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Optimization of multi-effect distillation with brine treatment via membrane distillation and process heat integration

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HIGHLIGHTS

- An optimization approach to the design of multi-effect distillation and membrane distillation.
- Brine management is integrated.
- A superstructure-based optimization formulation is developed.

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ABSTRACT

The objective of this paper is to introduce an optimization approach to the design of an integrated system of multi-effect distillation (MED) and membrane distillation (MD). Brine from the MED system is further treated in the MD network to enhance the recovery of fresh water and to reduce brine disposal. The desalination system is thermally integrated with an industrial facility to use excess process heat to reduce the cooling load for the industrial process and to decrease the heating load for the desalination system. A superstructure-based optimization formulation is developed and solved to determine the key design and operating variables. A case study is solved to illustrate the usefulness of the proposed approach.

1. Introduction

Shortage of water resources poses a major threat to large segments of the population especially in the Middle East, Asia, and Africa. Desalination plants represent a key element in addressing fresh-water scarcity. According to the International Desalination Association, there are about 18,000 desalination plants around the world provide 90 million m^3/day to more than 300 million people [30]. Desalination process can be categorized into three major classes: thermal, membrane, and chemical technologies. Examples of thermal desalination include multi-effect distillation (MED) and multi-stage flash (MSF). Membrane desalination such as reverse osmosis (RO) uses a membrane to separate water from salts in a pressurized system. Chemical desalination such as ion exchange employs chemical species. At present, most of the desalination plants employ thermal or membrane technologies. For details on the principles of operation and design of desalination technologies, the reader is referred to literature in this area (e.g., [13,15,16,18,22,23,43]). Desalination plants dispose concentrated brine which can lead to major negative physicochemical and ecological impacts on the environment [47]. Several techniques have been proposed for handling the brine by reducing its volume through evaporation and extracting the salts through crystallization (e.g., [2,9,32,39,45]).

Membrane distillation "MD" is an emerging desalination technology that offers several advantages such as modularity, almost complete rejection of inorganic salts, and relatively low feed-preheating temperature (e.g., [12,28,36,37]). It is also particularly attractive in handling brine and further concentrating it to produce secondary distilled water and a concentrated brine that can be rejected or evaporated to salt (e.g., [1,44]). Other advantages of MD include its modular nature, high recovery when brine recirculation is used, low levels of biofouling, and ability to use low-quality heat. There are various methods for inducing the permeation and for collecting the permeate. These methods include direct contact membrane distillation (DCMD), sweep gas membrane distillation (SGMD), vacuum membrane distillation, and air gap membrane distillation (AGMD). Review studies, theoretical

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models, and experimental results for the various MD methods can be found in literature (e.g., [5,35,36]). Recent advances in materials engineering have led to high-performance membranes that can be operated for extended periods while maintaining relatively high fluxes. For instance, polyethylene membranes have been reported to provide a distillate flux of approximately 120 $\frac{\text{kg}}{\text{m}^2\ \text{h}}$ for a feed solution containing 3.5 wt% of NaCl at 353 K [55]. The operating cost of MD systems can be significantly reduced when it is coupled with industrial facilities that offer excess process heat (e.g., [19,23,26]).

In addition to the experimental and modeling studies for individual desalination technologies, there is a research need for system design and optimization methodologies that enable cost-effective the synthesis of network configurations, optimization of design and operating parameters, integration of multiple desalination methods, reconciliation of various objectives (e.g., economic, environmental, energy), and coupling with adjacent facilities (e.g., industrial plants). Process synthesis techniques have been employed in the design of reverse osmosis networks (e.g., [38,53,56]) by creating a superstructure that embeds numerous network configurations and extracting the optimal solution using mixed-integer nonlinear programming (MINLP) formulations. The solution to the MINLP programs provides detailed information on the number, type, size, and arrangement of the units and the values of the design and operating specifications. El-Dessouky et al. [14] synthesized and assessed several configurations of MSF systems and used different criteria (e.g., fixed and operating costs, water recovery, and thermal performance) and sensitivity analysis to screen the alternatives. El-Halwagi [15] developed a shortcut optimization approach for the design of MSF networks by using “average conditions” and implicitly including the unit sizing and performance equations in the optimization model. Tanvir and Mujtaba [52] used MINLP models to synthesize and optimize MSF systems. Gabriel et al. [24] used linearization techniques to achieve global solutions of the linearized models for the design of MED networks. Process synthesis techniques have also been applied to desalination systems involving more than one type of technology with the objective of using “hybridization” to exploit the synergism in performance and energy needs. Elsayed et al. [20] proposed the use of warm lime softening prior to MD for the treatment of saline wastewater from heavy oil production. Wang and Chung [54] proposed an indirect-contact freeze desalination system coupled with MD. El-Zanati and El-Khatib [21] analyzed the use of MD systems integrated with nanofiltration and reverse osmosis. Gryta et al. [27] reported on the use of a hybrid ultrafiltration/MD network for the treatment of oily wastewater. Skiborowski et al. [50] proposed a superstructure-based approach for the design of RO-MED hybrid systems. Marcovecchio et al. [41] and Helal et al. [29] developed an algorithmic approach for the design of RO-MSF desalination systems.

Energy source and quantity are critical factors in the selection and design of desalination systems. Semiat [49] reported that the cost of energy is normally around 30–44% of the cost of desalinated water. The thermodynamic limit for minimum energy consumption in seawater desalination is 0.78 kW h/m^3 at 0% recovery and 1.2 kW h/m^3 at 50% recovery [18]. Actual systems consume several folds of the minimum. For instance, MED typically uses 4.0–7.0 kW h/m^3 of thermal energy [25] and 2.0–2.5 kW h/m^3 of electrical energy for pumping [4]. The extent of greenhouse gas (GHG) emissions associated with a desalination system can be significant depending on the type of energy used in the system and the extent of energy efficiency [46]. Several approaches have been proposed to reduce the cost, energy consumption, and GHG emissions. These include the use of energy-recovery devices, enhancement of heat transfer and energy efficiency, incorporation of renewable energy sources, and integration of desalination with power plants [8,25]. In practice, many desalination systems. Almulla et al. [6] analyzed the economic and operability benefits from the integration of MSF, MED, and RO desalination with power plants and showed that significant improvements can accrue as a result of such integration.

The objective of this work is to develop an optimization framework for integration MED and MD for desalination of seawater and brine along with the thermal coupling of the MED-MD network with excess process heat from industrial facilities. Specifically, this work introduces the following contributions that are quite distinct from the aforementioned literature:

- Simultaneous process synthesis and optimization of the MED and MD networks with the determination of the optimal desalination tasks, unit sizes, design and operating conditions, and cost.
- Heat integration of MED and MD with adjacent industrial plants. This is a more complex task than the convention thermal coupling of a desalination system with a power plant where the source of heat of the steam leaving the turbine is singular with well-defined characteristics. In comparison, an industrial process has various hot and cold streams at different qualities and with different heat tasks. There is also the need to consider intra-process heat integration in addition to inter-process (desalination-industrial plant) thermal coupling.
- An optimization formulation that systematically extracts the optimal design from the numerous alternatives while considering all system components and variables of interest. The optimization variables include the sizing and configuration of the MED and MD networks, the extent of heat integration with industrial facilities, and the design and operating variables such as the top brine temperature (TBT) for MED and the feed-preheating temperature for MD. This is much more efficient than the conventional approach of develop a model for the process and conducting multiple what-if scenarios to compare a limited number of options.

2. Problem statement

Given is an industrial facility with a number of hot and cold streams. The heat duty and supply and target temperatures for each stream are known. The facility requires a certain flowrate of desalinated water, D_{Total}. Two desalination technologies: MED and MD are to be used to provide the necessary flowrate of desalinated water from seawater. It is desired to develop an optimization approach that determines the optimal configuration of the desalination system and the integration between the two technologies as well as the thermal coupling between the industrial facility and the desalination system. Fig. 1 is a schematic representation of the problem.

The optimization variables include:

- Excess heat transferred from the industrial facility to the desalination system
- Flowrate of seawater fed to the desalination system
- Distillate flowrate from the MED effects and from the MD network
- Number and size of MED effects

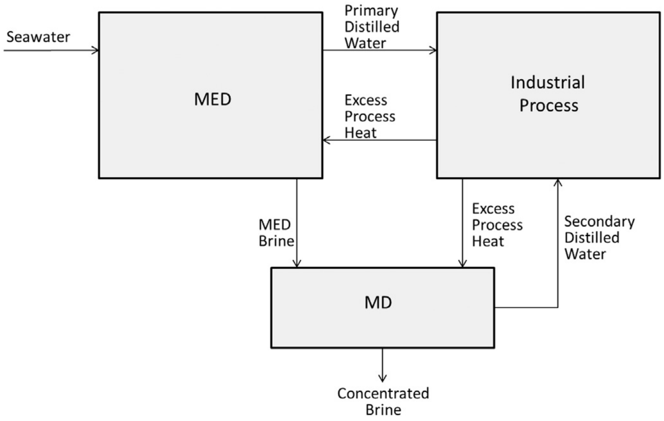

Fig. 1. Schematic representation of the problem statement.