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Scope Oriented Thermoeconomic analysis of energy systems. Part II: Formation Structure of Optimality for robust design

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ABSTRACT

This paper represents the Part II of a paper in two parts. In Part I the fundamentals of Scope Oriented Thermoeconomics have been introduced, showing a scarce potential for the cost accounting of existing plants; in this Part II the same concepts are applied to the optimization of a small set of design variables for a vapour compression chiller. The method overcomes the limit of most conventional optimization techniques, which are usually based on hermetic algorithms not enabling the energy analyst to recognize all the margins for improvement. The Scope Oriented Thermoeconomic optimization allows us to disassemble the optimization process, thus recognizing the Formation Structure of Optimality, i.e. the specific influence of any thermodynamic and economic parameter in the path toward the optimal design. Finally, the potential applications of such an in-depth understanding of the inner *driving forces* of the optimization are discussed in the paper, with a particular focus on the sensitivity analysis to the variation of energy and capital costs and on the *actual operation-oriented* design.

1. Introduction

Thermoeconomic approaches to the optimization of energy systems have been developed since the seventies and earlier, due to the pioneristic contributions by Tribus, Evans and El-Sayed. In the early eighties a group of scientists developed a reference optimization problem, the well known *CGAM problem* [1], in order to compare and reciprocally validate their methodologies for thermoeconomic optimization; the research on thermoeconomics received a strong impulse, with hundreds research articles and some insightful review articles published in little more than two decades. The Thermoeconomic Functional Approach [2] is based on a functional analysis of the system and on the adoption of the Lagrange multipliers method: a set of non-linear equations is usually obtained, which may be solved by numerical techniques. Approaches based on the Lagrange multipliers method are also used for the optimization of energy systems by the Exergetic Cost Theory [3] and the Engineering Functional Analysis [4]; while the former approach has revealed particularly explicative for the cost accounting of existing systems [5] and has posed the bases for the modern thermoeconomic diagnosis of malfunctions [6], the latter still identifies the thermoeconomic optimization as a best application. A different approach was proposed in [7], which consists of an iterative procedure based on exergoeconomic variables like the *relative cost difference* and the *relative exergetic efficiency difference*, whose values suggest to the energy analyst the best path toward the optimal design. Actually, however, thermoeconomic optimization is not as widely used as it could be expected. The obstacles encountered in real world applications are related to:

1. The complexity of the analytical model in case of complex layouts. This aspect often induces the plant designer to adopt thermoeconomic approaches more for optimization at single component/subcomponent level [8,9] than at system level.
2. The scarce benefits that could be exploited, which are related to the abatement of the computational resources consumed due to the identification of more accurate solution search directions.
3. The presence of several available alternatives represented by large scale optimization techniques like linear and non-linear programming and evolutionary search algorithms.

As concerns the optimization algorithms, a main distinction can be made between those which use feasible points only during the iterations and those which explore also regions outside the feasibility space. Several applications of both typologies can be found in the literature [10–12]; most of them, however, share a common limit represented by the hermetic behaviour with respect to the optimization problem.

Let us clarify this concept. When the analyst introduces the objective function and the constraints (either represented by equalities and inequalities), the optimal solution is determined;

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Nomenclature

AESC	average exergy saving cost [€/kW$_{ex}$]
B, b	exergy flow [kW] and specific exergy content [kJ$_{ex}$/kg]
B^*	exergetic cost [kW]
c	unit exergoeconomic cost [€/kWh]
$d\text{Cost}_{PT}^{cond}$	cost unbalance term at the PT function of the condenser
EE	embodied exergy
F	fuel [kW]
h	specific enthalpy [kJ/kg]
$\bar{k}$	marginal unit exergetic cost, dimensionless
$\dot{m}$	mass flow rate [kg/s]
P	product [kW]
PM, PT	Product Maker and Product Taker
s	specific entropy [kJ/kgK]
SOT	Scope Oriented Thermoeconomics
T	temperature [K, °C]
T_0	ambient temperature
TV	throttling valve
W	Shaft work
Z, z	capital cost [€] and unit capital cost

Greek letters

Γ	design option
ψ	generic path between two design options
Δ	variation in the value of the associated magnitude
$\delta_{cause}^{component}$	cost associated with an exergy destruction in a certain component, related to a specific cause
η	isoentropic efficiency

Superscripts

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

Subscripts

cold uses	cooling exergy delivered to the final users
dest	destroyed
economic	economically dominated effect
marg	marginal
thermod.	thermodynamically dominated effect
4thr	final point of an irreversible expansion occurring in a TV

also, depending on whether the designer has a full knowledge of the optimization algorithm, he could eventually associate to the solution some additional informations concerning its reliability and stability. In most cases, however, the algorithm does not enable the analyst to recognize all the margins for improvement; this is a great limit because in a typical optimization problem we have both physical constraints, with an intrinsically binding nature, and "auxiliary" constraints (related to socio-economic or environmental issues) which could eventually be removed at a non-null cost. Hence, providing the energy analyst with an in-depth understanding of the inner *driving forces* of the optimization is a premise for the implementation of enhanced optimization processes.

In this paper, representing the 2nd part of a paper in two parts, a very explicative approach to thermoeconomic optimization will be presented, which is essentially based on the Scope Oriented Thermoeconomic (SOT) method introduced in [13]. In the Part I the SOT approach revealed inadequate for the cost accounting of existing plants, due to its intrinsically "marginal" (i.e. differential) syntax; with reference to the same case study adopted in Part I, a large potential will emerge in this paper for the optimization of plant design. After having introduced the marginal approach to SOT analysis and having applied it to the optimization of a small set of design variables, the potential applications will be discussed.

2. The case study and the optimization problem

The energy system examined in this paper is the same 1.5 MW$_c$ vapour compression chiller presented in [13], operating with R134a as working fluid; its schematic lay-out is shown in Fig. 1. As observed in [13], the scheme includes a generic component named "expander", whose behaviour is assumed to range from the irreversibility-dominated expansion occurring in a Throttling Valve (TV, which obviously covers almost the totality of the practical applications) to the isentropic efficiency occurring in an ideal turbine ($\eta_{is}^{exp} = 1$), which represents a reference thermodynamic condition in the Carnot inverse cycle. Just few practical applications of active expanders have been proposed [14,15], achieving very low exergetic efficiencies; however, coherently with the methodological purpose of this paper, the technological/economical feasibility of the component "turbine" will not be discussed here.

The optimization problem is formulated as follows: basing on the cost figures for purchasing and installing each component given in Appendix A, let us determine the values of the condensation temperature T_3 and the isentropic efficiencies η^{comp} of the compressor and η^{exp} of the expander that minimize the *Total Exergetic Cost* (TEC) of the 1.5 MW$_c$ cooling energy rate delivered to the user at a −20 °C temperature. The concept of TEC will be explained in the next section. As concerns the boundary conditions, which in terms of mathematical modelling represent the constraints, we assume:

- Absence of subcooling of the condensate (i.e. saturated liquid at state 3) and absence of superheating of the vapour (i.e. dry saturated vapour at state 1).
- Fixed 1.5 MW$_c$ cooling capacity.
- Absence of irreversibility due to heat transfer across a finite ΔT at the evaporator, that means $T_{1c} = T_{2c} \cong T_1$. This hypothesis is evidently non-realistic. It is introduced because of the explicative purpose of this paper, aimed at offering an innovative representation of the interactions between the design variables. As the effect of exergy destruction due to the heat transfer

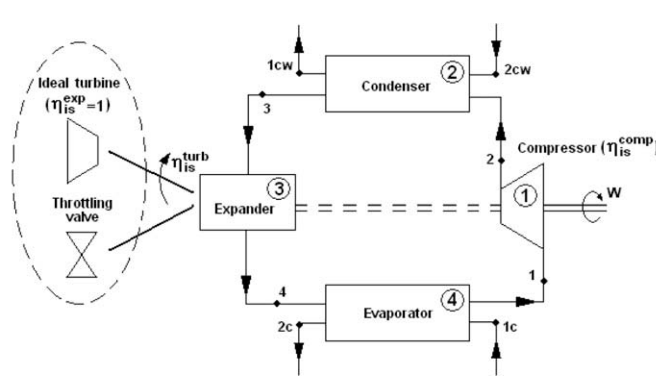

Fig. 1. Simplified scheme of the examined refrigeration cycle.