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Optimal design of thermal membrane distillation systems with heat integration with process plants

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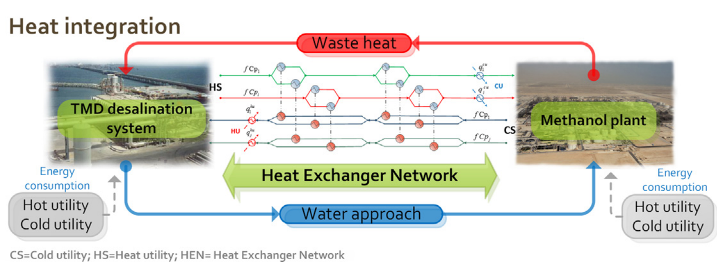
HIGHLIGHTS

- An optimization model for thermal integration for sweater desalination is proposed.
- A thermal membrane distillation module is integrated with a process.
- The objective function maximizes the net annual profit.
- Results show substantial benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an optimization approach for the design of thermal membrane distillation (TMD) systems that are thermally coupled with processing facilities. A superstructure representation and an optimization formulation are introduced to obtain simultaneously the optimization of the TMD unit and the heat-exchange network (HEN) that integrates heating and cooling in the process facility. The superstructure and associated optimization formulation seek to identify the system configuration along with design and operating variables such as heat-exchanger areas, membrane area, extent of thermal coupling between the process and TMD, and the TMD feed-preheating temperature. The objective function maximizes the net annual profit which accounts for the revenues from the sales of purified water, the avoided cost of the treated wastewater, and the total annualized costs accounting for the capital investment of the added heat transfer units and the TMD network, the operating costs for the heating and cooling utilities and the operating expenses for the TMD system. The proposed optimization formulation is applied to a case study where a TMD system is integrated with a methanol plant and the results show significant economic benefits for the implementation of the proposed methodology.

1. Introduction

The limited supplies of fresh water coupled with the over-exploitation of the available fresh water bodies represent major challenges for the sustainable development and call for cost-effective strategies for water management [1]. There are several regions around the world where desalination is the primary source

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of fresh water [2]. Treatment and recycle/reuse of industrial wastewater can also play a key role in managing water resources. There are several technologies for the industrial wastewater treatment and seawater desalination. Fig. 1 shows common categories and technologies. Thermal processes include vapor compression, multistage flash, multi-effect distillation, humidification/dehumidification, and freeze concentration [3]. Membrane systems include reverse osmosis [4], ultrafiltration [5], and pervaporation [6].

Thermal membrane distillation (TMD) is a new technology that lies at the interface between thermal and membrane technologies. It is a non-isothermal separation process that is based on heating up the feed solution to be distilled to some moderate temperature to create partial evaporation of water. The produced water vapor passes preferentially through a hydrophobic-microporous membrane. The vapor that permeates through the membrane is condensed and collected as a highly pure liquid on the permeate side. The driving force in this process is the difference in chemical potential across the membrane, which is strongly dependent on the vapor pressure difference between the feed and the permeate sides [7]. Fig. 2 shows a representation of a direct contact TMD module. Seawater or wastewater is preheated to induce some evaporation but not to completely evaporate the feed. The water vapor travels through the membrane and is condensed on the permeate side using a recirculating permeate-sweeping liquid [8]. Different configurations can be found in recent literature [9]. Recent advances in membrane development have led to improved performance and enhanced mass and heat transfer rates [10] and have paved the way for the potential of cost effective commercialization.

In spite of the important advances in the design of seawater-desalination and wastewater-treatment systems through TMD modules, one of the primary drawbacks is still the associated to the high energy consumption associated with vaporizing the permeate. Elsayed et al. [8] proposed a sequential process integration framework to extract excess heat from industrial facilities and use it to drive TMD without taking into account the design for the associated heat exchanger network. Proper extraction of heat should involve the simultaneous synthesis of process heat-exchange networks (HENs) and the TMD network as well as the related capital costs. In this context, several approaches have been reported for the synthesis of process HENs by transferring heat from the process hot streams to the process cold streams [11], furthermore, the sustainable development has been highlighted in the application of thermal engineering [12]. In this context, several methodologies for energy integration in the process industry have been reported, including deterministic and stochastic optimization approaches [13], computer fluid dynamic models [14], heuristic rules [15] and thermo-hydraulic models [16]. Moreover, these methodologies have been applied to several cases, involving biogas production [17], batch processes [18], absorption refrigeration cycles [19], eco-industrial parks [20], retrofitting existing processes [21], Kraft pulp mills [22], desalination [23], across different plants [24], involving multi-purpose heat transfer units [25], considering optimal cleaning [26], scheduling [27], for retrofitting large scale processes [28], involving different costs [29] and temperature progression [30].

For the specific case of TMD, Dotremont et al. [31] proposed a desalination system as a sustainable solution for the industry. Lee et al. [32] presented a mathematical model that integrates a

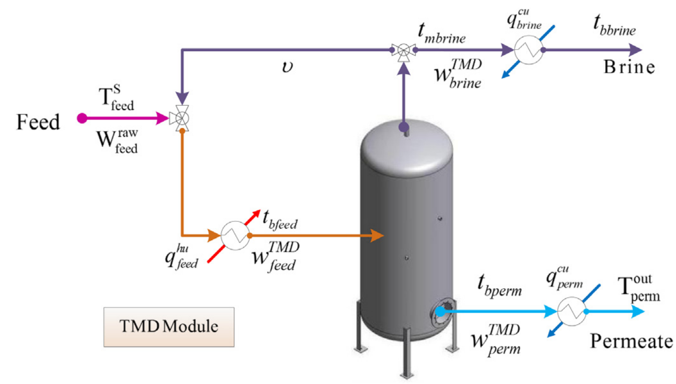

Fig. 2. TMD direct contact configuration.

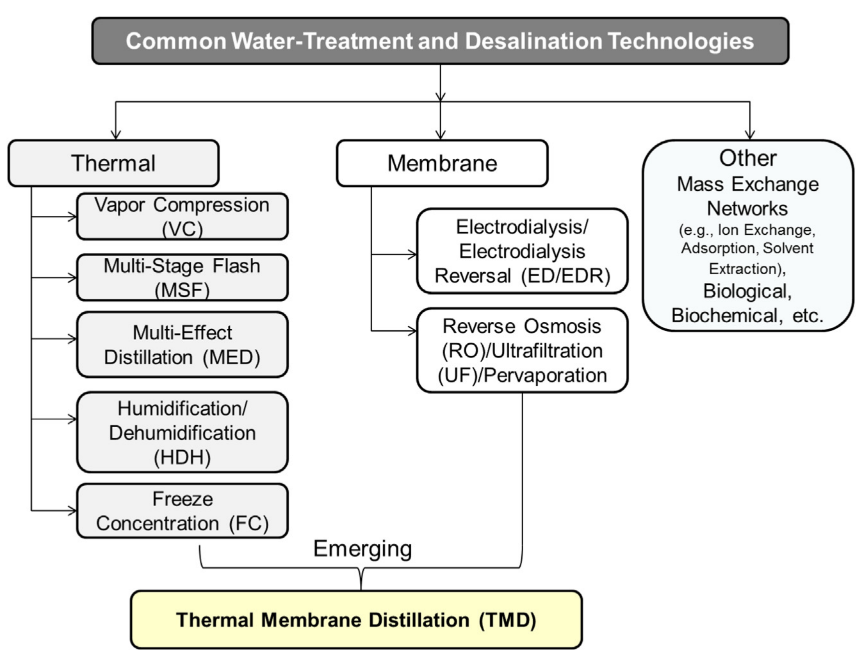

Fig. 1. Common water treatment and desalination technologies.

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