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Optimising thermal efficiency of direct contact membrane distillation by brine recycling for small-scale seawater desalination

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HIGHLIGHTS

- Brine recycling increased water recovery and thermal efficiency of DCMD.
- Optimal thermal efficiency was achieved at water recovery from 20 to 60%.
- Increasing feed temperature & decreasing circulation flow enhanced thermal efficiency.
- DCMD of seawater at ≤70% water recovery could be achieved without membrane scaling.
- Excessive water recovery (≥80%) could lead to severe membrane scaling.

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ABSTRACT

A technique to optimise thermal efficiency using brine recycling during direct contact membrane distillation (DCMD) of seawater was investigated. By returning the hot brine to the feed tank, the system water recovery could be increased and the sensible heat of the hot brine was recovered to improve thermal efficiency. The results show that in the optimal water recovery range of 20 to 60% facilitated by brine recycling, the specific thermal energy consumption of the process could be reduced by more than half. It is also noteworthy that within this optimal water recovery range, the risk of membrane scaling is negligible — DCMD of seawater at a constant water recovery of 70% was achieved for over 24 h without any scale formation on the membrane surface. In contrast, severe membrane scaling was observed when water recovery reached 80%. In addition to water recovery, other operating conditions such as feed temperature and water circulation rates could influence the process thermal efficiency. Increasing the feed temperature and reducing the circulation flow rates increased thermal efficiency. Increasing the feed temperature could also mitigate the negative effect of elevated feed concentration on the distillate flux, particularly at a high water recovery.

1. Introduction

Desalination is a practical approach to augmenting fresh water supply in coastal areas [1]. Large-scale seawater desalination can be readily implemented using reverse osmosis (RO) and conventional thermal distillation [2]; however, the provision of small-scale seawater desalination for small and remote coastal communities remains a significant challenge. Indeed, RO requires intensive pre-treatment, high-pressure pumps, and duplex stainless steel piping, all of which are expensive and not practical for small-scale seawater desalination [3,4]. In the context of small-scale seawater desalination, membrane distillation (MD) can be a favourable alternative particularly because of the potential to use solar thermal and low-grade heat directly as the primary source of energy [5,6]. Unlike conventional thermal distillation processes, which require a large physical footprint, MD can retain most positive attributes of a typical membrane process, including modulation, compactness, and process efficiency [7,8]. The optimal thermal energy consumption of MD can be lower than that of conventional thermal distillation [9].

MD is a hybrid separation process that involves phase-change thermal distillation and microporous hydrophobic membrane separation [7,8,10]. In MD desalination, the hydrophobic nature of the membrane allows for the transport of water vapour while preventing the permeation of liquid water. As a result, dissolved solutes (i.e. inorganic salts that cannot be evaporated) and suspended particles can be completely rejected by MD. In addition, unlike in RO, the driving force for mass transport in MD is the partial water vapour pressure difference

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across the membrane, which is mainly induced by a transmembrane temperature difference. Thus, water flux in MD is negligibly affected by the feed water salinity. In other words, MD can be used for desalinating hypersaline feed streams or to achieve high water recovery desalination [11–16]. Given the discontinuity of the liquid phase across the membrane and a small hydraulic pressure on the membrane surface, MD is less susceptible to membrane fouling compared to RO, and hence does not require extensive pre-treatment [7]. More importantly, due to the absence of high hydraulic pressure, which is required for RO, non-corrosive and inexpensive plastic materials can be used for MD infrastructure (i.e. membrane modules, vessels, and piping), thus significantly reducing capital costs. Furthermore, by using a microporous membrane to facilitate the transport of water vapour, MD is more compact and thus has a significantly smaller footprint compared to conventional thermal distillation. Finally, MD is often operated at feed temperature ranging from 40 to 80 °C, which coincides with the optimal range of most thermal solar collectors [17]. Given these attributes, MD is arguably the most promising candidate for portable, stand-alone, and solar driven seawater desalination applications [17–19].

In practice, the use of MD for seawater desalination is still largely restricted to pilot-scale demonstrations [7]. Technical challenges, namely intensive energy consumption and membrane pore wetting, must be overcome before seawater desalination by MD can be commercially realised. As a phase-change separation process, MD consumes significant heating and cooling energy to perform the phase conversion. Consequently, all MD processes reported in the literature demonstrate an energy consumption of several orders of magnitude higher than that of RO [18,20,21]. In addition, to sustain its separation functionality, MD requires the membrane pores to be dry. In seawater applications, organic matter and scale formed on the membrane surface can alter the membrane hydrophobicity, which may lead to liquid intrusion into the pores, and, subsequently, water flux reduction and deteriorated distillate quality [22–24].

Depending on the methods applied to generate its driving force, MD can be divided into four basic configurations, including vacuum, air gap, sweeping gas, and direct contact membrane distillation. Among these configurations, direct contact membrane distillation (DCMD) has the simplest arrangement [7], and is deemed best suited for small-scale desalination applications [7,8]. DCMD has also been the most studied configuration in the MD literature [7]. However, heat loss due to conduction through the membrane in DCMD can be significant because of its simple arrangement (i.e. the hot feed and the cold distillate are both in contact with the membrane). Thus, DCMD may have a lower thermal efficiency (i.e. higher thermal energy consumption per unit volume of distillate) compared to other MD configurations.

Several attempts have been made to reduce energy consumption and thus enhance thermal efficiency of DCMD desalination processes. As a notable example, Lin et al. [25] investigated the coupling of DCMD with an external heat exchanger to recover the latent heat accumulated in the distillate stream, thus enhancing process thermal efficiency. The authors demonstrated that if infinite membrane and heat-exchanging surface area was available, a minimum specific heat consumption of DCMD (i.e. with a heat exchanger) of 0.03 MJ/L could be achieved by optimising the ratio between the feed and distillate flow rates. However, it is impractical to have an infinite membrane and heat-exchanging surface; thus, in practice, brine recycling can be used to improve water recovery and thermal efficiency [25]. Brine recycling for water recovery and thermal efficiency enhancement has also been suggested by Saffarini et al. [26]. Brine recycling enhances the utilisation of the available membrane surface area. In other words, brine recycling can be used to optimise the thermal efficiency without the need of increasing membrane surface area (or module size). The cost of membranes is significant [27] and this attribute is particularly important for small-scale desalination applications. It is noteworthy that no previous studies have experimentally evaluated brine recycling in DCMD of seawater.

A major challenge for brine recycling during DCMD of seawater is to manage the negative effects of increased feed salinity associated with high water recovery on water flux, distillate quality, and membrane scaling. This study aims to elucidate the relationship between thermal efficiency, water recovery, and membrane scaling in DCMD of seawater with brine recycling. The effects of operating conditions, including water recovery, feed temperature, and water circulation rates, on thermal efficiency of the process were systematically examined. The risk of membrane scaling at a high water recovery from actual seawater was also investigated.

2. Materials and methods

2.1. DCMD test unit

A flow diagram of the DCMD unit used in this study is shown in Fig. 1. The membrane cell, provided by Aquastill (Sittard, The Netherlands), was composed of two polypropylene (PP) semi-cells. Each semi-cell had a flow channel with depth, width, and length of 0.2, 10, and 50 cm, respectively, forming an active membrane area of 500 cm^2. A flat-sheet, low-density polyethylene (LDPE) membrane (also provided by AquaStill) having nominal pore size of 0.3 μm, thickness of 76 μm, and porosity of 85% was installed between the two semi-cells to form the feed and distillate channels. PP spacers were used in both channels for improved flow turbulence. Two variable-speed gear pumps (Model 120/IEC71-B14, Micropump Inc., Vancouver, Washington, USA) were used to circulate the feed and distillate through the membrane cell. Two rotameters, positioned before the inlet of each channel, were used to monitor the circulation flow rates of the feed and distillate.

Feed water from a storage tank flowed into the MD feed tank by gravity via a float valve. The MD feed tank was heated using a submerged heating element connected to a temperature control unit. A temperature sensor positioned immediately before the inlet of the feed channel was used to regulate the feed water temperature. Another temperature sensor was installed at the outlet of the feed channel to monitor the feed temperature drop along the channel. A peristaltic pump (Masterflex, John Morris Scientific Pty Ltd., Australia) was used to bleed the concentrated brine from the MD feed tank when necessary (see Section 2.3). A chiller (SC200-PC, Aqua Cooler, Sydney, New South Wales, Australia) was used to control the distillate temperature through a stainless steel heat-exchange coil submerged directly into the distillate tank. The temperatures of the distillate entering and leaving the cell were monitored by two other temperature sensors. A digital balance (PB32002-S, Mettler Toledo, Inc., Hightstown, New Jersey, USA) connected to a computer was used to weigh the excess distillate flow for determining the water flux.

2.2. Analytical methods

Electrical conductivity of the feed and distillate was measured using Orion 4-Star Plus meters (Thermo Scientific, Waltham, Massachusetts, USA). Contact angle of the membrane surface before and after experiments was measured by the sessile drop technique using a Rame-Hart Goniometer (Model 250, Rame-Hart, Netcong, New Jersey, USA). Milli-Q water was used as the reference liquid for the contact angle measurements. Morphology and composition of the membrane surface were examined using a low vacuum scanning electron microscope (SEM) coupled with an energy dispersive spectrometer (EDS) (JOEL JSM-6490LV, Japan). The membrane samples were air-dried and then directly used (i.e. without coating) for SEM-EDS analysis.

2.3. Experimental protocols

2.3.1. Feed solutions

Milli-Q water, synthetic 35,000 mg/L NaCl solution, and pre-filtered seawater were used as feed solutions. Seawater was collected from