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Scope-Oriented Thermoeconomic analysis of energy systems. Part I: Looking for a non-postulated cost accounting for the dissipative devices of a vapour compression chiller. Is it feasible?

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ABSTRACT

The authors of the main thermoeconomic methodologies developed in the last two decades have recently focused their efforts on the analysis of dissipative devices, i.e. those components whose productive purpose is neither intuitive nor easy to define. Coherent and unanimously accepted cost structures have been identified for dissipative components, while ambiguities still exist as concerns the cost allocation principles to be adopted. Being this aspect evidently cost-influencing, accurate analyses focused on the *subjectivity of results* are needed. This paper is structured in two parts. In the Part I an in-depth study of some critical issues arising from the thermoeconomic analysis of a 1.5 MW_c industrial chiller is presented. The attention is focused on the role of the condenser and the throttling valve (considered as a limit condition for an expander with very low isentropic efficiency); marginal analyses performed on the condensation pressure and the isentropic efficiency of the expander provided elements to assess the rational of the cost allocation principles. Attempting to refugee any cost allocation criterion based on postulates, the concept of *Scope* is identified as a possible non-arbitrary basis for cost allocation in dissipative devices; consequently, a new topology is defined, abandoning the conventional classification between dissipative and productive units, toward a new distinction between *Product Makers* and *Product Takers* functions. The proposed approach is applied to the cost accounting of the examined chiller, revealing inadequate and less explicative than the conventional thermoeconomic approaches due to its “intrinsically differential” nature. In the Part II of this paper the proposed approach will be applied to an Optimization problem, revealing very flexible and insightful.

1. Introduction

Thermoeconomic analysis of energy systems has been covering a primary role among the emerging disciplines in the field, due to the in-depth understanding it provides as concerns the interactions between components and with the environment. Several methodologies have been proposed, some of them [1,2] being oriented to perform cost accounting (CA) of existing energy systems, i.e. to properly allocate the cost of the resources consumed on the intermediate and final products of the plant, others [3–5] focusing on the Optimization problem (TO), i.e. attempting to make the energy analyst capable to detect trade-off values for the main design variables. Thermoeconomic CA has been indicated as a rational premise to price assignment in multi-products components, while TO has been facing some difficulties related to the complexity of the analytical relations between physical design parameters (temperatures, pressures, flow rates, etc.) and thermoeconomic key-variables like *efficiencies* and *distribution ratios*. As a consequence, decomposing the overall energy system in subsystems to be optimized separately [6,7] is usually the best strategy to make TO to represent a real alternative to other optimization techniques like evolutionary algorithms.

New horizons have been recently opened by thermoeconomics as concerns diagnosis and prognosis of malfunctions for energy systems operating at off-design conditions [8,9]; finally, peculiar aspects related to thermoeconomics of variable demand energy systems have been recently addressed [10,11]. After this brief overview on the main currencies as concerns research activities in thermoeconomics, it is opportune to discuss more in details the problems of the objectiveness in cost allocation rules, the relation between average and marginal costs and the cost accounting of dissipative devices. The two first items, strongly interrelated, were developed by Prof. A. Valero and his research group in several contributions [12,13], which ultimately led to the creation of a Structural Theory of Thermoeconomics. In order to subtract the CA methodologies, and in particular the cost allocation rules, to the “bad parent” of subjectivity, a detailed analysis showed that,

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Nomenclature

A	heat exchange area (m^2)
AESC	Average Exergy Saving Cost (€/kW$_{\text{ex}}$)
b	specific exergy (kJ/kg)
B	rxergy flow (kW)
B^*	exergetic cost (kW)
CA	cost accounting
$\bar{c}_p$	average specific heat value (kJ/kg K)
$\Delta\text{Cost}^{\text{cond}}_{\text{PT funct}}$	cost unbalance at the PT function of the condenser
CHP	combined heat and power
COP	coefficient of performance
EE	Embodied Exergy Consumption Rate (kW$_{\text{ex}}$)
F	fuel (kW$_{\text{ex}}$)
h	specific enthalpy (kJ/kg)
k^*	unit exergetic cost, dimensionless
I	irreversibility
$\dot{m}$	mass flow rate (kg/s)
P	product
PM, PT	*Product Maker* and *Product Taker*
q_4	specific cooling effect at the evaporator (kJ/kg)
r	latent heat of vaporisation (kJ/kg)
s	specific entropy (kJ/kg K)
SOT	Scope-Oriented Thermoeconomics
T	temperature
TO	thermoeconomic optimization
TV	throttling valve
U	thermal transmittance (kW/m^2 K)
x	vapour quality
W	shaft work
Z	capital cost (€)

Vectors and matrices

$\mathbf{x}$	vector of physical design variables

Special symbols

$(\Delta X)_{T_3>T_0}$	variation in the parameter X due to the assumption of a $T_3 > T_0$
$(X)_{T_3=T_0}$	X evaluated at $T_3 = T_0$

Greek letters

$\delta^{\text{component}}_{\text{cause}}$	cost associated with an exergy destruction
γ	cost distribution ratio at the throttling valve
κ	unit exergy consumption
η_{is}	isoentropic efficiency
Π_{Carnot}	carnot factor of heat/cold at $T \neq T_0$
ω	equivalent exergy cost/saving (kW$_{\text{ex}}$)

Superscripts

comp	compressor
cond	condenser
opt	optimal value
p,T	mechanical and thermal fractions of exergy
exp	expander
throttle	at the throttling valve

Subscripts

0	at reference, dead state conditions
cw	cooling water
dest	destroyed
l	liquid
marg	marginal
prod	associated with the product
sat	saturation conditions
v	specific volume (m^3/kg)
v	vapour

under particular restrictions, average and marginal costs coincide and that the well-known *propositions* of Symbolic Exergoeconomics [1] may be directly derived by the differential equations of a Lagrangian cost function; the restrictions refer to the assumption of Eulerian characteristic equations (linear in design parameters such as *unit exergy consumptions*, *distribution ratios*, etc.) for each component, both as concerns the exergy and capital resources entering it. Regardless of the viability of these restrictions (which might introduce relevant approximations, especially as concerns the capital resources of components when examined over a wide range of sizes), a limit of this approach is that it is strongly based on the concept of efficiency, as recognized in [13]. Once underlined the great merit of the above-referred works in looking for objectivity, it is evident that margins for subjective approaches (and, consequently, results) still exist in all the cases where the productive purpose of any plant component is either ambiguous or controversial.

This is the case of the energy systems that include dissipative devices, i.e. those components with a non-clear exergetic product, which reject to the environment some residue flows (with a non-null exergy content) or “destroy exergy without gaining something thermodynamically useful”; when considered in isolation from the rest of the plant, their productive purpose cannot be identified, because the dissipative components are included in the lay-out to serve productive components, to reduce the operating costs or to enable the system to fulfil emission standards [14].

Since the origins, scientists have recognized that allocating the entire exergy loss associated with a residue flow to the dissipative device where it is located would introduce relevant distortions, and that a criterion is needed for the allocation of a *residue* on the components that have generated it. In closed-loop cycles a reasonable criterion consists of using a function, called *negentropy*, which is obtained multiplying the entropy variation through a component by the ambient temperature T_0 [15]; the rational of this approach, very suitable for the allocation of thermal exergy loss in the condenser of steam power plants or vapour compression chillers, is based on two main facts:

- in closed-loop cycles, the objective of the condenser can be identified with “dissipating heat and reducing the entropy of the working fluid (acquired throughout the cycle either by entropy generation due to irreversibility or by heat exchanges) to close the cycle;
- the Gouy–Stodola theorem expresses the exergy destruction as a linear function of entropy generation. Consequently, the use of negentropy is coherent with the fact that the lower is the exergetic efficiency of a component, the higher the fraction of the exergy lost with the residue flow that is “paid” by the component.

Finally, in a recent work [16] a detailed analysis was carried out to provide an effective representation of the interactions between the productive and the dissipative parts of a component; it was shown that the production of a residue concurs to achieve a lower “productive efficiency”, being the residue produced functionally equivalent to an additional fuel consumption. Once clarified the rational approach for the internalization of residue flows in the CA analysis, the authors of the above cited paper underlined that “the choice of the best residue distribution among possible alternatives is still an open research line”. The relevance of the topic is evi-