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Seawater membrane distillation desalination for potable water provision on remote islands — A case study in Vietnam

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ABSTRACT

Membrane distillation (MD) is considered the most suitable process for small-scale seawater desalination to augment fresh water supply in remote areas. In this study, a pilot seawater MD desalination process was trialled for potable water supply on a remote and isolated island in Vietnam. The pilot MD system was based on air gap membrane distillation (AGMD), which is considered the most energy-efficient configuration of MD. The AGMD configuration allowed for the utilization of the latent heat of water vapor condensation to pre-heat the seawater feed, thus reducing the energy consumption of the pilot system. This energy-efficient configuration, however, had a small temperature difference between the hot feed and the coolant streams and therefore exhibited low water flux. Nevertheless, the low water flux of the pilot system was compensated by the large membrane surface area of the spiral-wound AGMD membrane modules. Equipped with a total membrane surface of 77.7 m^2, the pilot AGMD process operated at the evaporator inlet and coolant inlet temperature of 70 °C and 25 °C respectively could produce 46 L h^{-1} of pure distillate that met the Vietnamese potable water standards. Particularly, the measured specific energy consumption of the pilot AGMD system was only 87 kWh.m^{-3}, resulting in a production cost of 20.5 US$ per m^3 of potable water.

1. Introduction

Fresh water shortage is a major hurdle to the social and economic growth of many remote islands in Vietnam, and An Binh island of Ly Son District can be a notable example. An Binh is a small island with the size of 0.69 km^2 and an approximate population of 450 people. Due to its unique geological structure, An Binh has no ground water. There is a seawater reverse osmosis (RO) desalination plant installed on An Binh island; however, this plant has been out of function for several years due to the issues with membrane fouling that entails costly membrane replacement. Fresh water use on An Binh island has to rely on limited seasonal rainwater and costly fresh water imported from Ly Son island locating at 7 km from the An Binh island. Therefore, fresh water is a vital but scarce resource to people living on An Binh island. In this context, deployment of a robust and cost-effective seawater desalination process to augment the fresh water resource and provide sufficient potable water is of an urgent need for An Binh island.

Membrane distillation (MD) has been considered the most suitable process for small-scale, decentralized seawater desalination for fresh water provision on remote and isolated islands [1–3]. As a thermally driven membrane separation process, MD embodies several notable attributes such as: low operating pressure and temperature, simple feed water pre-treatment, and high rejection of dissolved salts and other non-volatile substances [4–6]. Given these attributes, MD offers robust and cost-effective means of fresh water provision via seawater desalination. Indeed, a great number of pilot MD processes have been demonstrated for seawater desalination for fresh water production in many locations around the world [2,7–10]. Of a particular note, most of the pilot MD processes demonstrated for seawater desalination rely on air gap membrane distillation (AGMD), which is one of the four basic MD configurations [5,6]. This is because AGMD enables the internal water vapor condensation and the recovery of its latent heat without the need for external heat exchangers and condensers as required in other MD configurations [7,8,10].

In this study, for the first time in Vietnam, a pilot seawater AGMD desalination process was trialled for potable water provision on An Binh island. The pilot AGMD process was fed with real seawater collected from a beach well on the island. The influences of key operating conditions on the performance of the pilot process were examined. Then, an extended pilot operation with the real seawater feed under the optimal conditions was conducted to demonstrate the technical and economic feasibility of seawater AGMD desalination for potable water supply on An Binh island given its unique geological and social attributes.

2. Materials and methods

2.1. Materials

A pilot AGMD system was used in this study (Fig. 1). The pilot system had 3 identical spiral-wound AGMD membrane modules positioned above a cool feed water tank and a hot oil bath. The spiral-wound AGMD membrane modules were provided by Aquastill (Sittard, The Netherland). The specifications of these membrane modules are shown in Table 1. Each membrane module had 12 evaporator channels, 12 coolant channels, and 24 distillate channels. The arrangement of the water channels inside the spiral-wound AGMD membrane modules is illustrated in Fig. 2. Microporous hydrophobic low-density polyethylene (LDPE) membranes with nominal pore size of 0.3 μm, thickness of 76 μm, and porosity of 85% were used to form the evaporator channels, while the coolant channels were created by using plastic-coated aluminium

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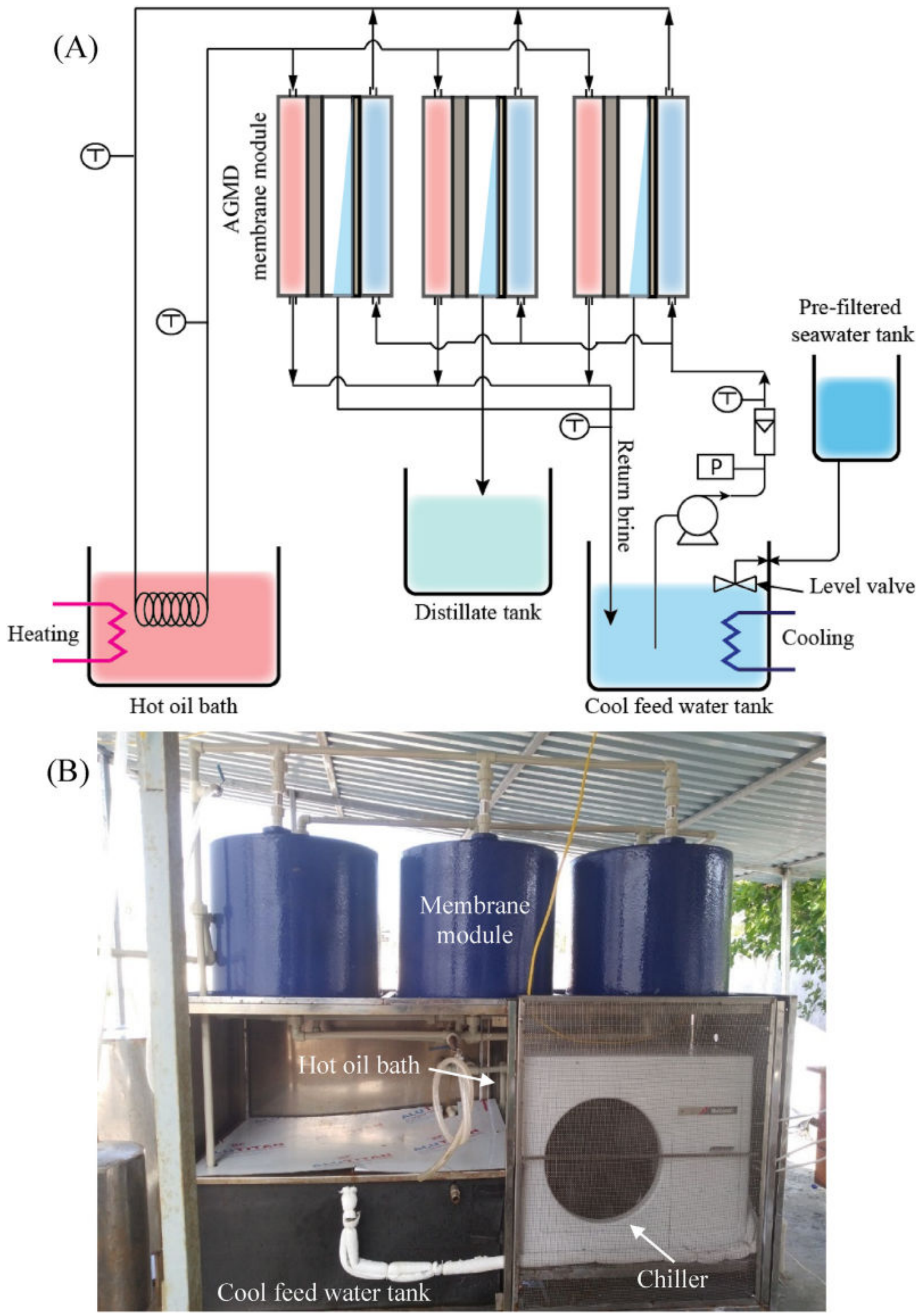

Fig. 1. (A) the schematic diagram and (B) the picture of the pilot AGMD system used in this study. The pilot system had three parallel AGMD membrane modules placed above the cool feed water tank and the hot oil bath (behind the chiller).

foils. Plastic mesh spacers (i.e. 1 mm thick) were alternately inserted between the evaporator and coolant channels to form the distillate channels. All water channels with the same length × width of 2.7 × 0.4 m were spiral-wound inside the membrane module. Given this arrangement, each membrane module had an active membrane surface area of 25.9 m^2 packed in a cylindrical volume with the diameter × height of 0.6 × 0.5 m. The membrane modules and other components of the pilot ADMD system were made from plastic to avoid corrosion caused by the saline environment on the island.

During the AGMD process, the cool seawater feed was pumped into the coolant channels (Fig. 1). As it travelled along the coolant channels, the cool seawater feed functioned as a coolant for the condensation of water vapor on the other side of the aluminium foils, and hence it was pre-heated by the latent heat of water vapor condensation. The pre-heated seawater leaving the coolant channels was then circulated through stainless-steel coins submerged in the hot oil bath to be additionally heated prior to entering the evaporator channels. When flowing along the evaporator channels, the hot seawater evaporated to generate

Table 1
Specifications of the spiral-wound AGMD membrane modules provided by Aquastill.

Effective membrane surface area (m^2)	25.9
Diameter of the module (m)	0.6
Height of the module (m)	0.5
Length of envelope (m)	2.7
Width of envelope (m)	0.4
Thickness of the evaporator channels (mm)	2.0
Thickness of the coolant channels (mm)	2.0
Thickness of the distillate channels (mm)	1.0
Number of evaporator channels	12
Number of coolant channels	12
Number of distillate channels	24

water vapor at the feed membrane surface. Due to the difference in water vapor pressure, water vapor from the feed membrane surface moved through the membrane pores and the air gap before arriving at the cool aluminium foil surface, where it was condensed to distillate. As fresh water was extracted from the hot seawater feed inside the evaporator channels, the hot seawater was concentrated and cooled. The warm and concentrated seawater (i.e. brine) leaving the evaporator channels was then returned to the feed water tank for the next cycle [11].

A submerged corrosion-resistant pump was used for water circulation in the pilot AGMD process. A magnetic flow meter was placed prior to the inlet of the coolant channels to measure water circulation rate. Temperature sensors (i.e. PT100 type) were placed prior to the inlet and after the outlet of the coolant and evaporator channels for monitoring and regulating water temperatures. A heater was used to heat the hot oil bath while the temperature of water in the cool feed water tank was maintained constant using a chiller (Fig. 1).

Actual seawater was used as the feed water to the pilot AGMD system in this demonstration. Seawater from a beach well on An Binh island was pre-filtered using microfiltration (MF) hollow fiber membrane (i.e. pore size of 1.0 μm) before feeding to the AGMD feed tank. Key characteristics of the pre-filtered seawater feed are presented in Table 2.

2.2. Analytical methods

The total dissolved solids (TDS) of the water samples were measured using the gravimetric method. An Orion 4-Star Plus pH/conductivity meter (Thermo Scientific, Waltham, Massachusetts, USA) was used to measure the pH and electrical conductivity of water samples.

During the pilot AGMD process, the distillate production rate (i.e. Q in $L.h^{-1}$) was determined using a 1000 mL graduated cylinder to measure the volume of distillate obtained in a 2-min time interval. Water flux (i.e. J_{water} in $L.m^{-2}.h^{-1}$) of the pilot AGMD process was calculated as below:

$$J_{water} = \frac{Q}{A} \quad (1)$$

where A was the membrane surface area of the modules (77.7 m^2).

The electrical energy consumption of the pilot AGMD process was monitored using an electricity meter equipped with the pilot system. The specific energy consumption (*SEC*) of the pilot AGMD process was calculated as:

$$SEC = \frac{P}{Q} \times 1000 \quad (2)$$

where *SEC* was in $kWh.m^{-3}$, P was the total power fed to the pilot system (kW), and Q was the distillate production rate ($L.h^{-1}$). The value of *SEC* presented the amount of electrical energy required to produce 1 m^3 of distillate from the seawater feed. In this study, electrical energy was consumed for heating, cooling, and a small portion for water pumping (including the pump of the MF pre-filter), and it was provided by the photovoltaic (PV) panel field installed on An Binh island. This PV panel field sufficiently provided electricity to the whole community on the island during daytime.

2.3. Experimental protocols

Two sets of experiments were conducted with the pilot MD system in this study. The first set of experiments were to examine the influences of operating conditions on the performance of the pilot system with respects to distillate production, distillate conductivity, and *SEC*. In these experiments, when the system had reached stable operating conditions (e.g. evaporator inlet temperature and water circulation rate), it was operated for 1 hour and its distillate production, distillate conductivity, and *SEC* were measured once in every 10 minutes. The second set of experiments were to assess the performance of the pilot MD system during an

Table 2
Key characteristics of the pre-filtered seawater feed to the pilot ADMD process.

Key characteristics	
pH	8.2 ± 0.1
Total dissolved solids, TDS ($mg.L^{-1}$)	27,000 ± 500
Electrical conductivity ($\mu S.cm^{-1}$)	38,300 ± 100
Total organic carbon, TOC ($mg.L^{-1}$)	<1.0

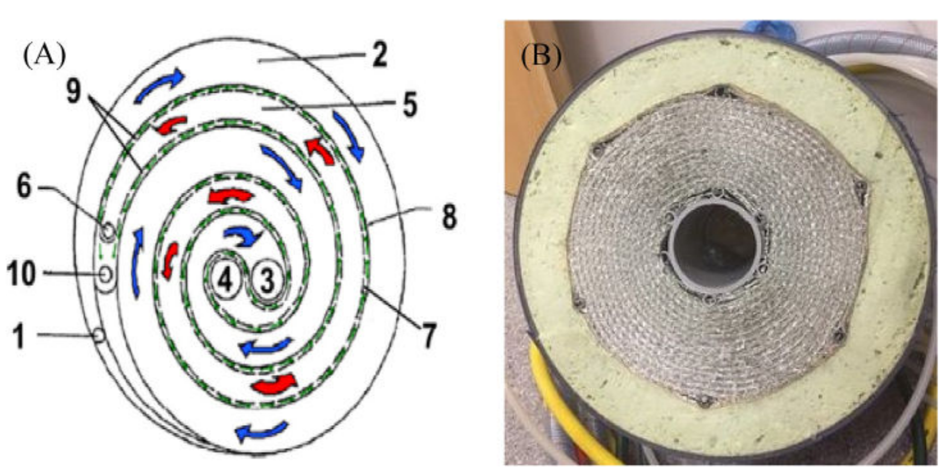

Fig. 2. (A) the arrangement of water channels inside the spiral-wound AGMD membrane module (with courtesy from Ref. [12]) and (B) the picture of a cross-cut of the spiral-wound AGMD membrane module: (1) coolant inlet, (2) coolant channel, (3) coolant outlet, (4) evaporator inlet, (5) evaporator channel, (6) evaporator outlet, (7) distillate channel, (8) aluminium foil, (9) LDPE membranes, and (10) distillate outlet.

extended operation. The system was run for 7 days at constant operating conditions during daytime and put in standby mode at night. During this extended operation, daily average distillate production, distillate conductivity, and *SEC* of the pilot system were measured and recorded.

3. Results and discussions

3.1. Influences of operating conditions on the performance of the pilot AGMD system

Operating conditions of the pilot AGMD process include the coolant inlet temperature, the evaporator inlet temperature, and the water circulation rate. Amongst these operating conditions, the coolant inlet temperature has the least influence on the performance of the AGMD process [10,13]; therefore, only the evaporator inlet temperature and the water circulation rate were varied to examine their influences on the performance of the pilot AGMD process with the real seawater feed.

The experimental results demonstrate that operating the pilot AGMD process at high evaporator inlet temperature was beneficial with respects to the distillate production rate and the specific energy consumption (*SEC*). As shown in Fig. 3, elevating the evaporator inlet temperature increased the distillate production rate and reduced *SEC*. At the evaporator inlet temperature of 50 °C, the pilot AGMD process produced 23 L of distillate per hour and consumed nearly 140 kWh to obtain 1 m^3 of the distillate. When increasing the evaporator inlet temperature to 70 °C, the distillate production rate of the pilot AGMD process mostly doubled reaching 46 L h^{-1} while *SEC* reduced by 35% from 140 kWh.m^{-3} to 91 kWh.m^{-3}. It is necessary to note that elevating the evaporator inlet temperature at the constant water circulation rate resulted in an increase in both heating and cooling inputs to the pilot system (i.e. to additionally heat the warm feed water before the evaporator inlet and cool the warm brine returning to the feed tank). Nevertheless, the distillate production increased at a higher rate compared with the heating and cooling inputs, thus leading to the decrease in the *SEC* value of the pilot AGMD process. This is consistent with the results reported in previous studies using lab-scale and pilot AGMD processes [10,11].

Given the highest distillate production rate of 46 L h^{-1}, the water flux of the pilot AGMD process calculated using equation (1) was about 0.6 L m^{-2} h^{-1}. The obtained water flux of this pilot AGMD process was noticeably lower than those previously reported in the MD literature [10, 13–15]. The low water flux of the pilot AGMD process reported here was attributed to the small temperature difference between the coolant and the hot feed streams resulted from the long membrane channels (i.e. 2.7 m) of the AGMD modules. The measured temperature difference (ΔT) between the coolant outlet and the evaporator inlet was only 2.5 °C at the evaporator inlet temperature of 70 °C and the water circulation rate of 360 L h^{-1}. It is worth reminding that ΔT is considered the driving force for the water vapor transfer across the membrane in the MD process; therefore, the small ΔT inevitably led to the low water flux of the pilot AGMD process. Higher water flux can be achieved by either using membrane modules with shorter membrane channels or increasing the water circulation rate to raise ΔT [16]; however, these approaches might compromise the energy efficiency of the pilot AGMD process. More importantly, the pilot AGMD process operated at low water flux is less prone to membrane fouling and wetting which are vexing technical challenges to most MD processes reported in the literature [17]. Membrane fouling and wetting might result in the termination of the AGMD process. Therefore, low water flux operation to avoid membrane fouling and wetting was suitable for seawater desalination application on remote An Binh island.

The purity of the obtained distillate slightly changed with the evaporator inlet temperature. As demonstrated in Fig. 3, the electrical conductivity of the distillate increased from 45 μS.cm^{-1} to 57 μS.cm^{-1} when the evaporator inlet temperature was elevated from 50 °C to 70 °C. Indeed, the MD process can theoretically achieve a complete salt rejection and hence the distillate purity is negligibly affected by the operating feed temperature. The distillate electrical conductivity variation during the pilot AGMD process might be caused by the slight contaminations of the distillate tank and the dissolved gases from the air. Nevertheless, the low distillate electrical conductivity reported here confirms that distillate of high quality can be obtained directly from the AGMD desalination process of seawater with simple pre-treatment.

The water circulation rate exerted similar effects on the performance of the pilot AGMD process when comparing with the evaporator inlet temperature (Fig. 4). Increasing water circulation rate when the evaporator inlet and the coolant inlet temperatures were fixed resulted in a higher ΔT and hence increased distillate production rate. Higher ΔT required more heating and cooling inputs to the pilot system but the increase of heating and cooling inputs was lower than that of the distillate production rate. As a result, the measured *SEC* of the pilot AGMD process decreased when the water circulation rate was increased from 180 L h^{-1} to 360 L h^{-1}. The AGMD membrane modules used in this study were designed with the maximum water circulation rate of 600 L h^{-1}. However, a mild water circulation rate (i.e. ≤360 L h^{-1}) was deliberately

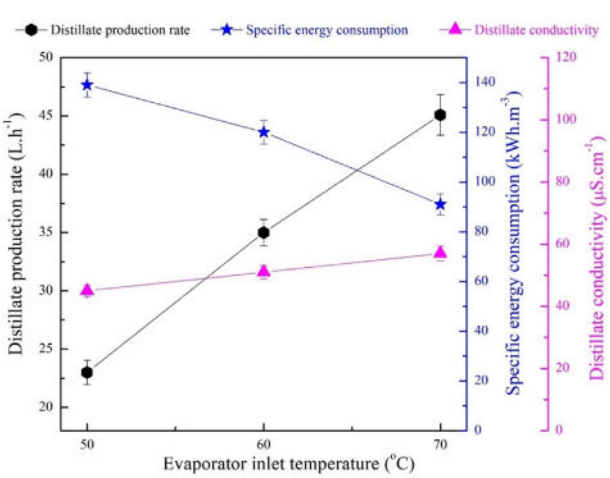

Fig. 3. The distillate production rate and specific energy consumption (*SEC*) of the pilot AGMD system with the real seawater feed at different evaporator inlet temperature ($T_{evap.in}$). Other operating conditions: water circulation rate F_{water} = 360 L h^{-1}, coolant inlet temperature $T_{cool.in}$ = 25 °C. Error bars represent the standard deviations of 6 measurements.

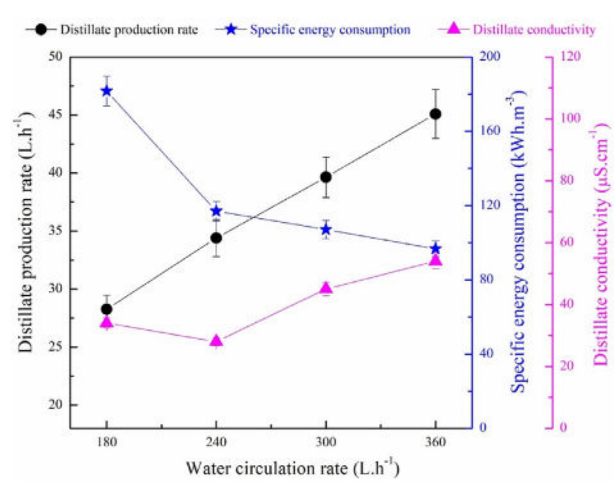

Fig. 4. The distillate production rate and specific energy consumption (*SEC*) of the pilot AGMD process with the real seawater feed at different water circulation rates. Other operating conditions: evaporator inlet temperature $T_{evap.in}$ = 70 °C, coolant inlet temperature $T_{cool.in}$ = 25 °C. Error bars represent the standard deviations of 6 measurements.

selected for this pilot demonstration to successfully avoid membrane wetting.

3.2. Performance of the pilot AGMD system during the extended operation

The optimal operating conditions from the pilot AGMD tests described in section 3.1 were used to assess the viability of the extended pilot AGMD operation with the real seawater feed. The experimental results obtained from the 7-day operation (i.e. spanning from the 26th July to the 2nd August 2020) demonstrate that seawater AGMD desalination is a practical approach to potable water provision at An Binh island (Fig. 5). During the extended operation, the pilot AGMD process was operated continuously during day time and ceased at night time. From the first to the seventh day of the pilot operation, the distillate production rate remained mostly constant at 45.8 L h^{-1} and *SEC* was around 87 kWh.m^{-3}. The distillate electrical conductivity varied between 40 μS.cm^{-1} and 60 μS.cm^{-1}. This low distillate electrical conductivity manifests that membrane fouling and wetting were effectively avoided during the extended pilot AGMD operation. The deliberately controlled low water circulation rate and water flux along with the high contact angle of the LDPE membrane (i.e. 126°) are the factors behind the success in preventing membrane fouling and wetting during the extended pilot AGMD process of the real seawater feed. Indeed, previous lab-scale studies have demonstrated that membrane fouling and wetting during seawater MD desalination processes can be effectively prevented by simple filtration pre-treatment of the seawater feed and controlling water flux to mitigate the negative effects of polarization on membrane fouling/scaling [14,17].

The key characteristics of the distillate obtained from the extended pilot AGMD process were provided in Table 3. The distillate was slightly acidic with pH of 6.5, which is typically for distilled water from a distillation process. It had total dissolved solids (TDS) and electrical conductivity of 28 mg L^{-1} and 39 μS.cm^{-1}, respectively. The total organic carbon (TOC), heavy metals, and Coliforms were undetectable in the obtained distillate. Given these specifications, the distillate obtained from the pilot seawater AGMD desalination with the real seawater feed met the Vietnamese potable water standard (QCVN 01:2009/BYT). However, to ensure its taste, the distillate was flowed through a mineral cartridge prior to supply to the end users on An Binh island.

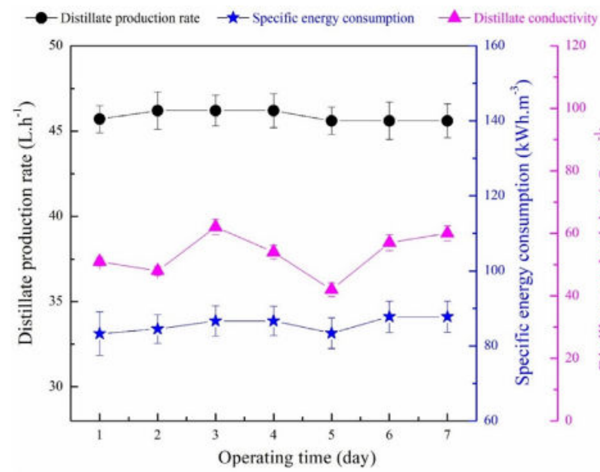

Fig. 5. The distillate production rate, specific energy consumption (*SEC*), and the distillate electrical conductivity during the extended pilot AGMD operation with the real seawater feed. Operating conditions: evaporator inlet temperature $T_{evap.in}$ = 70 °C, coolant inlet temperature $T_{cool.in}$ = 25 °C, water circulation rate F_{water} = 360 L h^{-1}. Error bars represent the standard deviations of 5 measurements.

Table 3
Key characteristics of the distillate obtained from the pilot AGMD process with the real seawater feed.

Key characteristics	
pH	6.5
Total dissolved solids, TDS (mg.L^{-1})	28
Electrical conductivity (μS.cm^{-1})	39
Total organic carbon, TOC (μg.L^{-1})	<4
Lead (μg.L^{-1})	<2
Manganese (μg.L^{-1})	<5
Mercury (μg.L^{-1})	<0.6
Arsenic (μg.L^{-1})	<1
Brommua (μg.L^{-1})	<1.5
Coliforms	0

3.3. Feasibility consideration of seawater AGMD desalination for drinking water provision on Ly Son island

The cost of drinking water from a desalination plant consists of capital expense (CAPEX) and operating expense (OPEX). As MD is an emerging process, the capital expense of seawater MD desalination process is hardly estimated but is envisaged to be significantly reduced in the future. Thus, in this pilot study, only the operating expense was considered and assessed. As the pilot seawater AGMD desalination process did not involve any chemicals or consumables, the operating expense of the potable water of this process was the sum of labour and energy costs. The labour and the electricity cost on An Binh island at the time of the pilot study was 13 US$ per day and 0.08 US$ per 1 kWh, respectively. Given the distillate production rate of 45.8 L h^{-1} (i.e. ~1 m^3.day^{-1}) and *SEC* of 87 kWh.m^{-3}, the operating expense of the pilot AGMD process was 20.6 US$ per 1 m^3 of potable water per day. This potable water production cost is highly practical in the context that people on An Binh island normally pay >50 US$ for 1 m^3 of potable water imported from Ly Son island. Therefore, the results reported in this study highlight the suitability of MD for strategic seawater desalination application.

4. Conclusions

This study trialled a pilot seawater AGMD desalination process for potable water provision on An Binh island of Ly Son District in Vietnam. The pilot system was composed of three energy-efficient spiral-wound AGMD modules. Using the AGMD membrane modules, the latent heat of water vapor condensation was utilized to pre-heat the seawater feed to reduce the energy input to the pilot AGMD process. The experimental results demonstrate that the pilot AGMD process using the AGMD membrane modules achieved limited water flux (i.e. 0.6 L m^{-2} h^{-1}) but could produce 46 L of high-quality distillate per hour with the specific energy consumption of 87 kWh.m^{-3} when operating at the evaporator inlet and coolant inlet temperature of 70 °C and 25 °C, respectively. An extended 7-day operation of the pilot AGMD process with real seawater feed was performed without any issues of membrane fouling and wetting, thus confirming both technical and economic feasibility of the seawater AGMD desalination application for potable water supply on An Binh island in Vietnam.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Le Quy Don Technical University; Vietnam Ministry of Science and Technology.

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