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# Optimal operating conditions analysis for a multi-effect distillation plant according to energetic and exergetic criteria.

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ABSTRACT

In order to reduce the energy cost while improving the process operation, a study which aims to analyze the influence of the operational parameters variations and determine the optimal operating conditions of a pilot multi-effect desalination system (MED) at CIEMAT-Plataforma Solar de Almería (PSA) has been performed. An equation-based object-oriented mathematical model of the experimental MED plant, implemented using the modeling language Modelica and previously developed, calibrated and validated, has been adapted to carry out this study. Firstly, an energetic and exergetic analysis of the process under nominal conditions has been carried out, revealing the key sources of energy and exergy consumption. On the one hand, the thermal energy contained in the mass outflows are the main responsible source of the high energy consumption, on the other hand the entropy generation and the heat exchanged with the environment are the responsible of the exergy degradation. Secondly, a study on the influence of the operational parameters shows that the production of the real plant under nominal conditions is far from the maximum simulated values and some operational parameters have not a great influence in the process with respect to the rest. Finally, using a genetic optimization algorithm implemented in the modeling tool, a optimization process taking into account different energy and exergy performance criteria, sets optimal operational set points.

## 1. Introduction

The immense pressure on water resources due to unsustainable development and wrong policies have affected fresh water quality and its availability. In the next few decades, the shortage of fresh water resources will be some of the major problems to be tackled by humanity [1]. Seawater desalination represents an interesting solution for the problem of the water scarcity, even more if we consider that renewable energy sources have become a real alternative [2]. There are available different desalination technologies based on different principles, phase change thermal, membrane and alternative processes, all are operated by either conventional energy or renewable energy source [3].

Nowadays, reverse osmosis is covering the largest fraction of the new desalination world demand, although thermal distillation continues being one of the main technologies used in desalination [4], especially in energy-rich countries. Thermal distillation processes present some benefits, for example they are able to be driven by a low energy thermal source, they are reliable, easy to operate and maintain and produce high purity fresh water. Furthermore, these processes are able to deal with harsh feed waters (high temperature, high salinity) or even with water pollution [5]. These thermal processes demand two different forms of energy: the main energy consumption is in the form of thermal energy and a smaller energy consumption is in the form of electric energy for driving actuators and pumping systems (feeding, cooling, vacuum, brine disposal and distillate extraction).

Among the thermal desalination technologies, multi-stage flash (MSF) and multi-effect distillation (MED) are the main ones monopolizing the largest part desalinated water world production by means of thermal processes. Table 1 summarizes the typical energy consumption of the MSF and MED processes. Thermal distillation technologies are considered energy inefficient, representing the energy cost the 50% of the total fresh water cost production. The high energy consumption has restricted its use to countries rich in fossil fuels or to

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**Table 1**
Thermal distillation energy consumption [12].

| | MSF | MED |
|---|---|---|
| Electrical energy consumption ($kWh/m^3$) | 2.5–5 | 2–2.5 |
| Thermal energy consumption (kJ/kg) | 190–280 | 145–230 |
| Total equivalent energy consumption ($kWh/m^3$) | 19.6–27.3 | 14.5–21.4 |

specific thermal solutions like dual purpose co-generation plants and solar desalination systems [6]. However, the fact that MED is less affected by water quality, feed salinity, and doesn't require intensive pretreatment, makes this technology a good option when working conditions are very hard.

In order to improve their performance, the trend in the last decades has been to couple the MED plants with heat pumps. Some works can be found in the literature at this respect, for example Al-Juwayhe et al. [7] analyzed four different types of single-effect evaporator desalination systems driven by heat pumps, thermal vapor compressor (TVC), mechanical vapor compressor (MVC), absorption, and adsorption. Garcia-Rodriguez et al. [8] and later Wang et al. [9] performed an analysis of an MED-double absorption heat pump.

Recently, new ways are being investigated to improve the process performance. On the one hand, forward osmosis [10] or nano filtration (NF) coupled to MED as a pretreatment [11], allows working at higher temperatures with higher efficiencies. This configuration eliminates the bivalent ions (soft scaling components), that limit the MED operation temperature at 70 ° C, increasing in this way the operation temperature range. On the other hand, MED hybridizations with other thermodynamic cycles allows improving the efficiency, for example the hybrid MED adsorption cycle (AD) can operate below ambient conditions increasing even more the operation temperature range and the overall performance. Hybrid combinations between NF, RO and AD coupled whit MED are proposed and show higher performance [11]. Finally, the use of solar energy (photovoltaic and thermal) for desalination processes is taking a significant role because it reduces energetic cost and environmental impact, specially for MED desalination processes due to its greater compatibility with solar energy and the electrical and thermal energy consumption.

The large difference between the theoretical minimum energy required for seawater desalination (4 kJ/kg [13] approximately) and the real requirements, not only for thermal distillation but for the rest of desalination technologies [14], leaves clear the importance to increase the knowledge regarding the potential improvements. The study of operational parameter influences and the optimal operational conditions according to different criteria are one of the ways to find the potential improvements that could allow developing efficient operational strategies. Nevertheless, the fact that different desalination techniques use diverse forms of energy, showing differences both in quantity and quality, makes more difficult to improve the knowledge and to optimize the process, or even the comparison between different facilities or technologies.

A lot of studies based on experimental data and mathematical models have been carried out in order to analyze and improve the performance of MED processes. For example, Fernandez-Izquierdo et al. [15] studied the energy performance of a multi-effect distillation unit operated out of nominal conditions and determined new operation points optimizing the performance ratio and the production. Ali and El-Fiki [16] developed a model to investigate the effect of the design parameters on the performance of an existing MED-TVC plant and of the operational parameter variations on the operating conditions. Kamali et al. [17,18] developed a model as an effective tool in order to perform parametric studies that assess the performance ratio and the optimum parameters of a MED-TVC plant, taking into account only the thermal energy consumption. Amer [19] developed a mathematical model to evaluate the thermal performance and to determine the optimum operating and design conditions of a MED-TVC system. Janghorban et al. [20] modeled and optimized a MED-TVC plant based on thermal energy consumption criteria. Recently, Frantz and Seifert [21] performed a thermal analysis of a MED unit powered by a solar tower plant in order to optimize the thermal efficiency for a certain range of heating steam temperatures. Finally, Palenzuela et al. [22] characterized at steady state the influence of the variation in certain operational parameters over the thermal performance and the distillate production of the pilot MED plant used in the present work.

In these works, the most employed technique to find potential improvements and optimize the process is the analysis of the thermal energy balance, which is the most important factor in order to improve the performance of thermal driven desalination plants. But when the most evident energy savings have been achieved, find potential improvements and optimizing the process becomes a complex work where the traditional performance indices do not provide information about other types of energy used in the process or about the quality of the process. In these cases the exergy analysis could be a relevant tool since it helps to define potential improvements, to optimize the process, to find irreversibilities and with the problem of using different types and qualities of energy. Different works using this tool have been already presented. Choi et al. [23] presented an exergy analysis of a MED-TVC plant to identify the exergy losses due to irreversibilities. Sharqawy et al. [14] studied the effect of the system properties as well as the environment dead state on the exergy variation and performed an exergy analysis for a MED plant. Recently, Janghorban et al. [24] carried out an exergoeconomic analysis of a MED coupled to an absorption heat pump system to investigate the effect of key parameters on the energy performance of the system and to optimize it. Finally, Piacentino [25] developed an advanced thermodynamic and exergy costing study of a MED plant.

First, the present work contributes to the previous scientific production, studying and discussing the influence of the operational parameters variations over the traditional and exergetic performance indexes in a MED plant, also the present work shows the benefits of energetic and exergetic studies for advanced optimization tasks. Second, optimizations according to the traditional and exergetic performance as criteria have been performed using genetic optimization algorithms and a highly detailed dynamic mathematical model of a MED plant previously validated. Optimization based on exergetic performance indexes take advantage of the possibilities offered by a new exergetic approach proposed in this work that take into account both thermal and electrical consumption.

## 2. Materials and methods

### 2.1. AQUASOL system

The facility under consideration in this paper is a forward feed MED unit installed at Plataforma Solar de Almería (PSA). It was manufactured by ENTROPIE and consists in 14 effects in a vertical arrangement with decreasing pressure from the 1st to the 14th effect. This unit has been modified many times with different purposes, the largest under the framework of AQUASOL project [26]. The main objective of the project was the development of a hybrid solar-gas desalination system which met at the same time the requirements of low-cost, high efficiency and zero liquid discharge. The facility allows 24-hour plant operation and the system is flexible regarding the heat source.

In the MED plant (see Fig. 1), each effect is composed of two tube bundles, evaporator and preheater, being the thermal energy supplied to the MED plant through the first evaporator (*point 1* and *point 2*). Hot water flows inside this evaporator and delivers heat to the feed water being sprayed over the tube bundle, which is partially evaporated. The vapor generated in the evaporator is partially condensed over the tube bundle of the preheater, cooled by the feed water and the remaining vapor that has not been condensed is transported by natural convection