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Application of vacuum membrane distillation for small scale drinking water production

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HIGHLIGHTS

- Loose crystal deposition (scaling) was observed in the V-MEMD module.
- Permeate vacuum pressure and feed flow velocity influenced the crystal formation.
- Periodic water flushing was effective to remove the deposits in V-MEMD.
- V-MEMD is suitable for small scale application with a projected 70% recovery.

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ABSTRACT

This study evaluated the applicability of a modified design vacuum enhanced-multi effect membrane distillation (V-MEMD) for drinking water production with feed solution containing NaCl and $CaSO_4$. The applicability was studied in terms of flux, scale formation and ease of cleaning. A slight flux decline (18–20%) was observed with loosely deposited crystals in the membrane module during the 920 min of the operation. Larger formation of crystal (volume weighted mean size, D[4,3]) was observed in the final feed brine ($D[4,3]_{\text{brine feed}} = 455.96\ \mu m$) compared to that inside the module ($D[4,3]_{\text{brine module}} = 62.68\ \mu m$). The loose crystal deposition was attributed to the absence of hydraulic pressure, low feed temperature, high turbulence ($Re = 5665.6$) and short membrane retention time (21.6 s). The crystal formation in the membrane module, $D[4,3]_{\text{brine module}}$ increased with reduced permeate side vacuum and lower feed velocity. Periodic DI water flushing was found to be efficient to remove the scaling. The feed component mass balance showed that most of the components were able to be removed with 2 L DI water flushing. A 70% recovery ratio was projected for a scaled-up unit, highlighting the suitability of the V-MEMD as a small scale system for drinking water production.

1. Introduction

Around 40% of the world's population lives in arid and semi-arid regions with low rainfall. Globally, these regions are facing challenges of falling water tables and increasing ground water salinity, resulting in water scarcity [1]. In Australia, these inland arid and semi-arid areas are mostly populated by indigenous people that rely on the brackish groundwater as drinking water source [2]. The brackish groundwater in Australia is highly saline, with total dissolved solids (TDS) ranging from 15,000–30,000 mg L^{-1} [3]. That apart, some of this brackish ground water contains high ion concentrations such as ferrous. The consumption of low quality drinking water has been linked to the poor health rate within these indigenous communities [4].

The challenge of applying pressure driven membrane desalination process such as reverse osmosis (RO) for treating saline inland brackish ground water is the osmotic pressure constraint, high electric energy requirement and low recovery rate at high salinity [5]. This results in a high volume of brine waste, requiring inland brine management [6]. Further, RO operations are built as large centralized desalination plants due to the energy recovery capacity in large plants [7]. As such, RO systems are mainly suitable for areas of high population density.

Presently, membrane distillation (MD) technology, a thermal integrated membrane process, is an imminent technology for the production of drinking water from high saline water. As a vapor pressure operated system, MD is not restricted by salt concentration in saline feed solutions and therefore can achieve good quality distillate with

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minimal brine discharge [7]. Further, MD system can be built as a standalone compact system suitable for small community application. The temperature requirement for MD operation is generally between 60 °C and 80 °C [7,8]. The relatively low temperature rate compared to traditional distillation process enables MD to be coupled to alternative energy source such as solar [7].

The potential of MD as a stand-alone solar operated system has been investigated by previous studies. For instance, a modelling study established the feasibility of solar-powered MD for water production from brackish water [9]. Another study demonstrated the potential of hollow fiber direct contact membrane distillation (DCMD) for fluoride removal from brackish water, achieving a maximum permeate flux of 35.6 $L\,m^{-2}\,h^{-1}$ at 80 °C feed temperature. However, the study observed membrane scaling from $CaCO_3$ precipitation [10].

It is important to acknowledge that the characteristics of saline brackish groundwater, specifically the presence of sparingly soluble salts, could intensify scaling development in MD thermal operation. For instance, a DCMD study on drinking water production with seawater reported permeate flux decline attributed to fouling that was intensified under MD thermal application [11]. Two other studies investigated the performance of MD for the production of high purity water from tap water and these studies observed precipitation of $CaCO_3$ onto the membrane surface [12,13]. A long-term DCMD study with actual seawater reported a permeate flux decline from 23.8 $L\,m^{-2}\,h^{-1}$ to 14.4 $L\,m^{-2}\,h^{-1}$ after 30 days of operation and observed membrane fouling due to inorganic scalants [14]. It is therefore essential to investigate the scaling development in MD to verify the feasibility of MD application as a stand-alone system for saline brackish groundwater.

Our previous study established the operation capacity of a modified design VMD system under saline condition [15]. This novel system is referred to as 'one stage vacuum multi effect membrane distillation (V-MEMD)'. This system uses the concept of a multi stage effect design, in which the system is incorporated with an internal heating and cooling unit. These features make the V-MEMD system beneficial as a compact designed unit that operates at low feed temperature. A detailed scaling evaluation on this system would provide valuable information of the performance and related maintenance issues for practical site application. In this regard, a number of bench-scale MD studies investigating scaling performance, have highlighted the prevalence of $CaSO_4$ scaling in MD, in comparison to other types of salts such as $CaCO_3$ and Na_2SiO_3 [16–18]. $CaSO_4$ is one of the common inorganic salts in natural water sources such as groundwater [16]. Further, the solubility capacity of $CaSO_4$ reduces as the temperature is increased, which is referred to as inverse solubility. Previous studies have highlighted on the inverse solubility behavior of $CaSO_4$ at temperature higher than 50 °C [16,19]. Upon exceeding the soluble capacity, $CaSO_4$ precipitates from solution to solids. Hence, in this paper, the scaling development of the V-MEMD system was analyzed with $CaSO_4$ under saline condition. This study evaluated the influence of different operating conditions on the scaling development. Further, the effectiveness of cleaning cycle procedure for the V-MEMD system was evaluated in terms of recovery rate. These investigations enabled to determine the performance and maintenance requirement of the V-MEMD system for practical site application.

2. Material and methods

2.1. Experimental set up

2.1.1. One stage vacuum multi effect membrane distillation (V-MEMD)

Experiments were conducted with a V-MEMD system designed by MemSYS, Germany. This system is composed of a steam raiser, a membrane module (vapor–liquid stage) and a condenser, which combines the basic concept of VMD with a multi effect distillation process system. As three effects; heating effect (steam-raiser), evaporation-condensation effect and cooling effect (condensation) occur in a single system, it is termed one stage V-MEMD (Fig. 1). In the V-MEMD system, the thermal setting is based on the steam raiser/heating temperature, T_h [15,20]. This enabled the system to be operated at a low bulk feed temperature. Compared to a conventional VMD design, the V-MEMD system design has the advantage of less heat loss due to internal heating and condensation [20]. In the one-stage V-MEMD system, water is heated by an external heat source and turned into steam in the steam raiser unit. Hot steam flows and condenses at the condensation foil (made of polypropylene material), releasing heat to the feed water. The space between the foil and membrane is the feed water channel. In the feed channel, the feed water is heated by the heat energy released from the steam raiser unit and evaporates upon contact with the membrane surface. The vapor that penetrates through the membrane is condensed in the condensing stage as permeate. In this system, a larger pressure difference between the feed and permeate side was achieved with the presence of a vacuum pump at the permeate side. The vacuum pump sucked non-condensable gases. If non-condensable gases are not removed, it accumulates in the system and reduces the heat and mass transport. In the meantime, tap water was used as cooling water source for the condenser. The cooling water was not re-circulated to maintain a constant cooling temperature range. Outlet and inlet cooling temperature values were retrieved from the temperature sensor. The inlet temperature was 23.4 ± 0.2 °C and the outlet temperature was 25.5 ± 0.5 °C. The modular design of the V-MEMD system enables less specific heat transfer and heat consumption [20]. At the same time, the assembly of this system by single plate and frame structures enables easy sizing up according to capacity requirement. For instance, the one stage system can be incorporated with three to four membrane stages, increasing the output while maintaining a compact-size system.

2.2. Membrane

The membrane module in this system used a Polytetrafluoroethylene (PTFE) flat sheet hydrophobic membrane (General Electric, US). The membrane size was 0.33 m × 0.48 m with an effective membrane area of 0.16 m^2. The porosity and the thickness of membrane were 70 ~ 75% and 179 μm, respectively.

2.3. Feed solution

Scaling experiments were conducted with a saline $CaSO_4$ feed solution, a mixture of $CaCl_2$ and Na_2SO_4 with NaCl (feed I). The initial total dissolved solids (TDS) of feed I was 55.6 $g\,L^{-1}$. Meanwhile, feed II comprised of a mixed solution of Ca^{2+}, SO_4^{2-}, Mg^{2+}, Na^+, Cl^- and Fe^{3+} representing the main components of a saline groundwater at an initial TDS of 64.2 $g\,L^{-1}$ (Table 1). Deionized (DI) water and 0.1 M HCl acid were used as cleaning solutions.

2.4. Experimental procedure

2.4.1. Scaling measurement

The scaling development investigation study on the V-MEMD system was carried out with 20 L of saline $CaSO_4$ solution (feed I) at operating conditions of heating temperature, $T_h = 60$ °C, feed velocity, $v_f = 0.9\ ms^{-1}$, and permeate pressure, $P_v = 10.0$ kPa (condition I). To investigate the influence of permeate pressure rate on scaling development in the V-MEMD system, P_v was varied from 10.0 kPa to P_v of 12.5 kPa (condition II) and P_v of 15.0 kPa (condition III). The higher permeate pressure corresponds to a lower vacuum condition. Meanwhile, to investigate the influence of turbulence, v_f was varied from 0.9 ms^{-1} to 0.6 ms^{-1} (condition IV) and 0.3 ms^{-1} (condition V) with constant P_v of 10.0 kPa. The details of the experimental conditions are given in Table 2.

For the purpose of experimental investigation of scaling, a number of measurements were used as below: