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Evaluating energy consumption of air gap membrane distillation for seawater desalination at pilot scale level

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ABSTRACT

This study aimed to optimise an air gap membrane distillation (AGMD) system for seawater desalination with respect to distillate production as well as thermal and electrical energy consumption. Pilot evaluation data shows a notable influence of evaporator inlet temperature and water circulation rate on process performance. An increase in both distillate production rate and energy efficiency could be obtained by increasing the evaporator inlet temperature. On the other hand, there was a trade-off between the distillate production rate and energy efficiency when the water circulation rate varied. Increasing the water circulation rate resulted in an improvement in the distillate production rate, but also an increase in both specific thermal and electrical energy consumption. Given the small driving force used in the pilot AGMD, discernible impact of feed salinity on process performance could be observed, while the effects of temperature and concentration polarisation were small. At the optimum operating conditions identified in this study, a stable AGMD operation for seawater desalination could be achieved with specific thermal and electrical energy consumption of 90 and 0.13 kW h/m^3, respectively. These values demonstrate the commercial viability of AGMD for small-scale and off-grid seawater desalination where solar thermal or low-grade heat sources are readily available.

1. Introduction

Desalination is a practical approach to increase and secure drinking water supply in coastal areas [1]. Drinking water supply from seawater using large-scale reverse osmosis (RO) and conventional thermal distillation has been implemented in many parts of the world. However, the provision of drinking water to small and remote coastal communities remains a significant challenge. Conventional thermal distillation is less energy efficient and requires a larger physical footprint compared to RO. On the other hand, RO, as a pressure-driven membrane separation process, requires intensive pre-treatment, high-pressure pumps, and duplex stainless steel piping. As a result, RO may not be suitable for small-scale seawater desalination applications, particularly in areas with unreliable or limited power supply. In this context, membrane distillation (MD), given its ability to use solar thermal and low-grade heat directly as the primary source of energy, has been identified as a potential candidate for small-scale and off-grid seawater desalination applications [2–5].

MD is combination of membrane separation and phase-change thermal distillation [6,7]. In MD, a hydrophobic, microporous membrane is used as a barrier against the liquid phase, but allows the vapour phase (i.e., water vapour) to pass through. As a result, MD, like a conventional thermal distillation process, can offer ultrapure water directly from seawater. MD can also retain most advantages of a typical membrane process, including modulation, compactness, and process efficiency [6,7]. Thus, the physical and energy footprints of MD can be lower than those of conventional thermal distillation [8,9]. In addition, given the absence of high hydraulic pressure and the discontinuity of the liquid phase across the membrane, MD is less susceptible to membrane fouling and does not require intensive feed water pre-treatment compared to RO [6,10]. More importantly, MD systems can be manufactured from non-corrosive and inexpensive plastic materials, leading to significantly reduced capital and maintenance costs. Finally, the feed operating temperature of MD is often in the range of 40–80 °C, which is also the optimal operating temperature with respect to thermal efficiency of most thermal solar collectors

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[11]. Given these attributes, MD is a promising candidate for small-scale, stand-alone, and solar-driven seawater desalination applications [3,11–13].

Despite a range of attributes that are highly suitable for small-scale and off-grid seawater desalination, there are still several technical challenges to the practical realisation of MD. Amongst them, low thermal efficiency is the most significant. As a thermally driven separation process, MD requires thermal energy to facilitate the phase conversion of liquid water into vapour. The specific energy consumption of all MD processes reported in the literature to date is several orders of magnitude higher than that of RO [4,12,14].

MD can be operated in four basic configurations, including direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), vacuum membrane distillation (VMD), and air gap membrane distillation (AGMD). DCMD has the lowest thermal efficiency due to significant heat conduction through the membrane. In SGMD and VMD, the introduction of sweeping gas and vacuum, respectively, mitigates the heat loss due to conduction, and hence improves the process thermal efficiency. However, the process complexity also increases as an external condenser must be employed to obtain fresh water. Thus, practical applications of SGMD and VMD for seawater desalination are still limited. AGMD has a higher thermal efficiency compared to DCMD but lower process complexity compared to SGMD and VMD. Therefore, AGMD has been the most widely studied configuration for seawater MD desalination at pilot-scale level [15–17].

In AGMD, a stagnant air gap is maintained between the membrane and the condenser channel by using a condenser foil. The stagnant air gap functions as a thermal insulation layer. As a result, the heat loss due to conduction, which is intrinsic to DCMD, is noticeably reduced in AGMD. Moreover, because the distillate and coolant are separated by the condenser foil, in a single-pass AGMD process seawater at ambient temperature can be used as the coolant prior to being externally heated and fed into the evaporator channel. The latent heat of condensation can be recovered to pre-heat the feed, thus reducing the thermal energy consumption of AGMD [10,18,19]. It is noteworthy that amongst the aforementioned configurations, only AGMD permits the latent heat recovery without an external heat exchanger. In addition, cooling, which must be used in other configurations, can be excluded in single-pass AGMD, hence further reducing its thermal energy consumption. However, the stagnant air gap also increases the overall resistance to mass transfer; therefore, AGMD is usually operated at a lower water flux compared to other configurations [16,17,20].

To date, there have been only few studies on process optimisation of AGMD desalination at pilot-scale with respect to distillate production and thermal and especially electrical energy consumption. As a notable example, Guillen-Burrieza et al. [15] investigated the performance of two pilot-scale AGMD systems using synthetic NaCl solutions as the feed. They elucidated the influences of feed inlet temperature and water circulation rate on water flux, distillate quality, and thermal energy consumption of the systems. However, they did not consider membrane fouling propensity and electrical energy consumption [15]. Koschikowski et al. [10] reported experimental investigations on eight stand-alone, solar-powered pilot AGMD systems for drinking water production from seawater. The distillate production rate of the systems for one typical day and for over three years of operation was evaluated. Nevertheless, Koschikowski et al. [10] did not assess the energy consumption of their systems.

Given the significant research gap with respect to the optimisation of energy consumption and water production rate of AGMD for seawater desalination, this study aims at elucidating the influences of operating conditions on the performance and thermal and electrical energy consumption of a single-pass, pilot-scale AGMD process. The effects of temperature and concentration polarisation effects and feed salinity on distillate production rate and energy consumption of the process were analysed. The feasibility of a single-pass pilot AGMD to produce fresh water from actual seawater without any pre-treatment was also demonstrated.

2. Materials and methods

2.1. Materials

2.1.1. Pilot AGMD system

A pilot AGMD system (Fig. 1) was used. The system consisted of a spiral-wound AGMD membrane module (Aquastill, Sittard, The Netherlands), a feed tank, a water-circulating pump, temperature and pressure sensors, and a magnetic flow meter. The spiral-wound membrane module had 6 evaporator channels, 6 condenser channels, and 12 distillate channels. Each evaporator channel was formed with microporous low-density polyethylene (LDPE) membranes with nominal pore size of 0.3 μm, thickness of 76 μm, and porosity of 85%. Aluminium foils were used to create the condenser channels. Mesh spacers, 1 mm in thickness, were inserted between the evaporator channels and condenser channels to create the distillate channels. Mesh spacers with thickness of 2 mm were also used in the evaporator and condenser channels to minimise temperature and concentration polarisation effects. Key characteristics of the spiral-wound membrane module are summarised in Table 1.

The spiral-would AGMD membrane module had been designed specifically to recover the latent heat of condensation. Briefly, saline solution from the feed tank first entered the condenser channels of the membrane module to primarily function as the coolant. When the saline feed solution (coolant) was flowing along the condenser channels, it facilitated the condensation of water vapour that crossed the membranes from the evaporator channels, and simultaneously was pre-heated. The pre-heated saline solution leaving the condenser channels was further heated using an external heat exchanger. The heated saline solution was then fed into the evaporator channels, where water vapour was formed and diffused across the membranes to the distillate channels. The warm concentrate (i.e., the brine) leaving the evaporator channels was returned to the feed tank. To simulate single-pass operation, the distillate was also returned to the feed tank, and a cooler was employed to maintain the constant temperature of the saline solution in the feed tank (Fig. 1).

Temperatures of the process stream at the inlet and outlet of the condenser and evaporator channels were measured using four temperature sensors. The hydraulic pressure drop along the spiral-wound membrane module was measured using two pressure sensors. A magnetic flow meter was placed before the inlet of the condensers channels to measure the water circulation rate. The temperature and pressure sensors and the flow meter were connected to the supervisory control and data acquisition system of the pilot system for continuous measurement and data recording. Electrical conductivity of the feed and the distillate was measured using Orion 4-Star Plus meters (Thermo Scientific, Waltham, Massachusetts, USA). Distillate production rate of the process was measured using a 500 mL gradual cylinder and a stopwatch.

2.1.2. Feed solutions

Tap water, synthetic NaCl solution, and seawater were used as feed solutions. Seawater was collected from Bulli beach (New South Wales, Australia) and was used without any pre-treatment. The seawater had electrical conductivity, pH, and total dissolved solids of 55.0 ± 0.5 mS/cm, 8.35 ± 0.05, and 35,000 ± 250 mg/L, respectively. The total organic carbon (TOC) concentration of this seawater was less than 2 mg/L. The synthetic NaCl solution having