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Solar desalination by air-gap membrane distillation: a case study from Algeria

Djamel-Eddine Moudjeber[a], Alba Ruiz-Aguirre[b], Daniel Ugarte-Judge[c], Hacene Mahmoudi[a,*], Guillermo Zaragoza[d]

[a]*Faculty of Technology, University Hassiba Ben Bouali of Chlef, BP 151, Chlef, Algeria, Tel. +213 7 72475418; Fax: +213 27 72 6304; email: demoudjeber2@yahoo.fr (D.-E. Moudjeber), Tel. +213 7 77170833; Fax: +213 27 72 6304; email: h.mahmoudi@univ-chlef.dz (H. Mahmoudi)*
[b]*Engineering Department, Universidad de Almería – CIESOL, Ctra. Sacramento, s/n, 04120 La Cañada de San Urbano, Almería, Spain, Fax: +34 950 365015; email: alba.ruiz@psa.es*
[c]*Physical Sciences and Engineering Department, Université de Perpignan, 52 Avenue Paul Alduy, 66100 Perpignan, France, email: ugartedaniel88@gmail.com*
[d]*CIEMAT, Plataforma Solar de Almería, Ctra. de Senés s/n, 04200 Tabernas, Almería, Spain, Tel. +34950387941; Fax: +34 950 365015; email: guillermo.zaragoza@psa.es*

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ABSTRACT

Experiments were conducted with a commercial membrane distillation module, which has an air-gap membrane distillation (AGMD) and spiral-wound configuration. Tests were performed simulating the salinity and temperature of the water using as a case study the Albian aquifer in Algeria. Solar thermal energy from a field of stationary flat-plate solar collectors was supplied to the module. The total productivity of the AGMD system was analyzed for different operational conditions and compared with that from the RO system. The effect of brackish water temperature on the energy consumption was scrutinized, and the energy requirements assessed toward the design of a pilot unit for decentralized autonomous solar desalination. Results showed that for producing a higher volume of distillate, module with less surface area is better. Also, it was found that recovery ratio increases linearly with the temperature difference in both modules. The maximum value was 6% for the highest feed flow rate operated in module 1 with highest surface area. These values are much lower than those obtained with RO processes, which can reach 45%.

Keywords: Solar desalination; Albian aquifer; Air-gap membrane distillation (AGMD); Case study

1. Introduction

Many authors have noted the importance of using renewable energy in desalination, especially in arid regions such as in the Middle East North Africa (MENA) countries [1–4]. Solar energy seems to be the most adequate renewable resource for producing freshwater in this region [1]. Furthermore, membrane distillation (MD) is considered as a new emerging

*Corresponding author.

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thermal separation process suitable for desalination of brackish or seawater. In the MD process, a microporous hydrophobic membrane separates a hot stream from a cold stream with a temperature difference creating a vapor pressure difference that forces the vapor from the hot feed to pass through the membrane pores. The hydrophobicity of the membrane prevents the liquid passing through the membrane pores as long as the hydrostatic pressure is lower than the liquid entry pressure (LEP). A high LEP is achieved with a small pore size, low surface energy, and high surface tension for the feed [5]. Therefore, working with a low hydrostatic pressure gives a theoretical salt rejection factor (SRF) of 100%v (i.e. pure distillate). MD has other advantages, such as being able to run at atmospheric pressure and at temperature ranging between 60 and 80˚C, enabling the use of low-grade heat or renewable energies such as solar energy [6].

There are five possible configurations of MD: direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), permeate gap membrane distillation (PGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD). In all configurations, the hot water is in contact with the hydrophobic membrane. However, the difference is in the design of the cold side and the place where the distillate is collected in each case. The size of the air cavity plays a vital role in the efficiency of AGMD modules [7–9].

The MENA country of Algeria has great potential for use of MD technology since it has huge renewable energy resources, especially solar and wind power. Since its independence, Algeria has developed its own national strategy for renewable energy with the aim of sustainable development without causing environmental pollution [10]. However, there is a need to find out how to better exploit MD and solar energy technology for producing freshwater on a large scale.

In the current study, experiments were conducted with a commercial MD module which had an AGMD and spiral-wound configuration. Tests were performed simulating the salinity and temperature of the water using as a case study the Albian aquifer in Algeria. Solar thermal energy from a field of stationary flat-plate solar collectors was supplied to the module. The total productivity of the AGDM system was analyzed for different operational conditions and compared with that from the RO system. The effect of brackish water temperature on the energy consumption was scrutinized, and the energy requirements assessed toward the design of a pilot unit for decentralized autonomous solar desalination.

2. Air-gap membrane distillation

With AGMD, the stagnant air-gap reduces heat losses due to conduction thus increasing the thermal efficiency of the process (Fig. 1). In this configuration, the stagnant air separates the membrane from the condensation surface. However, it also imposes a mass transfer resistance which lessens the distillate flux. Consequently, the width of the air-gap plays an important role in the performance of AGMD modules [7–9]. All commercial MD modules use flat-sheet membranes. There are also plate and frame modules, which have shown difficulties in achieving a proper tightness and heat efficiency [6,11,12], and spiral-wound modules [13].

In the spiral-wound configuration, the flat-sheet membrane and the rest of compounds (spacers and condensation foils) are enveloped and rolled around a tube. This configuration allows enhancing the internal heat recovery (Fig. 1). The hot feed water flows through the evaporator channel and exits the module with a lower temperature after the evaporation. Water vapor passes through the membrane and condenses on the foil of the condenser channel. The latent heat of condensation and the sensible heat by conduction are transferred through the condenser foil to preheat the feed water in the condenser channel. So, less external heat from the solar collector is needed, reducing the specific thermal consumption of the process.

3. Case study region and design of a pilot unit for decentralized autonomous solar desalination

Algeria, the largest country in Africa, has a total area of 2,381,740 km^2 [14]. Its population is

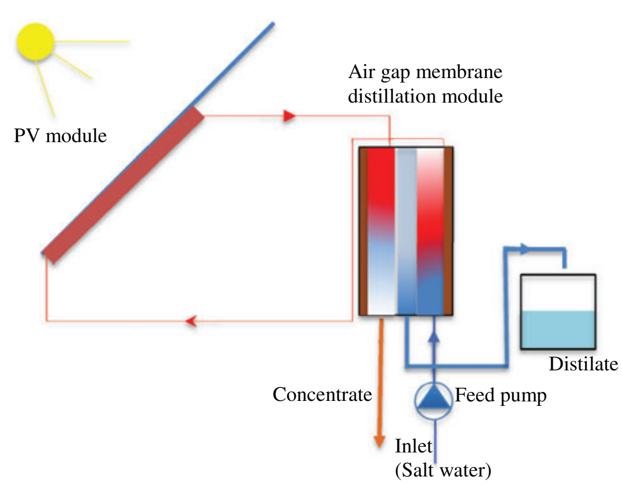

Fig. 1. Schematic diagram of AGMD process.

approximately 39.5 million with an annual growth rate of 1.7% [14]. The country is divided into four main physical regions, which extend from east to west across the country in parallel zones. A comprehensive description of the different zones was given by Mahmoudi et al. [15]. The northern zone which extends 80–190 km inland from the coastline has a typical Mediterranean climate with four seasons. This is the most humid area in the country, with an annual precipitation ranging from 400 to 1,000 mm [15]. This region has faced a chronic freshwater shortage for more than two decades mainly due to a lack of rain which has led to a significant drop in water reservoirs levels. To face this situation, thirteen mega desalination plants with a total capacity of 2.3 million m^3/d were constructed along the 1,400-km coastal line [16].

The southern 80% part of the country constitutes desert and is characterized by chronic lack of potable water. As a result, only 20% of Algeria's population lives in this region [17]. To remedy this situation, the country's government has launched an ambitious program for the demineralization and transfer of brackish water to the south, by taking advantage of the Continental Intercalaire (C.I.) aquifer, commonly referred to as the Albian aquifer [17]. This is an enormous geothermal reservoir (of water temperatures ranging from 35 to 70˚C), that covers approximately 1 million km^2, with its largest portion (~700.000 km^2) within Algerian territory. Aside from its low salinity, the reservoir water is of fairly good quality [17]. Moudjeber et al. [17] demonstrated the importance of using low-pressure reverse osmosis (LPRO) with blending for the Albian aquifer. According to the authors, it can help to produce high-quality freshwater and minimizing brine discharge in the aquifer.

The Algerian Sahara is characterized by the C.I. aquifer discovered in 1954 [18]. It is an extensive horizontal sandstone reservoir and ranks as one of the largest groundwater systems in the world commonly known as Albian aquifer, which is composed of Upper Carboniferous to Lower Cretaceous rocks and present underneath an area of about 1 million km^2 shared between Algeria, Tunisia, and Libya (Fig. 2). The basin contains approximately 60 trillion m^3 of brackish groundwater water. The depth of the reservoir varies between 400 m in the west to more than 1,800 m in the east [19]. Deeper wells can provide water at 100–400 L/s flow rate and average total dissolved solids (TDS) less than 2 g/L. Highest discharge temperature can reach 73˚C [20].

Moudjeber et al. [17] reported that with respect to the acceptability criteria defined by the Algerian potable water standards, the total salt content (i.e. mineralization) of the Albian aquifer is in line with the maximum allowable concentration, which is 2,000 mg/L. Desalination is thus a potential solution to allow for use of this water source for producing potable water.

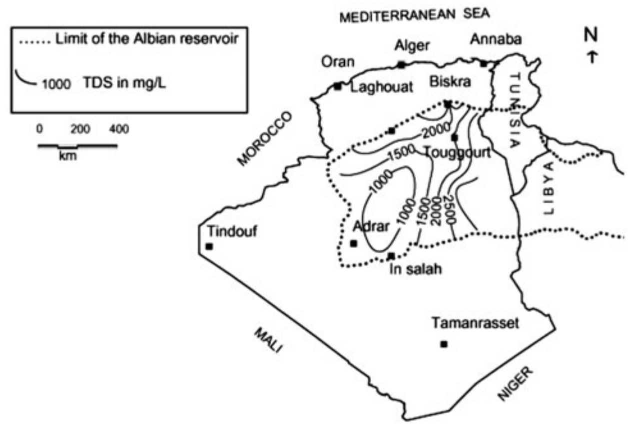

Fig. 2. The Albian reservoir.
Source: Reprinted from Ref. [21] with permission from Elsevier.

The sunshine duration overall Algerian national territory exceeds the 3,000 h annually (Table 1) reaching up to 3,900 h on the high plateaus and the Sahara [22]. The potential of non-conventional or renewable energy is thus dominated by solar energy source with applications (photovoltaic or thermal) that are very favorable in the south of Algeria [23].

In the current study, the design of a pilot unit for decentralized autonomous solar desalination is presented. The system was based on MD; using AGMD spiral-wound modules which were previously tested with water simulating the conditions of the Albian aquifer, namely a temperature of the feed water of 34.5˚C and a salinity of 4 g/l. The characterization of the modules was done calculating the distillate production and the heat efficiency, evaluated through the specific thermal energy consumption. Also, the quality of the product was evaluated by measuring the conductivity of the distillate. The influence of temperature and feed flow rate was analyzed by varying them inside the allowed ranges.

4. Methodology

4.1. Desalination system description

Two commercial MD modules made by Aquastill (Sittard, the Netherlands) were tested at Plataforma Solar de Almería in Spain (PSA): Module 1 and Module 2 (Fig. 3). Both were spiral-wound modules with an AGMD configuration. The membrane of the two modules was made of PE with nominal pore size of 0.3 μm, porosity of 85%, and thickness of 76 μm. The

Table 1
Solar potential in case study region of Algeria [22]

Regions	Coastal	High plateaus	Sahara
Surface (%)	4	10	86
Average sunshine duration (h/y)	2,650	3,000	3,500
Average energy received (kWh/m^2/y)	1,700	1900	2,650

Fig. 3. Module 1 (left) and Module 2 (right) at PSA.

materials used for the condenser foil, the spacers, and the shell were PET-AL-PET, PP, and polyurethane, respectively. Both have the same number of condenser channels, evaporator channels, and distillate channels, being 6, 6, and 12, respectively. The difference between the modules was the length of the envelope, which results in different membrane surface area. In module 1, the length was 1.5 m resulting in 7.2 m^2 of membrane surface area, while in module 2, the length was 5 m and the corresponding membrane surface area is 24 m^2. The height of both modules was the same, but the diameter was higher in module 2; module 1 had a diameter of 0.4 m and module 2, 0.6 m.

The heat necessary to carry out the operation was supplied by a field of static solar thermal collectors (Solaris CP1 Nova by Solaris, Spain). Solaris CP1 is a flat-plate collector with a total dimension of 2,082 mm × 1,082 mm × 85 mm. The absorber surface was 2 m^2 and was made of aluminum with high efficiency selective coating of microtherm. The exposed face was a tempered glass 3.2 mm thickness with low iron content, while the other sides were thermally insulated with mineral wool of 25 mm thickness (Fig. 4). The solar field was arranged in two files consisted of five flat-plate collector each and had inertial energy storage to operate under stationary conditions. The nominal thermal power was 7 kW for a temperature of 90˚C using water as heat transfer fluid. The solar field was connected to the MD module through a heat exchanger. So two independent loops were established and the saline feed did not pass through the solar field.

4.2. Desalination pilot experiments

The experiments which were performed at PSA during the months of June and July 2014 were carried out for a salinity of 4 g/l and a feed water

Fig. 4. Solaris CP1 Nova by Solaris.

temperature of 34.5˚C to simulate the conditions of the Albian aquifer. To achieve this salinity, a solution of marine salts was used. To keep the salinity constant, the operation was performed at a batch mode, returning the brine and the distillate to the feed tank. The feed tank was coupled to a much larger tank cooled with a compressor chiller so as to keep the feed temperature constant. Experiments were carried out for two different feed flow rates (400, 600 l/h). The higher feed flow rate was established as the maximum in order to avoid surpassing the LEP. The temperatures of the evaporator channel varied from 60 to 80˚C and were achieved using the solar field to further heat the pre-heated feed water coming out of the coolant channel. Temperatures below 60˚C are too low to produce a significant amount of distillate and temperatures above 80˚C could damage the membrane. Experiments lasted at least 60 min, with the first 15 min required for stabilization.

Electromagnetic flow meters (Promag 50P15 by Endress + Hauser), pressure transmitters (S10 absolute by WIKA), and resistance thermometers with standard head IP67 equipped with thermowell were employed for the measurements. A pyranometer (CM6B by Kipp + Zonen) was used to measure the global solar radiation on titled angle (35˚). All the measurements were monitored and controlled by a supervisory control and data acquisition (SCADA) connected through a programmable logic controller (PLC). Measures of feed and distillate conductivities were done manually every 15 min. Monitored data were averaged every 15 min for comparison. The analysis of the desalination system was done in terms of distillate quality, production, and energy efficiency, evaluating the distillate flux, the recovery ratio (RR), the specific thermal energy consumption (Q_{spec}), and the SRF. Equations used were the following:

$$\text{Distillate flux}\left(\frac{1}{\text{h m}^2}\right) = \frac{\dot{m}_\text{d}}{\rho_\text{d} \cdot \text{effective membrane area}} \quad (1)$$

where $\dot{m}_\text{d}$ is the mass flow rate of distillate (kg/h) and ρ_d is the density (kg/l).

$$\text{RR}\,(\%) = \frac{\dot{m}_\text{d}}{\dot{m}_\text{f}} \cdot 100 \quad (2)$$

where $\dot{m}_\text{f}$ is the mass flow rate of feed water (kg/s).

$$Q_{\text{spec}}\left(\frac{\text{kWh}}{\text{m}^3}\right) = \frac{\dot{Q}}{\dot{V}_{\text{dist}}} \quad (3)$$

where $\dot{Q}$ is the rate of thermal energy supplied to the system (kWh) and $\dot{V}_{\text{dist}}$ is the volume of distillate produced.

$$\text{SRF}\,(\%) = \frac{C_\text{f} - C_\text{d}}{C_\text{f}} \times 100 \quad (4)$$

where C_f is the conductivity of the feed and C_d is the conductivity of the distillate.

5. Results and discussion

The performance of the desalination system is shown in Figs. 5–7 in terms of distillate production, RR, and the thermal efficiency, respectively. The distillate production was characterized with the volume flow rate per unit of surface of the membrane, the RR as the fraction of the feed water that was transformed into distillate, and the thermal energy was represented as the specific thermal energy consumption. Fig. 5 shows the values of the distillate production as a function of the evaporator channel temperature and feed flow rate for the two modules. In module 1, all the values were above 1.5 L/h m^2 with a maximum of 5 L/h m^2 for the highest feed flow rate. However, in the module 2, the maximum value was below 1.5 L/h m^2 even for the maximum feed flow rate. Therefore, to produce a higher volume of distillate, results suggest that module 1 with its lower membrane surface area is better. In both modules, the distillate production increases when the temperature of the evaporator channel is enhanced because the driving force of the

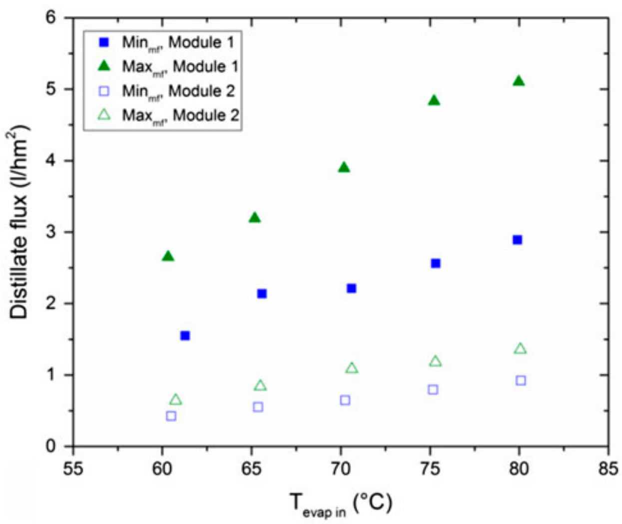

Fig. 5. Distillate flux (l/hm^2) as a function of temperature of the evaporator channel (°C) for two feed flow rates: 400 l/h (Min$_{mf}$) and 600 l/h (Max$_{mf}$) for the two modules: Module 1 and Module 2.

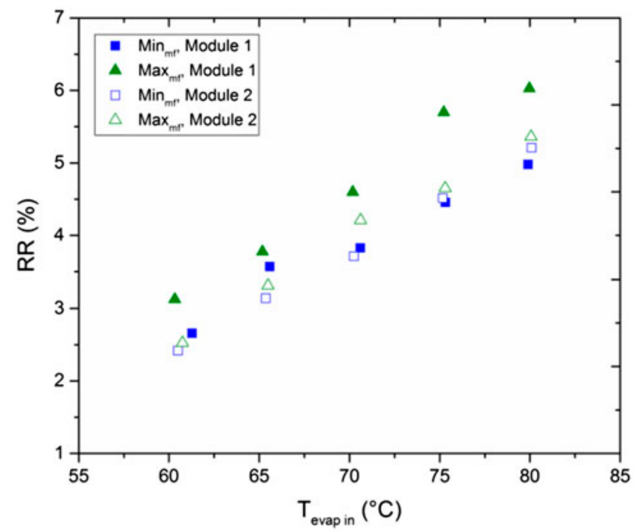

Fig. 6. RR (%) as a function of temperature of the evaporator channel (°C) for two feed flow rates: 400 l/h (Min$_{mf}$) and 600 l/h (Max$_{mf}$) for the two modules: Module 1 and Module 2.

process is higher. Moreover, distillate production is favored when a higher feed flow rate is used. This is because a higher volume of hot feed water enters in the evaporator channel, and the thermal energy input is enhanced leading to a higher driving force.

Another parameter to quantify the distillate production is the RR. Fig. 6 shows the values of the RR as a function of temperature of the evaporator channel and feed flow rate for the two modules. It can be seen that the RR increases linearly with the temperature difference in both modules. The maximum value was 6% for the highest feed flow rate operated in module 1. These values are much lower than those obtained with RO processes, which is usually not less than about 20% and can reach 45% in large plants.

Fig. 7 shows the values of the specific thermal energy consumption as a function of temperature of the evaporator channel and feed flow rate for the two modules. The measured specific energy consumption varied from 75 to 200 kWh/m^3. The minimum values were obtained for module 2 while the maximum values are those of module 1. An increase in the temperature of the evaporator channel causes a decrease in the specific thermal energy consumption. This was due to the driving force of the process (i.e. temperature difference) being enhanced. The increase in production means that there is more latent heat passing to the feed water. Furthermore, if we compare both modules, the values of specific thermal energy consumption for module 1 are higher than those in module 2. This follows an opposite trend to that

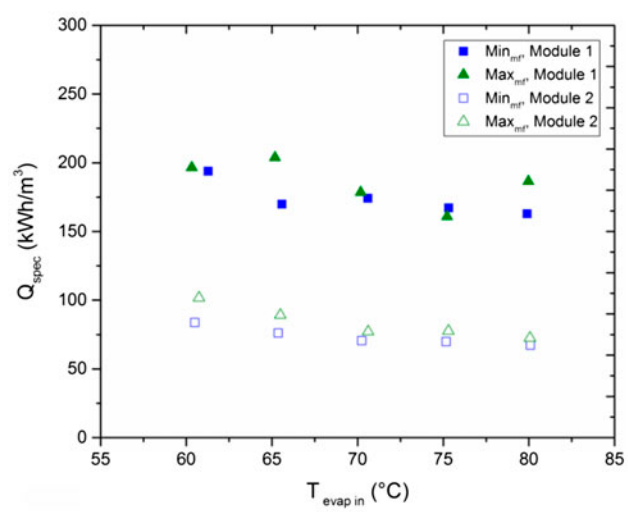

Fig. 7. Specific thermal energy consumption (kWh/m^3) as a function of temperature of the evaporator channel (°C) for two feed flow rates: 400 l/h (Min$_{mf}$) and 600 l/h (Max$_{mf}$) for the two modules: Module 1 and Module 2.

observed for the production. We can speculate that the reason is the residence time of the hot feed water inside the module. The residence time depends directly on the length of the channel, so it is lower in module 1. This causes a higher temperature difference at both sides of the membrane, increasing the distillate production. However, a shorter residence time means that internal heat recovery is worse, making module 1 more thermally inefficient.

Table 2
SRF (%) for module 1 and module 2

Module	SRF (%)
1	99.65 ± 0.08
2	99.5 ± 0.2

Compared with the results obtained for other commercial systems evaluated at PSA [24], both modules assessed in the current study showed better heat efficiencies. Besides the good internal heat recovery of the modules, what has to be taken into account is that the feed water temperature was 34.5°C which reduced the specific thermal consumption since it was necessary to supply less external heat. Finally, the quality of the distillate was analyzed with the SRF (Table 2). The values were above 99% in all the experiments for the two modules. The average values were higher in module 1.

6. Concluding remarks

It has been shown that for producing a higher specific volume of distillate, module with less surface area is better. Also, it was found that RR increases linearly with the temperature difference in both modules. The maximum value was 6% for the highest feed flow rate operated in module 1 with lowest surface area. These values are much lower than those obtained with RO processes, which can reach 45%.

In closing, the AGMD system coupled with solar collectors is a promising approach for a sustainable solution to the water shortage problem in the case study region. By coupling the scheme to a renewable energy system, it has the added advantage of reducing carbon dioxide emissions.

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