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Modular matrix design for large-scale membrane distillation system via Aspen simulations

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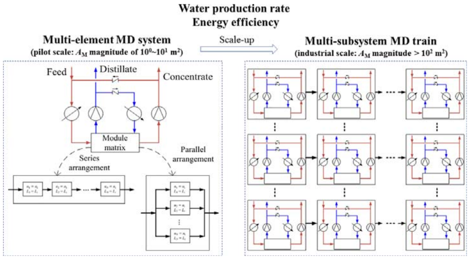
GRAPHICAL ABSTRACT



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ABSTRACT

Membrane distillation (MD) is emerging as a promising technology for treating the reverse osmosis brines. However, limited cases were reported on the design of a large-scale direct contact MD (DCMD) system. The practical scale-up options for modular matrix design in a multi-element MD system and a multi-subsystem MD train were explored by commercial flowsheet simulator Aspen Plus. Compared to the benchmark single module system, which showed drastically deteriorating membrane performance with increasing membrane area, the multi-element DCMD system with modules in parallel matrix was found to perform better with water production improved slightly but specific power consumption (*SPC*) greatly reduced down to 0.5% of the single module system. The optimal matrix was obtained at module number of eight for a 20 m^2 module due to trade-off relationship between module specifications and effective process driving force in MD. Supported by theoretical analysis, it was found that the matrix array pattern had no influence on the performance of the multi-subsystem DCMD train. Further investigation showed that an 18-subsystem MD train with a membrane area of 200 m^2 achieved a 16 times water production rate with only 10% of the *SPC*, as compared to that of single system with the same membrane area.

1. Introduction

As one of the key global challenges, water scarcity seriously threatens the lives of over one-third of the world's population. It is vital to search for new solutions and/or resources to overcome water shortage. Among all measures, desalination offers an enormous and steady supply of high quality water. However, with increasing energy cost and reduced natural resources, the conventional desalination approaches such as distillation and multi-effect distillation (MED) are considered energy intensive. In recent years, membrane technologies have arisen rapidly

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as energy friendly solutions for desalination, particularly reverse osmosis (RO) [1,2]. Nevertheless, with the increasing demand for RO plants, a new problem is the enormous amount of high-salinity brine disposal which has greatly affected the ecological balance [3–5]. Therefore, low cost and environmental friendly approaches of brine treatment are desired for future desalination. Membrane distillation (MD) is an emerging desalination technology operated at moderate temperature and ambient pressure, in which water vapor generates from the hot brine diffuses through a hydrophobic porous membrane and condenses at the cold distillate stream in the direct contact MD (DCMD) mode. Driven by a transmembrane temperature gradient, i.e., vapor pressure difference, MD is not strongly affected by the brine salinity [6] and hence has a great potential in treating RO brine to maximize the water recovery ratio and potentially achieve zero liquid discharge [7,8]. Also, compared to the pressurized membrane processes such as RO [9–12], MD could be relatively energy competitive in terms of energy consumption when low-grade waste heat is readily available. Despite MD offering attractive benefits of simple operation and a compact system, thus far there are few large-scale industrial practices in the world [13]. One of the reasons is the lack of MD module design developed specifically for large scale or industrial applications. Also, sparse investigations have been done on the evaluation of energy consumption associated with the application of industrial-scale MD modules [14].

The concept of modular assembly for membrane separation originated from the development of the hollow fiber solvent extraction process, by connecting a number of module units in series or parallel to achieve high efficiency [15]. In recent years, the concept of multi-stage modules has been extended to MD process design, with the commonly adopted matrix of series and parallel modular arrangements. For instance, an experimental study on a pilot-scale solar-powered air gas MD (AGMD) system has compared the performance of one compact flat-sheet module over a multi-stage modular design, which showed a 4-fold higher performance ratio (defined as the ratio between total heat input and latent heat required for distillate generation) and a much higher water recovery ratio of 4.5% in a single pass [16]. Lu et al. also investigated the optimal stage number for the multi-stage AGMD system by means of the state-space approach [17]. Attempts were made by He et al. [18] to explore the benefits of a cascade cross-flow hollow fiber modules integrated with heat exchangers. Experimental results showed that a water recovery ratio up to 60% was obtained. Also, through modeling, it was claimed that a theoretical value of gain output ratio (GOR) above 20 could be achieved. A recent study by Chung et al. [19] showed that the scalable multi-stage vacuum MD (VMD) system required lower total capital cost. With the flexibility of multi-stage MD system, the solar-power MD desalination can well adapt to the climate changes [20]. As the series and parallel modular arrangements are the commonly adopted matrix in multi-stage processes, Khalifa et al. experimentally studied the process performance of different arrangement of three AGMD modules each with a membrane area of 0.0074 m^2 [21]. However, none of the above studies has provided a thorough evaluation on the influence of multi-stage arrangement in large-scale MD associated with the fundamental transport mechanisms, operating conditions, membrane permeability and energy balance.

Process flowsheet simulations combined with previously studied vapor transport mechanisms through the membrane in MD (i.e., Knudsen flow, Poiseuille flow and molecular diffusion flow [6,22–25]) can provide valuable guidance in designing large-scale MD systems. Our previous Aspen work on the development of zero-liquid discharge MD systems established a user-defined MD unit operation model to simulate the heat and mass transfer for evaluating module performance and process efficiency [26]. The thermal polarization effects and conductive heat loss through membrane matrix were also included in the model. Subsequently another simulation study proposed an improved one dimensional (1-D) transport model (user-defined operation unit) in a MD module with boundary correction [27], which was also employed in a recent study to explore aspects for more efficiency energy utilization in MD [28].

Hence, this current study attempts to integrate the same user-defined transport model into the MD process design via Aspen Plus, where modular matrix concepts are explored as alternative scale-up options in large-scale MD systems. Theoretical analysis is provided to estimate separation parameters, material and energy balances, and production capacity of a scale-up MD process based on a single-unit system. The effect of modular array patterns, i.e., series and parallel arrangements, in MD operation is evaluated via two different scenarios in terms of water production rate and specific power consumption (*SPC*). In scenario #1, with an MD system with a single compact module as benchmark, an MD system consisting of multi-modules/elements in parallel or series matrix is analysed and compared. This scenario is seen in most pilot-scale and quasi-industrial applications. Sensitivity analyses are carried out to optimize the number of stages (module elements), operating conditions and total membrane area to achieve an energy efficient MD system. Scenario #2, a complex MD train consisting of multi-subsystems in parallel and series arrangements is simulated to resemble the concept of the distribution network of a real desalination plant.

2. Theory and methodology

2.1. Theoretical analysis of MD process

2.1.1. Performance indices in MD

As a potential alterative for energy friendly desalination, the preferable MD process should have a large capacity of water production with low energy consumption. In this study, the MD permeation flux (i.e., transmembrane mass flux, J_M, in kg m^{-2} s^{-1}) and specific power consumption (*SPC*, in kWh kg^{-1}) are used to evaluate the MD performance.

The J_M describes the membrane efficiency of water production, as defined with

$$J_M = \frac{W_P}{A_M} \tag{1}$$

where W is the mass flowrate (kg/s), and the subscript P indicates the distillate produced; A_M is the membrane area (m^2). The permeation rate is mainly determined by the vapor pressure difference across the membrane (driving force) and the MD coefficient, which is associated with the membrane material properties and pore structure [29].

The required energy for MD process mainly includes the thermal input and electricity. With the assumption of available low-grade waste heat (e.g., from power plant or geothermal sources) and cooling supply, the main energy requirement in DCMD is the electricity to drive the pumps for recirculating feed and permeate streams [31,33]. Thus, the *SPC* is used as a main parameter to assess the MD system performance in terms of the pumping electricity cost, defined as the pumping energy (kWh) required for producing 1 kg distillate:

$$SPC \equiv \frac{E_1 + E_2}{W_P} \tag{2}$$

where E is the electric power (kWh/s) required to drive the recirculating pump and the subscript of 1 and 2 indicates the lumen side and shell side, respectively. The E is the product of the recirculating volumetric flow rate (m^3 s^{-1}) and hydraulic pressure drop (Pa) along the flow direction. Assuming a fully-developed laminar flow in the module, the *SPC* of MD can also be expressed as:

$$SPC = \frac{8}{J_M}\frac{1}{D_{i,1}}\left(\frac{G_1^2\mu_1}{\rho_1^2} + \frac{G_2^2\mu_2}{\rho_2^2}\frac{\varphi}{1-\varphi}\right) \tag{3}$$

where ρ and μ are fluid density (kg m^{-3}) and dynamic viscosity (Pa s), respectively; G is the recirculating mass flux rate in kg m^{-2} s^{-1}; ϕ is