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Structural optimization of seawater desalination: I. A flexible superstructure and novel MED–MSF configurations

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HIGHLIGHTS

- We structurally optimize thermal desalination systems.
- We develop a superstructure representing existing and novel thermal desalination structures.
- The superstructure is optimized without binary variables using BARON.
- Optimization of feed routing results in substantial improvements.
- New desalination structures are identified.

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ABSTRACT

A methodology is proposed to identify improved thermal-based desalination structures. It is based on the notion of superstructure, allowing for the simultaneous representation of numerous feed, brine and vapor routing schemes. By adjusting the flow routings, the superstructure is capable of representing the common thermal desalination structures, as well as an extremely large number of alternate structures, some of which might exhibit advantageous behavior. The superstructure is built around a repeating unit which is a generalization of an effect in a multi-effect distillation system (MED) and a stage in a multi-stage flash system (MSF). The superstructure is proposed as an improved tool for the structural optimization of thermal desalination systems, whereby the optimal selection of components making up the final system, the optimal routing of the vapors as well as the optimal operating conditions are all variables simultaneously determined during the optimization problem. The proposed methodology is applicable to both stand-alone desalination plants and dual purpose (water and power) plants wherein the heat source to the desalination plant is fixed. It can be extended to also consider hybrid thermal–mechanical desalination structures, as well as dual purpose plants where the interface of power cycle and desalination is also optimized for.

1. Introduction

1.1. Pressing need for desalination

The global demand for a steady, economical supply of fresh water continues to increase. One of the main known modes of increasing the existing water supply is seawater desalination; a proven process that can reliably convert the seemingly limitless supply of seawater to high-quality water suitable for human consumption. Already, desalination plants operate in more than 120 countries in the world, including Saudi Arabia, the United Arab Emirates, Spain, Greece and Australia. While large-scale desalination plants have been available for a long time, further installations are expected to increase at an alarmingly fast rate, with most of the desalination plant installations expected to be of either the thermal or membrane type. It is projected that by just 2016, the global water production by desalination will increase by more than 60% from its value in 2010 [1]. In Gulf countries in specific, where energy costs are low and where the high salinity waters complicate the use of membrane-based technologies, thermal desalination technologies are foreseen to continue to dominate the market in the nearby future. Thus, the need to enhance thermal desalination technologies, which include the multi-effect distillation (MED) and multi-stage flash distillation (MSF) plants, continues to be a pressing issue. It has already been tackled by many authors, and will be addressed in the work presented herein.

Seeking to contribute improvements to this field, authors have undertaken varying approaches. Several authors, through parametric

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studies, investigated the influence of numerous variables to gauge their relative importance on performance of MED plants [2–6]. These variables include the total number of effects, the temperature and salinity of the incoming feed, the temperature of the heating steam, as well as the temperature of the evaporator in the last effect. While such studies occasionally provide useful insights, most of the relationships that arise, e.g., distillate production is heavily dependent on the number of effects, are mostly expected. Moreover, the results of such studies are of limited use to designers, mainly because parametric studies do not consider interaction between the different system variables. The need for optimization is clear.

To optimize thermal desalination plants, authors have resorted to differing objective functions. In certain situations, the objective functions are economic related such as minimizing unit product cost or minimizing specific heat transfer areas. In others, the objectives are tied to the thermodynamics such as maximizing distillate production or exergy efficiency [7–9]. While single objective functions are frequently resorted to, multi-objective optimizations are generally preferable. The main reason is that single objective optimization does not necessarily yield applicable designs. For instance, if the distillate production is maximized as part of a single objective study, the associated costs are not directly considered. The result is generally an uneconomical unimplementable plant. In contrast, multi-objective optimization studies can consider both efficiency and economic measures, resulting in more realistic designs. Further, multi-objective optimization allows the quantification of the trade-offs between competing criteria.

The works directed to improve thermal desalination have taken numerous fronts. Some authors have considered the stand-alone optimization of thermal-based configurations. While some of these authors optimized operating conditions associated with pre-existing configurations, others proposed alternative schemes – such as the MSF–MED proposed in [10,11] – which they subsequently optimized and compared to conventional structures. Other authors meanwhile have examined hybrid thermal-membrane based technologies seeking to make use of the ease of their integration. By suggesting alternative flow routing possibilities, authors propose that the resulting hybridized structures offer significant synergetic benefits. These advantages include, but are not restricted to, the reduction of capital costs through use of common intake and outfall facilities, the potential for reduced pretreatment and an increase in top brine temperature in thermal desalination [12–18]. Other authors propose integrating thermal desalination configurations with thermal vapor compression systems as an efficient means of increasing total distillate production, reducing cooling water requirements and potentially reducing heat transfer area requirements, all while being characterized by simple operation and maintenance [19,20].

While the aforementioned contributions have resulted in more efficient desalination plants with improved economics, one significant drawback impedes even larger improvements. The general practice of fixing both the hardware, i.e., technology choice such as MED or MSF, involved in a plant, as well as its flowsheet prior to optimization, results in more tractable optimization problems but has obvious shortcomings. It can be easily seen that an alternate optimization approach whereby both the hardware and the flowsheet could be modified during the optimization process is preferable. This is especially true since there is no guarantee that any of the common configurations already proposed in literature is optimal under any conditions. For studies concerning hybrid plants in particular, the more flexible optimization could yield breakthroughs as there might be significant benefit from deviating from the conventional setups specific to stand-alone structures. Herein, a methodology for simultaneous optimization of flowsheet and design/operation using the notion of superstructure is utilized [21]. The superstructure is composed of a series of units, allowing for vapor formation by two processes. One option is evaporation of brine within an effect, and subsequent condensation of the produced vapor in a feed preheater or a subsequent effect; this is in essence an MED stage. An alternate mode of vapor formation involves the flashing of brine entering into a flash box, and condensation in a preheater, or in a subsequent effect; this is similar to the MSF process.

The general need to investigate modifications in hardware and flow patterns has been looked into. Authors generally proceed to propose a series of modifications they envision to be advantageous. They subsequently optimize the resulting arrangements, and compare the results to those exhibited by conventional structures to decide on the merit-worthiness of their ideas. Unfortunately, such a series of steps is time consuming and their success in yielding improved results depends highly on both the author's experience and creativity. This method is further restrictive because the testing of the huge number of combinations of different possible flowsheets and hardware is infeasible.

Note that herein, desalination-only plants are assumed. However, by design the methodology can be easily extended to a number of alternate applications, including optimizing cogeneration hybrid facilities. This is achievable since the model of the superstructure tool proposed can easily be integrated with the model of a power plant. One way to optimize a dual-purpose plant is to keep the interface between the power cycle and the desalination unit fixed and optimize each on its own. The case study presented in our manuscript is in that way directly applicable. The only element missing would be to optimize the interface, which is in essence the flow rate and temperature of the steam taken from the power cycle (extraction or back-pressure) used as a heat source for the desalination.

2. Superstructure concept for optimizing thermal desalination structures

Herein, we propose a flexible methodology that is capable of adjusting the process diagram of thermal desalination configurations. It is based on the concept of a superstructure, and is able to adjust the hardware component set, the routing of all the different flows entering and exiting each of the eventual components making up the system, as well as adjusting the sizing of all the necessary components. Through this process, all the existing thermal desalination configurations can be represented, in addition to an extremely large number of alternative configurations, making it ideal for the systematic comparison of alternatives and the generation of new ones. Note that the superstructure is a notion employed in process design that illustrates all the different hardware and connectivity possibilities to be considered for optimal process design [21].

The methodology allows for improved optimization studies involving thermal configurations. Further, it can be easily adjusted to be used in optimization studies of hybrid configurations involving membrane-based technologies and thermal vapor compression systems, considered in the second part of the article. The tool can be modified to investigate co-generation by integrating it with a power plant model. To illustrate the usefulness of the proposed methodology, the results of several multi-objective optimization studies are presented, whereby the performance improvements are quantified, while the optimal flow patterns are shown to deviate from the convention.

While the origin of the superstructure approach is in the chemical process industry, authors have recently utilized it in the field of desalination. Zak [22], by identifying physical processes shared by all thermal desalination technologies, constructed a superstructure capable of representing existing thermal desalination configurations as well as novel ones, however did not optimize it. Sassi and Mujtaba [23] used it to identify optimal RO networks for a variety of differing temperatures and salinities. The study confirmed, as expected, that such factors have a significant impact on the subsequent optimal design and operation. Skiborowski et al. [24], on the other hand, optimized a superstructure considering the combination of an RO network with an MED