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Application of advanced thermodynamics, thermoeconomics and exergy costing to a Multiple Effect Distillation plant: In-depth analysis of cost formation process

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HIGHLIGHTS

- A forward feed Multiple Effect Distillation plant is examined.
- An exergy analysis is performed at single effect and at subprocess levels.
- A thermoeconomic model is developed, that includes "residue" exergy flows.
- Specific costs are calculated for each chemical and thermal exergy flow.
- Asymmetries are found in the unit cost of distillate produced in different effects.

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ABSTRACT

The high thermal energy consumption per m^3 fresh water is one of the main barriers to the spread of thermally driven desalination processes and has limited their use to applications in countries with high reserves of fossil fuels or to specific technological solutions like dual purpose cogeneration plants and solar desalination systems. Being energy conversion efficiency a major issue to improve the performance of thermally driven desalination plants, thermoeconomic analysis has been attracting the efforts of researchers for the identification of margins for process improvement. In this paper a rigorous exergy and thermoeconomic analysis is presented for an 8 effect forward feed Multiple Effect Distillation plant, based on models developed in Engineering Equation Solver. The innovative contribution lies in the detailed methodological formulation with explicative notes on the main assumptions and in the high level of disaggregation used, which allows us to follow each specific subprocess and thus to acquire an in-depth understanding of the whole cost formation process. The results indicate that the monetary value associated with the physical and chemical exergy flows highly vary throughout the plant and that the contribution to the final cost of fresh water is higher for the distillate produced in the last effects.

1. Introduction

The increasing concern for fresh water scarcity in many areas of the world has stimulated a growing interest for seawater desalination technologies. Looking at the currently installed desalination capacity, at a global level, several factors have contributed to make mechanically-driven processes, and Reverse Osmosis (RO) in particular, cover a largest fraction: among these factors, the recent advances in membrane technologies, the low power consumption per unit product (especially when low salinity seawater or brackish water is to be processed) and the modular plant structure may be enumerated. Thermal Desalination Processes (TDPs), however, continue to play a relevant role in the worldwide desalination market, in spite of their high energy consumption per unit product; in fact, although dedicated combustion of fossil fuel to drive the process represents an economically viable option only in low-fuel-price scenarios [1,2], relevant efforts are being made at research and industrial level to improve the design and energy efficiency of thermal desalination processes [3]. Among the principal TDPs, Multi-Stage Flash and Multiple Effect Distillation (MED) plants may be indicated. Main frontiers for future spread of thermal desalination plants are represented by:

– Integration of TDPs as bottoming units of a power generation system, into a "dual purpose" or "cogeneration of electricity and water" configuration that can be either used for large-scale plants like combined cycles or gas turbines [4] or in small- to medium-scale plants including reciprocate engines [5] or micro-turbines. In such configurations the high grade (i.e. high exergy content) heat produced by fuel combustion is firstly converted into mechanical/electrical power; then, the low grade heat released is used to drive

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the desalination process, leading to a more rational design of the whole energy conversion chain;
- Integration of TDPs with renewable energy sources could allow for exploitation of low to medium grade heat produced, for instance, by solar thermal collectors, either plate or concentrating (parabolic through, dish or power tower) type [6].

A main instrument for the gradual improvement of MED design is represented by the use of reliable mathematical models. Several steady state models are available in literature: in the milestone book by Ettouney and El-Dessouky [7] both a simplified and a detailed mathematical model were provided, together with accurate empirical correlations for thermophysical properties and heat transfer coefficients of heat exchangers under fouled and clean conditions. Some other recent contributes provide accurate models for complete schemes, including the Thermal Vapour Compression section [8] or considering peculiar evaporator arrangements [9].

Along the last two decades several studies have also proposed thermoeconomic approaches to the problems of design, operation and maintenance of thermal desalination systems. Thermoeconomics, as an exergy-based technique, allows for a thermodynamically rational evaluation of the monetary value of material streams and must be always preceded by an accurate exergy analysis of the system. Many research works have been oriented to the exergoeconomic optimization of multiple effect distillation desalination systems. In a recent paper by Sayyaadi and Saffari [10], a multi-objective evolutionary algorithm was used to minimize the unit cost of product calculated by a thermoeconomic expression; the analysis identifies relevant margins for improvement by reduction of exergy destruction and product cost compared to a reference base case. Another interesting study by Manesh et al. [11] proposes an exergoeconomic multi-objective optimization of a MED-RO desalination plant, identifying a Pareto optimal frontier for the two objective functions "Gained Output Ratio" and "cost of desalinated water production"; this paper also defines an optimal coupling of the system with a site utility steam network, following the principles of process integration [12]. As reported by Sharaf [13], the exergy and thermoeconomic analysis is performed for a combined solar organic cycle with MED desalination process, pointing out that direct coupling of solar collectors with MED process is more viable than an integrated solar-Organic Rankine Cycle-MED scheme and that the parallel feed configuration is preferable over the forward feed and the backward feed ones. The above approaches, however, apply thermoeconomic analysis at a low disaggregation level, i.e. not presenting in details the exergoeconomic cost of each material stream. From this perspective, similar results could have been eventually achieved by assuming a similar disaggregation level and optimizing each plant section or the overall plant scheme by non linear mathematical programming techniques, as confirmed by Druetta et al. [14].

However, the potential of thermoeconomic analysis goes far beyond the cost minimization problem. Application of Exergy Costing, i.e. allocation of the cost of the resources consumed (in terms of capital investment for components, fuel consumption, etc.) based on the exergy content of material streams or energy flows, allows us to assign a monetary value to each stream [15]. Then, such a "cost accounting" procedure allows us to get a clear picture of the so-called *cost formation process*, i.e. the process through which the cost of the resources consumed are gradually charged to the material streams, increasing their monetary value [16] when passing from the beginning to the end of the "*productive chain*". In order to clarify this concept by an intuitive example, the cost (per unit exergy) of fuel in a power plant is lower than the cost per unit exergy of the high pressure steam entering the turbine, which is in its turn lower than the cost per unit exergy of the produced electricity: this is because, when passing from the former to the latter energy flow, exergy is gradually destroyed by irreversibility. In spite of the risk to appear as a fascinating intellectual exercise, thermoeconomic cost accounting has been proven to represent a useful procedure for a number of purposes:

a. In multiple-product facilities, like cogeneration or trigeneration plants, calculating a thermodynamically rational cost for each product provides a reasonable basis for price assignment. In a recent paper by Calise et al. [17], for a solar polygeneration system producing hot water for space heating in winter, cold water for space cooling in summer, electricity and desalted water for an insulated community [18], the exergoeconomic analysis allowed the authors to assign rational prices to each product and to build up a flexible tariff structure following the generation costs that evidently vary throughout the year with the solar radiation available;
b. In many energy conversion systems, like power plants and refrigeration cycles [19,20], calculating a rational monetary value for each material stream has been proven useful to detect anomalies or malfunctioning components (whose unit cost of output temporarily increases) or for "what if analyses" (i.e. to calculate the monetary loss eventually associated with additional exergy loss from material streams).

However, thermoeconomic cost accounting is not a trivial procedure, since many assumptions in the application of the method may affect the reliability of results. In a paper by Wang and Lior [21], an excellent comparative analysis of the fuel allocation obtainable by seven different methods (namely "Products Energy", "Product Exergy", "Power-Generation-Favored", "Heat-Production-Favored", "Exergetic-Cost-Theory", "Functional Approach" and "Splitting Factor") was presented. The authors pointed out that the results are very sensitive to the followed approach, identifying the "Functional Approach" and the "Splitting Factor" methods as the most reliable for a combined steam-injected gas turbine and thermal desalination system. Another critical aspect is related with the approach followed to include in the thermoeconomic model the energy or material streams to be disposed (for instance, the concentrated brine rejected or the surplus heat discarded to the cooling water in a MED plant); in [22] a cost was associated with the rejected streams, while several scientists have proposed innovative approaches [23], based on the concepts of "residue flow" and "dissipative component", to properly allocate the cost of these rejected streams.

At author's knowledge no papers in literature have provided a detailed picture of the cost formation process throughout a whole thermal desalination system; in this paper, such an in-depth analysis is performed, splitting the exergy flows associated with material streams into their "chemical" and "thermal" fractions, and also calculating the exergetic efficiency at sub-component levels. A detailed description of the model and the basic assumption is provided, to allow for a complete understanding of the keen arguments to be considered when developing a thermoeconomic model.

2. Case study and physical model

Due to the methodological scope of the paper, the focus is posed on a simplified and low-efficiency MED plant that is supposed to be fed by moderate temperature water produced by solar collectors. The scheme is an 8 effect MED plant with a "forward feed with feed pre-heaters" configuration and it has already been presented in details in [24]. In Fig. 1.a–c the simplified lay-out of the MED plant is shown, with a detailed list of the main symbols (that are also included in the nomenclature section) used in the mathematical model. Then it will be unnecessary to specify the intuitive meaning of each symbol while defining the physical model of the plant (the reader is invited to look at Fig. 1 and "Nomenclature" section for physical interpretation of each symbol).

The physical model does not differ significantly from those already available in literature, and it will be hence described very