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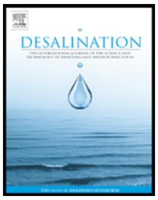

Evaluation of heat utilization in membrane distillation desalination system integrated with heat recovery

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HIGHLIGHTS

- An implicit expression of GOR was derived to quickly evaluate the heat utilization of desalination system.
- Low equivalent flowrates in both sides of hollow-fiber membranes are necessary for high GORs.
- High GOR is accompanied by the low water productivity in integrated DCMD system.
- Membranes with large heat resistances promote GOR.
- Non-linearly scale-up effect reveals a higher GOR of industrial DCMD system than lab-scale one.

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ABSTRACT

Aiming to optimize the system-level heat utilization, a pilot-scale direct contact membrane distillation desalination system integrated with heat recovery (DCMD–HX) was studied using Aspen Plus. An implicit expression of gain output ratio (GOR) was derived to reveal the interplay of heat utilization and process parameters including operating conditions, module specifications as well as membrane properties in the DCMD–HX desalination system. Compared to operating temperatures, the feed/permeate recirculating flowrates were identified as the most influential operational factors affecting the GOR. In the current settings, the maximal GOR of 6.0 was observed at low and equivalent feed- and permeate-side flowrates regardless of module specifications. Low flowrates, however, resulted in undesirable low water productivity, which was consistent with the trade-off relationship observed between the heat utilization efficiency and water recovery rate in MD. Employing membranes with high heat-transfer resistance (low conductivity and thicker membrane wall) helped to improve the GOR up to 32%. Simulated results also showed that the GOR value increased by 1.3-fold with the preheater parameter ΔT_{HX} varying from 5 to 0 °C. The non-linear scale-up relationship existed between the membrane area and heat utilization (i.e., GOR) was also observed, indicating the possible uncertainty in accurately predicting the GOR value for industrial-scale desalination systems based on lab-scale module testing.

1. Introduction

Due to the rising fresh water crisis worldwide in recent decades, desalination technologies have drawn much attention. As a promising alternative for seawater desalination, membrane distillation (MD) is operated at mild temperature and ambient pressure [1,2], in which water vapor generated from the hot brine diffuses through a hydrophobic porous membrane and condensates by the cold distillate stream in direct contact MD (DCMD) mode. Compared to conventional desalination processes such as multi-stage flash distillation (MSF), multi-effect distillation (MED) or reverse osmosis (RO) [1,3], MD has many inherent benefits: low sensitivity to salinity and high salt rejection; low vulnerability to membrane fouling and good performance under mild operating conditions; feasibility to utilize low-grade heat and renewable energy (e.g., geothermal heat or solar power) [4,5]. In recent years, several pilot-scale MD desalination systems have been developed to utilize solar energy for fresh water supply in arid regions [3,6–9]. Thus, such desalination technology serves dual roles in relieving global water shortage as well as energy crisis and enabling more and more arid areas/countries to access safe desalted water [10].

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In recent decades the resurgence of research interest in MD is mainly attributed to the advancement in polymer material developments and breakthroughs in membrane fabrication technologies [11–19], and novel module designs [20–28] as well as flow enhancement techniques to alleviate the temperature polarization phenomenon and enhance permeation flux [29–32]. However, the main challenge for the commercialization of large-scale MD desalination systems still remains due to the uncertainty in energy requirement. Fortunately, it was widely reported that MD can be quite economically competitive when low-grade heat such as industry waste heat, geothermal energy or solar power is available [2]. Nevertheless, even with no waste-heat or limited thermal energy available, system optimization by incorporating heat recovery units can extend the applicability of MD to more rural regions. Optimal heat recovery is also essential in reducing operational costs. Yet, thus far only limited studies are available in the literature on energy analysis in terms of heat utilization and the interplay of various operating parameters. Also, no standardized/universal correlations have been developed to evaluate system-level energy efficiency in MD [2].

In general, the energy consumption in DCMD systems includes the necessary thermal energy for heating the feed solution and cooling the permeate stream, as well as the electricity needed for the pumps and auxiliary devices. In most lab-scale or pilot plant studies, the MD energy consumption is evaluated via three thermally related metrics namely the thermal efficiency η, gain output ratio (GOR) and water production. As a common measure of the process efficiency for thermal desalination systems such as MD [33], the GOR is associated with useful heat and reflects how well the energy input is utilized for water production in a system, indicative of the maximum amount of heat recoverable with certain heat transferred across the membrane. Many attempts have been made to increase the GOR by incorporating heat recovery devices [34–36], improved module designs, effective insulation, optimized piping system and multi-staged operation [37–39]. However, a trade-off relationship is found between the GOR and permeation rate [40,41] i.e., high GOR could be achieved by designing a system with large membrane area, low flow velocity and more recovery stages; while the flux decreased due to either the decreased temperature driving force or severe temperature polarization effect. A module-scale thermodynamic analysis of DCMD modules suggested that high GOR could be achieved at a cost of extremely low water recovery rate in a single-pass DCMD system [42]. A well-designed MD system is expected to have a GOR higher than unity. For instance, a cascade of cross-flow hollow fiber MD devices integrated with a heat exchanger was reported to achieve a GOR as high as 12 at carefully optimized operating conditions [39]. Among a handful of GOR studies in this field, however, most MD pilot plants exhibited GOR values far below expectations [43]. To our best knowledge, only three out of the nine MD systems reported in the literature were found to have a GOR exceeding 3 while the rest less than unity [43]. Overall, a wide dispersion on the GOR values from 0.3 to 12 is found in reported MD systems with similar flowsheet structures indicating that the prediction of GOR could be effected by various complex factors such as flow conditions, operating temperatures, and even membrane properties. A full factorial analysis on operational factors affecting the GOR is yet to be comprehensively explored.

To achieve a system-level optimization in a predictive manner, process modeling for large-scale MD applications can provide valuable guidance. However, thus far there are limited process modeling studies focused on membrane module design to facilitate the overall MD performance and reduce energy consumption [36,40,44–47]. For process design purposes, flowsheet simulation tools such as Aspen Plus have become more convenient and powerful in revealing the interplay of key process parameters and system performance to guide practical applications. Due to the process complexity of combined heat and mass transfer, the establishment of MD operation units associated with transport mechanism using Aspen Plus is sparsely reported [48]. Recently, the process development of membrane distillation crystallization system for high salinity brine treatment with zero discharge [49] has shown the feasibility of the user unit operation model for simulating the module performance and evaluating process efficiency in MD brine process. Later on, further improvement was reported to establish a more accurate transport model (user customized operation unit in Aspen plus) in MD modeling incorporated with boundary correction [48].

With the improved one dimensional (1-D) transport MD model reported in [48], this current work aims to explore a direct contact membrane distillation desalination system integrated with heat recovery (DCMD–HX) for leveraging the advantages of MD practicability in the context of limited heat resource. An implicit expression of GOR was derived to conveniently correlate the DCMD–HX system efficiency in terms of heat utilization with single-unit hollow fiber module modeling. A full factorial analysis was conducted to identify the operational factors that are most influential in system-level heat utilization in terms of GOR. Necessary mathematical conditions were proposed for achieving maximal GOR in a given DCMD–HX desalination system. The newly-developed implicit GOR correlation was testified through a series of investigations such as the interplay between GOR and various process variables (dependent or independent), including flowrates, influent temperatures of feed and permeate streams, thermal efficiency of MD module that is strongly affected by membrane properties, as well as water recovery rate. The concept of “non-linear scale-up” was proposed for large-scale MD systems integrated with heat recovery in terms of thermal energy evaluation.

2. Theory and methodology

2.1. DCMD hollow fiber module modeling

In this study, an improved 1-D transport model was used to simulate the heat- and mass-transfer process of DCMD modules [48], in which a certain number of N hydrophobic PVDF hollow fiber membranes with an effective length of L are regularly packed into a cylindrical housing. The current transport equations with boundary correction, which showed higher accuracy in predicting the MD module performance [48], are summarized in Table 1. In both lumen and shell sides of DCMD module, the governing equations for mass, momentum and energy conservation together with the wall correlation equations and boundary conditions were solved simultaneously. Although this model is applicable to MD module with either shell or lumen-side feeding modes, only the latter was investigated in this study. Also, in this model both the effects of feed concentration on the change of vapor pressure and concentration polarization are considered negligible [50].

The current transport model has been verified previously [48], based on an established DCMD system for a series of experimental settings, including various feed inlet temperatures, fiber lengths and flow velocities. Also, the membrane properties were the same as that in previous verification experiments. Hence, the model verification was not repeated here and the verified MD model was used as a customized unit for Aspen flowsheet simulation in the following sections.

2.2. DCMD–HX desalination system

In this simulation study, an ideal heat exchanger (HX), in which the heat transfer takes place through infinitely large area and hence is not limited by heat exchanging kinetics [42], was used as the heat recovery unit and integrated into the DCMD desalination system to recover heat from the returning permeate stream, namely DCMD–HX. The recovered heat could be utilized to preheat the brine feed influent before entering the membrane module.

A series of pilot-scale hollow fiber modules were integrated into the MD flowsheet in Aspen Plus. The first set of module specifications is given in Table 2, while three pilot-scale hollow fiber modules with various packing densities and fiber lengths were used in the flowsheet simulations to correlate module performance with the GOR in the