$$Z_1 = 740.e^{\frac{P_1 - 28}{150}} . \left[1 + 5.e^{\frac{T_1 - 866}{10.42}}\right] . \left[1 + \left(\frac{0.45 - 0.405}{0.45 - \eta_1}\right)^{7}\right] . P_1^{0.8} \quad (13)$$

$$Z_2 = 3000. \left[1 + 5.e^{\frac{T_1 - 866}{10.42}}\right] . \left[1 + \left(\frac{1 - 0.953}{1 - \eta_2}\right)\right] . P_2^{0.7} \quad (14)$$

$$Z_3 = \frac{1}{T_0 . \varepsilon} . \left[217. \left(0.247 + \frac{1}{3.24.v_w^{0.8}}\right) . \ln\left(\frac{1}{1 - \varepsilon}\right) + 138\right] . \frac{1}{1 - \eta_\varepsilon} \quad (15)$$

$$Z_4 = 378. \left[1 + \left(\frac{1 - 0.808}{1 - \eta_4}\right)^{3}\right] . P_4^{0.7} \quad (16)$$

And the capital cost per unit of product is calculated by:

$$c_Z = \frac{\xi . Z}{P} \quad (16)$$

Exergy evaluation: The evaluation of the discussed power plant will be performed with the different methods discussed in previous sections:

- Exergy model (E-Model)
- Exergy and negentropy model (E&S-Model)
- Enthalpy and negentropy model (H&S-Model)
- Proposed exergy model (E&Diss-Model)

For each model a productive structure is defined. For the E&S-Model and the H&S-Model the same productive structure is used, the difference is that in the first case the flows of exergy are considered and in the other the flows of enthalpy.

Exergy model: In this case, the dissipative component is considered together with the component of the plant directly served by it. In order to apply the exergy model to the power plant the condenser is analyzed together with the turbine-alternator. In Fig. 2 the steam boiler (component 1) is fueled with flow $E_{0:1}$ and produces the flow $E_{1:6}$ which is fueled to the junction 6 that is also fueled by the flow $E_{4:6}$, produced in the pump (component 4) where is produced flow $E_{2:23}$ that fuels the turbine-alternator and the condenser that are considered as one subsystem (components 2 + 3). Components 2+3 produce the flow $E_{23:5}$ that in turn fuels the branching 5 where $E_{5:4}$ that feeds the pump and $E_{5:0}$ (Product of the cycle) are produced. The equations of the thermoeconomic model according to the E-Model are shown in Table 2 which also gives the productive and physical units considered for each cost equation.

Table 3 shows the values of the internal flows for the productive structure (Fig. 2) as well as their respective exergetic and monetary unit costs obtained with the E-Model. In this case, the physical and economic costs of the condenser are considered together with the turbogenerator as a single unit. With this model it is not possible to isolate the condenser to carry out a diagnosis of malfunctions or a local optimization. This is the limitation of the E-Model.

E&S-Model: Figure 3 shows the productive structure for this model. In this case, the steam boiler (component 1) is fueled with flows $E_{0:1}$ and S_1, producing flow $E_{1:8}$ that feeds the junction 8. The turbine-alternator (component 2) is fueled with flow $E_{5:2}$ and S_2, producing flow $E_{2:7}$ which in turn fuels branching 7 where flows $E_{7:0}$, $E_{7:3}$ and $E_{7:4}$ are produced. The condenser (components 3) is fueled with flow $E_{7:3}$ and $E_{5:3}$ producing flow S. Finally, the pump (component 4) is fueled with flow $E_{7:4}$ and S_4, producing flow $E_{4:8}$.

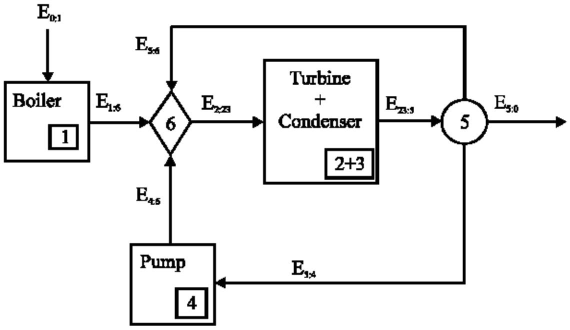

Fig. 2: Productive structure of the power plant for the exergy method

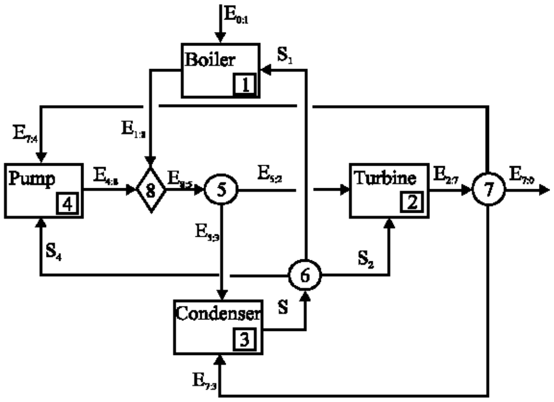

Fig. 3: Productive structure of the power plant for the exergy-negentropy method

Table 2: Equations of the thermoeconomic model for the E-Model

Productive unit	Physical unit	Equation
Boiler	Boiler	$c_{0:1}\cdot E_{0:1}+\xi\cdot Z_1 = c_{1:5}\cdot E_{1:5}$
	Turbine-alternator Condenser	$c_{2:23}\cdot E_{2:23}+\xi\cdot Z_2 = c_{1:0}\cdot E_{1:0}$
Waterpump	Water pump	$c_{5:4}\cdot E5:4 +\xi\cdot Z_4 = c_{4:6}\cdot E_{4:6}$
Branching 5		$c_{23:5}\cdot E_{23:5} = c_{5:0}\cdot E_{5:}+c_{5:4}\cdot E_{5:4}+c_{5:6}\cdot E_{5:6}$
Junction 6		$c_{1:6}\cdot E_{1:6}+c_{4:6}\cdot E_{4:6}+c_{5:6}\cdot E_{5:6} = c_{2:23}\cdot E_{2:23}$
Auxiliary equation		$c_{5:1} = 8.93.10^{-6}$
Auxiliary equation		$c_{5:0} = c_{5:4}$
Auxiliary equation		$c_{5:0} = c_{5:6}$

Table 3: Unit cost of the internal flows and products of the Rankine cycle according to the E-Model

Flow	Component flows	Value (kW)	k*	c (10^6 \$/kJ)
1:0	E_1	66815	1.000	8.9300
1:6	E_2-E_5	2590	22.58	22.147
2:23	E_2-E_4	26020	2.595	22.263
23:5	$E_6+E_7+E_8$	20213	3.341	27.199
5:0	E_8	20000	3.341	27.199
5:4	E_7	138	3.341	27.199
5:6	E_6	75	3.341	27.199
4:6	E_5-E_4	118	3.913	30.344

In the Rankine cycle, entropy is generated in the steam boiler in the turbine-alternator and in the

Table 4: Equations of the thermoeconomic model for the E&S-Model

Productive unit	Physical unit	Equation
Boiler	Boiler	$c_1.E_1+c_9.S_9+\xi.Z_1 = c_2.E_2-c_5.E_5$
Turbine-alternator	Turbine-alternator	$c_2.E_2-c_3.E_3+c_{10}.S_{10}+\xi.Z_2 = c_6.E_6+c_7.E_7+c_8.E_8$
Condenser	Condenser	$c_3.E_3-c_4.E_4+c_6.E_6+.Z_3 = c_9.S_9+c_{10}.S_{10}+c_{11}.S_{11}$
Water pump	Water pump	$c_5.E_5-c_4.E_4+\xi.Z_4 = c7.E_7+c_{11}.S_{11}$
Auxiliary equation		$c_5.E_5-E_5/E_4.c_4.E_4 = c_7+c_{11}$
Auxiliary equation		$c_1 = 2.10_{-6}\text{\$/kJ}$
Auxiliary equation		$c_2.E_2-E_2/E_3.c_3.E_3 = 0$
Auxiliary equation		$c_6.E_6-E_6/E_7.c_7.E_7 = 0$
Auxiliary equation		$c_7.E_7-E_7/E_8.c_8.E_8 = 0$
Auxiliary equation		$c_9.E_9-E_9/E_0.c_{10}.E_{10} = 0$
Auxiliary equation		$c_{10}.E_{10}-E_{10}/E_{11}.c_{11}.E_{11} = 0$

Table 5: Unit cost of the internal flows and products of the Rankine cycle according to the E-Model

Flow	Component flows	Value (kW)	k*	c (106 $/kJ)
0:1	E_1	66815.0	1.000	8.930
1:8	E_2-E_5	25902	2.834	24.087
4:8	E_5-E_4	118	3.944	30.580
8:5	E_2-E_4	26020	2.839	24.116
5:2	E_2-E_3	23563	2.839	24.116
5:3	E_3-E_4	2457	2.839	24.116
S	T_0• (S_3-S_4)	37661	0.192	1.465
S1	T_0•(S_2-S_5)	34292	0.192	1.465
S2	T_0•(S_3S_2)	3350	0.192	1.465
S4	T_0•(S_5S_4)	19	0.192	1.465
2:7	$E_6+E_7+E_8$	20213	3.341	27.199
7:3	E_6	75	3.341	27.199
7:4	E_7	138	3.341	27.199
7:0	E_8	20000	3.341	27.199

pump. This entropy must be rejected to the environment which is the function of the condenser providing the necessary negentropy for the cyclical operation of the system (Lozano *et al*., 1993). The equations of the thermoeconomic model according to the E&S-Model are shown in Table 4.

In Table 5, the unit exergetic cost of the negentropy flows is less than unity. This is because in this approach the product of the condenser is greater than its fuels. Since, the process is irreversible, its unit exergetic cost should be greater than unity, according to the second law of thermodynamics.

H&S-Model: This model is a modification of the E&S-Model. In this case, the negentropy flows are considered together with the enthalpy flows as a component of the exergy flows. The productive structure in this case is the same as used for the E&S-Model (Fig. 3). The main difference consists in the use of the flows of enthalpy instead of the flows of exergy. The equations of the thermoeconomic model according to the H&S-Model appear in Table 6.

Table 7 shows the results obtained with the H&S-Model. In this case, unlikely the E&S-Model, the exergetic unit cost of the negentropy flows is greater than unity.

Table 6: Equations of the thermoeconomic model for the H&S-Model

Productive unit	Physical unit	Equation
Boiler	Boiler	$c_{0:1}\cdot H_{0:1}+c_{S1}\cdot S_1+\xi\cdot Z_1 = c_{1:8}\cdot H_{1:8}$
Turbine-alternator	Turbine-alternator	$c_{5:2}\cdot H_{5:2}+c_{S2}\cdot S_2+\xi\cdot Z_2 = c_{2:7}\cdot H_{2:7}$
Condenser	Condenser	$c_{5:3}\cdot H_{5:3}+c_{7:3}\cdot H_{7:3}+\xi\cdot Z_3 = c_S\cdot S_S$
Water pump	Water pump	$c_{7:4}\cdot H_{7:4}+c_{S4}\cdot S_4+\xi\cdot Z_4 = c_{4:8}\cdot H_{4:8}$
Branching 5		$c_{8:5}\cdot H_{8:5} = c_{5:2}\cdot H_{5:2}+c_{5:3}\cdot H_{5:3}$
Branching 6		$c_S\cdot S = c_{S1}\cdot S_1+c_{S2}\cdot S_2+c_{S4}\cdot S_4$
Branching 7		$c_{2:7}\cdot H_{2:7} = c_{7:0}\cdot H_{7:0}+ c_{7:3}\cdot H_{7:3}+c_{7:4}\cdot H_{7:4}$
Junction 8		$c_{1:8}\cdot H_{1:8}+c_{4:8}\cdot H_{4:8} = c_{8:5}\cdot H_{8:5}$
Auxiliary equation		$c_{5:2} = c_{5:3}$
Auxiliary equation		$c_{0:1} = 8.93.10_{-6}$
Auxiliary equation		$c_{S1} = c_{S2}$
Auxiliary equation		$c_{S1} = c_{S4}$
Auxiliary equation		$c_{7:0} = c_{7:3}$
Auxiliary equation		$c_{7:0} = c_{7:4}$

Table 7: Unit cost of the internal flows and products of the Rankine cycle according to the H&S-Model

Flow	Component flows	Value (kW)	k*	c (106$/kJ)
0:1	H_1	66815	1.000	8.930
1:8	H_2-H_5	60194	2.836	24.104
4:8	H_5-H_4	137	3.790	29.684
8:5	H_2-H_4	60331	2.839	24.116
5:2	H_2-H_3	20213	2.839	24.116
5:3	H_3-H_4	40118	2.839	24.116
S	T_0• (S_3-S_4)	37661	3.030	25.582
S1	T_0• (S_2-S_5)	34292	3.030	25.582
S2	T_0• (S_3-S_2)	3350	3.030	25.582
S4	T_0•(S_5-S_4)	19	3.030	25.582
2:7	$E_6+E_7+E_8$	20213	3.341	27.199
7:3	E_6	75	3.340	27.199
7:4	E_7	138	3.341	27.199
7:0	E_8	20000	3.341	27.199

When the unit costs (exergetic and monetary) of the final products obtained by the E-Model (Table 2) are compared to these obtained by the H&S-Model (Table 5), the results are similar. In this case, the costs associated with the condenser are distributed among the negentropy flows.

E&Diss-Model: This model is a modification of the E-Model. In this case, the condenser is isolated from the turbine-alternator in the evaluation. Figure 1 shows the productive structure of the proposed model. In Fig. 4, flow $E_{0:1}$ fuels the steam boiler (component 1) where flow $E_{1:7}$ which fuels junction 7 is produced. Junction 7 is also fueled by flows $E_{4:7}$, produced in the pump (component 4) and a fictitious flow resulting from the condenser (component 3) operation which allows to close the cycle. Junction 7 produces flow $E_{7:5}$ that fuels branching 5 which produce flow $E_{5:2}$ and flow $E_{5:3}$. Flow $E_{5:2}$ fuels the turbine-alternator (component 2) that in turn produces flow $E_{2:6}$ that fuels branching 6. Branching 6 produce flows $E_{6:0}$, $E_{6:3}$ and $E_{6:4}$. Flows $E_{5:3}$ and $E_{6:3}$ fuel the condenser while flow $E_{6:4}$ fuels the pump where flow $E_{4:7}$ is produced. The system of equations according to the E&Diss-Model is shown in Table 8.

Table 8: Equations of the thermoeconomic model for the E&Diss-Model

Productive unit	Physical unit	Equation
Boiler	Boiler	$c_1 \cdot E_1 = c_2 \cdot E_2 - c_5 \cdot E_5$
Turbine-alternator	Turbine-alternator	$c_2 \cdot E_2 - c_3 \cdot E_3 = c_6 \cdot E_6 + c_7 \cdot E_7 + c_8 \cdot E_8$
Condenser	Condenser	$c_3 \cdot E_3 - c_4 \cdot E_4 = C_{cond} \cdot E^{UN}{}_{D\,cond}$
Water pump	Water pump	$c_7 \cdot E_7 = c_5 \cdot E_5 - c_4 \cdot E_4$
Auxiliary equation		$c_5 \cdot E_5 - E_5/E_4 \cdot c_4 \cdot E_4 = Z_4$
Auxiliary equation		$c_1 = 2 \cdot 10^{-6}$\$/kJ
Auxiliary equation		$c_2 \cdot E_2 - E_2/E_3 \cdot c_3 \cdot E_3 = 0$
Auxiliary equation		$c_6 \cdot E_6 - E_6/E_7 \cdot c_7 \cdot E_7 = 0$
Auxiliary equation		$c_7 \cdot E_7 - E_7/E_8 \cdot c_8 \cdot E_8 = 0$

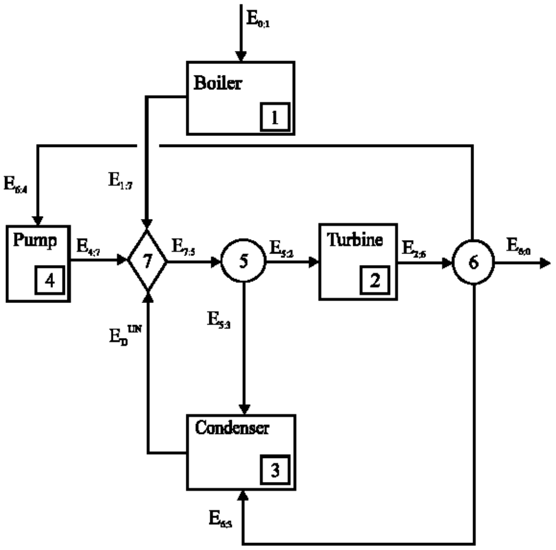

Fig. 4: Productive structure of the power plant for the E&Diss-Model method

According to Eq. 4 in order to calculate the efficiency of the condenser it is necessary to define the value of unavoidable exergy destruction. In general, this value can be determined from the operation conditions established by design or from applying an optimization technique to the component. This value must be carefully defined because the exergetic and thermoeconomic costs of the condenser depend on it. If a value smaller than the real limit of the component performance is selected, the efficiency will be lower than the real performance of the component, showing an unrealistic potential to improve the efficiency. On the other hand, if a value higher than the component limit is selected the efficiency will be high and existing saving opportunities will remain unnoticed. In this case, the value of unavoidable exergy destruction in the condenser is taken from the optimization of the Rankine cycle developed by Lozano *et al*. (1993): $E^{UN}_{D\,cond} = 1298$ kW.

The highest exergetic and exergoeconomic costs in this case, correspond to the unavoidable exergy destruction to dissipate the residual flow at the condenser. This is explained because the unavoidable exergy destruction is about 53% of the current exergy destruction, meaning that the system is destroying too much exergy to dissipate the residual flow. This highlights the benefit of the proposed method that allows assessing dissipative components in isolation. This approach includes all the benefits of the E-Model and overcomes its main limitation regarding the isolation of dissipative components.

Table 9: Unit cost of the internal flows and products of the Rankine cycle according to the E&Diss-Model

Flow	Component flows	Value (kW)	k*	c (10^6 \$/kJ)
0:1	E_1	66815	1.000	8.930
1:7	E_2-E_5	25902	2.580	22.147
4:7	E_5-E_4	118	3.913	30.344
7:5	E_2-E_4	26020	2.866	24.325
5:2	E_2-E_3	23563	2.866	24.325
5:3	E_3-E_4	2457	2.866	24.325
E_D^{UN}	-	1298	5.617	42.905
2:6	$E_6+E_7+E_8$	20213	3.341	27.199
6:0	E_8	75	3.341	27.199
6:3	E_6	138	3.341	27.199
6:4	E_7	20000	3.341	27.199

CONCLUSION

Since, themoeconomics is based on the concept of efficiency, a product must be defined to assess the efficiency of a component which is not possible for dissipative components. The most accepted approach used to assess dissipative components is the introduction of negentropy flows in the productive structures to define a product for dissipative components. This approach increases the number of flows to consider in the productive structure. Moreover, the product of dissipative components is higher that their fuel, resulting in unit exergy costs lower than the unity which is an inconsistency. This inconsistency is the result of using different thermodynamic properties (i.e., exergy and negentropy: the negentropy flow of dissipative components is higher than its exergy flow) for the exergy cost accounting of thermodynamic systems.

The unavoidable exergy destruction can be used to define the exergy efficiency of dissipative components and thus the unit exergy cost of dissipative components. With this approach the exergy cost accounting is developed using exergy flows (i.e., exergy and exergy destruction), thus avoiding the inconsistencies resulting from the introduction of negentropy flows. With this approach is not necessary to define the product for dissipative components. This allows the isolation of dissipative components in the thermoeconomic evaluation of thermal systems without the need of introducing negentropy flows. Moreover, fictitious flows are kept to a minimum (i.e., since, there is only one value of unavoidable exergy destruction per dissipative, there is only one fictitious flow per dissipative unit) compared to the introduction of negentropy flows (i.e., as many fictitious flows as productive components are served by a dissipative component are introduced). Thus, the evaluation remains as simple as possible.

NOMENCLATURE

c^* = Unit thermoeconomic cost
E^* = Exergy expense
k^* = Unit exergy cost
v_w = Velocity of the cooling water of the condenser
c = Unit exergoeconomic cost
E = Exergy
k = Unit exergy consumption
P = Pressure
P = Product
S = Negentropy
T = Temperature
Z = Purchase cost of productive unit

Greek letters:

η = Efficiency
Π = Thermoeconomic cost
ε = Thermal effectiveness of the condenser
ξ = Capital and maintenance factor

Superscript:

UN = Unavoidable
AV = Avoidable

Subscript:

cond = Condenser
F = Fuel
P = Product
D = Destruction
loss = Loss
diss = Dissipative
1 = Boiler
2 = Turbogenerator
3 = Condenser
4 = Water pump

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