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Comparative characterization of three commercial spiral-wound membrane distillation modules

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ABSTRACT

At Plataforma Solar de Almería (PSA), different commercial spiral-wound MD modules were tested coupled to a solar thermal field composed of stationary flat plate solar collectors. One of them is the Solar Spring module with a permeate-gap membrane distillation (PGMD) configuration. Two modules from Aquastill based on a configuration of air-gap membrane distillation (AGMD) were also tested. A characterization of the modules is presented based on an extensive set of experiments carried out using simulated seawater. The performance was evaluated by measuring the production of distillate per unit surface of membrane and the heat efficiency, calculated through the thermal energy consumption. Also, the quality of the product was evaluated by measuring the conductivity of the distillate. The tests were performed changing the most significant operational parameters in order to characterize their effect on the performance of the system. The feed flow rate was varied between 400 and 600 l h^{-1} and the temperature of the hot feed from 60 to 80°C. The results show that the internal design of the module is very important, and the differences in the channel length in these modules have a stronger effect in their performance for seawater desalination than the configuration of the gap.

Keywords: Membrane distillation; Experimental characterization; Spiral-wound modules; Permeate gap membrane distillation; Air gap membrane distillation

1. Introduction

The increasing scarcity of freshwater is a global problem with consequences that can be devastating, jeopardizing sustainable development and even the health of humans and their environment. This is caused by the increased demand for freshwater due to the growth in industrial, agricultural and recreational activities associated to population growth and may be exacerbated by climate change [1]. Desalination is a solution to provide freshwater in dry areas with access to brackish resources and/or seawater. In the last two decades, reverse osmosis (RO) has gained popularity being the technology most used (about 60% of the total installed capacity). However, this technology has the problems of salinity limitation and high electricity consumption. Nowadays, technologies that use renewable energy to obtain freshwater have gained importance since the availability of conventional energy sources such as oil or gas has decreased. Membrane distillation (MD) can use low-grade waste heat or renewable energy such as geothermal or solar energy and does not have the main disadvantages of RO, such as the high pressure required, the necessity of intensive pre-treatments and the problems of a discontinuous operation. MD is a thermal-membrane desalination technology in which a temperature difference created at both sides of a microporous hydrophobic mem-

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brane, leads to a vapour pressure difference that forces the vapour from the hot feed to permeate through the membrane pores. The hydrophobicity of the membrane avoids the liquid passing through the membrane pores as long as the hydrostatic pressure is lower than the liquid entry pressure (LEP). The LEP is a characteristic of the membrane and depends on the pore size, the surface energy and the surface tension. A high LEP is achieved with a small pore size, low surface energy and high surface tension for the feed [2]. Therefore, keeping a low hydrostatic pressure (lower than the LEP) it should be possible to obtain a salt rejection factor of 100%, producing a pure distillate. To guarantee a good separation with MD, membranes must have good thermal and chemical resistance, low thermal conductivity, high hydrophobicity, high porosity and a poor pore size distribution [3]. Therefore, the membrane is very important in the process and the type of module too. Most of the commercially available modules use flat-sheet membranes in plate and frame or spiral wound configurations. Spiral wound modules with integrated heat recovery are the most used for membrane distillation applications. In recent years, different studies focused on full scale demonstration systems have been carried out. Specifically, three systems based on spiral wound modules and designed by Fraunhofer Institute for Solar Energy Systems (ISE) have been analyzed for desalination in three different locations, Pantelleria, Gran Canaria and Namibia between 2010 and 2011 [4]. Other studies have been focused on the hybridization of different technologies of desalination such as the concentration of coal seam gas (CSG) RO brine using a spiral wound air gap membrane distillation module designed by Aquastill company [5]. The major components of a spiral wound module are the membrane, the hot and cold channels, the spacers, the inlets and the outlets of the module. All these components are enveloped and rolled in spiral foils. The membrane packing density usually ranges between 300 $m^2\ m^{-3}$ and 1000 $m^2\ m^{-3}$ [6].

The solar desalination department of Plataforma Solar of Almería (PSA) has an extensive line of research directed to the study of membrane distillation at pilot scale. Commercial plate and frame modules have already been evaluated [7,8]. A spiral-wound module from Solar Spring has also been analyzed [9]. A comparison of its productivity with that of another spiral-wound module manufactured by Aquastill was recently presented [10]. This paper compares three modules, two made by Aquastill with different membrane surface areas (24 and 7.2 m^2) and the module from Solar Spring (10 m^2 surface area). Up to date, such a comparison between commercial spiral wound modules, especially with the same design but different sizes, has not been published. A preliminary analysis of the performance of the modules, specifically, distillate production and quality, recovery ratio and thermal efficiency, are analyzed as a function of the operational conditions, with special emphasis on energy consumption and water production.

2. Material and methods

2.1. Configuration of the modules

Two full scale MD commercial systems with spiral wound modules were evaluated. In one of them, two different modules made by the Dutch company Aquastill were used. Both modules have an air gap membrane distillation configuration (AGMD), but one has a much longer membrane envelop than the other. Specifically, the module called Aquastill-1, has a membrane envelope of 1.5 m while the other module, Aquastill-2, has a 5 m membrane envelope. The envelope length affects the dimensions of the spiral-wound modules, so the Aquastill-1 module has a height of 500 mm and a diameter of 600 mm and the Aquastill-2 module has a height of 500 mm and a diameter of 400 mm (Fig. 1). The other system uses a permeate gap membrane distillation module (PGMD) built by the German company Solar Spring GmbH in collaboration with the Fraunhofer ISE [11] (Fig. 1). This module has a height of 900 mm and a diameter of 360 mm. Because the height of the modules of each company is different, in each case the module was inserted into a different but equivalent hydraulic system. In AGMD, stagnant air is introduced between the membrane and

Fig. 1. Aquastill-1 (above left), Aquastill-2 (above right) and Solar Spring (below) pilot units at the facilities of PSA.

the condensation surface, so the feed solution is only in direct contact with the hot side of the membrane surface. The vapour passes through the air gap to condense over the cold surface. In this configuration, heat losses by conduction through the membrane are significantly reduced, but additional resistance to mass transfer is created. PGMD is a modification of the previous configuration in which the channel is full of stagnant distillate and thus mass transfer resistance is reduced while conduction heat losses are still low (Fig. 2) [12].

In Table 1 the main characteristics of the modules are represented. All the materials used are plastic. The membrane of the Solar Spring module is made of polytetrafluoroethylene (PTFE), the condenser foil of ethylene tetrafluoroethylene (ETFE), the spacers of low density polyethylene (LDPE) and finally the shell of Glass-fiber Reinforced Plastic (GFK). The membrane of the Aquastill modules is of polyethylene (PE), while the condenser, the spacers and the shell are made of polyethylene terephtalate aluminium polyethylene terephtalate (PET-Al-PET), polypropylene (PP) and polyurethane (PU) respectively.

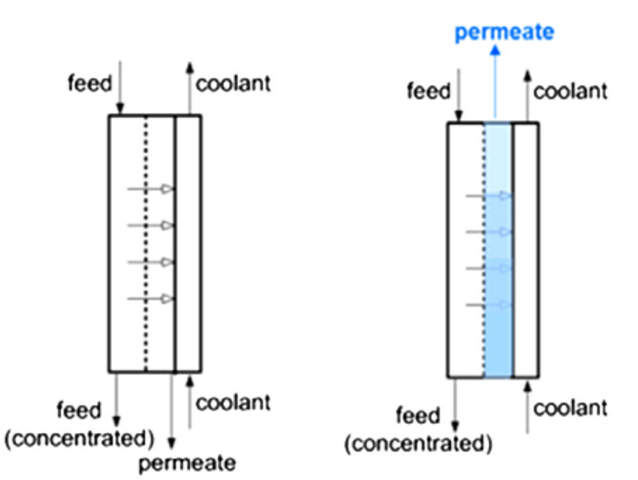

Fig. 2. AGMD (left) and PGMD (right) configurations.

Table 1
Description of spiral wound MD-modules used in this study

Membrane geometry	Solar spring	Aquastill-1	Aquastill-2
Surface area (m^2)	10	7.2	24
Membrane thickness (µm)	70	76	76
Porosity (%)	80	85	85
Nominal pore size (µm)	0.2	0.3	0.3
Module parameters			
Number of membrane foils	1	6	6
Channel length (m)	7	1.5	5
Channel height (m)	0.7	0.5	0.5
Channel thickness (mm)	3.2	2.01	2.01

2.2. Experimental set up and procedure

Fig. 3 shows a schematic diagram of the experimental set-up at PSA. The facility works as follows: feed water is pumped from the feed tank into the cold channel; in this condensation channel, the temperature of the water is increased by the internal heat recovery and then it flows through a heat exchanger to further raise its temperature. The heat exchanger receives heat directly from an external heat source which is a solar collector field. The solar field used has been described elsewhere [9]. Then, the hot water flows through the evaporation channel. In this channel, vapour passes through the membrane and the remaining brine is returned to the seawater tank. The vapour condenses on the condenser foil, in the AGMD it flows down to be collected at the bottom of the module, while in the PGMD it remains in the gap and overflows at the top of the module. In this particular case, the distillate is discharged to the seawater tank together with the brine to keep the salinity constant. Latent heat of condensation is recovered as sensible heat to increase the temperature of the feed while acting as coolant and minimize the external heat supply. There is also a transfer of sensible heat through the membrane. The hot and cold water circulate in counter-current in the evaporation and condensation channels respectively to increase heat recovery. Part of the heat is lost with the brine, which comes out of the module warm. Since the experiments were done with simulated seawater in batch mode, there was a need for cooling in order to avoid overheating of the seawater tank. In the experiments with the Solar Spring module, a larger tank was used as a buffer, refilling the feed tank of the system as its temperature was increasing. However, this proved not to be enough and some overheating occurred during the experiments. As a result, it was not easy to keep a constant feed temperature. In the case of the experiments performed with the Aquastill modules a similar strategy was followed, although in this case a compressor chiller was used in the connection of the seawater tank with the feed water tank.

2.3. Experimental plan

Experiments with MD modules were done to characterize these systems for desalination purposes. So, a solution of commercial marine salts (from the Mediterranean Sea) with total salinity of 35 g l^{-1} was used to simulate the average salinity of seawater. Experiments were done in stationary conditions for different values of the three main operational parameters. To guarantee steady-state operation, each experiment ran for 75 min, discarding the first 15 min. Feed flow rate was varied from 400 to 600 l h^{-1}, which is the maximum allowed in the modules. Temperatures of the evaporator channel were controlled with the solar heat that passed through the heat exchanger. The minimum temperature at the inlet of the evaporator channel was 60°C and the maximum 80°C. The variation inside this range was done with increments of 5°C. The temperature of the condenser chan-

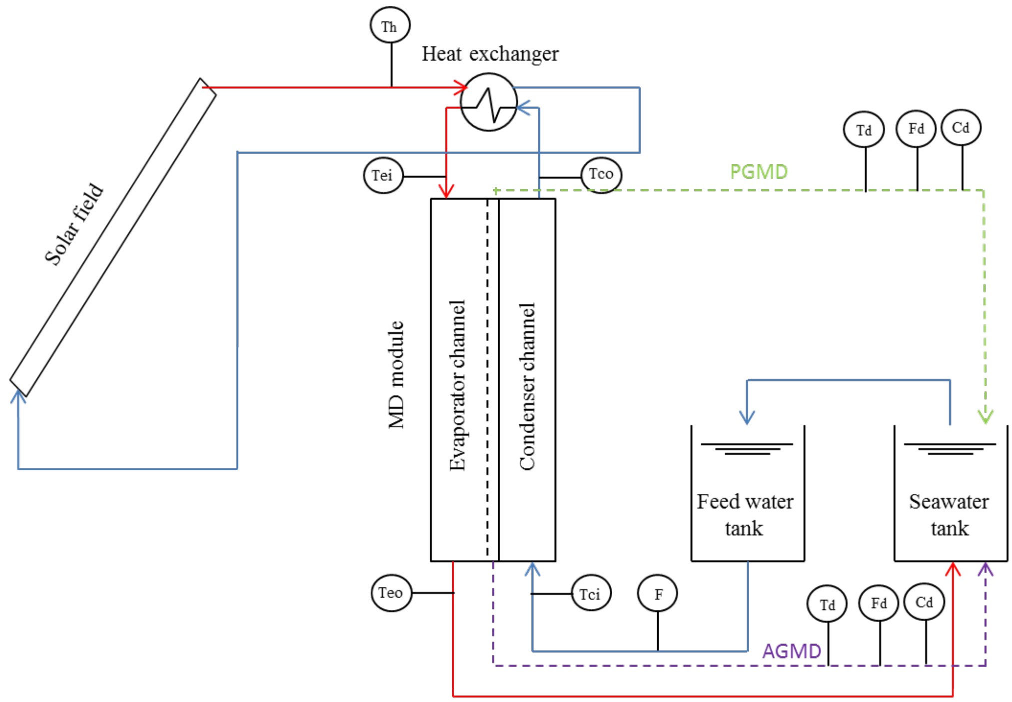

Fig. 3. Schematic diagram of the experimental set up.

nel was kept constant (inside a range of ± 1°C) in the case of Aquastill modules and was varying in the Solar Spring module, as explained above. Measurements of feed and distillate conductivities were taken manually every 15 min. In the Solar Spring experiments, distillate flow rate was measured every 15 min, so the performance parameters were averaged during 15 min intervals to obtain the corresponding measurement.

2.4. Performance parameters evaluated in this study

The production of distillate was studied by analyzing the distillate flux, calculated as the volume flow rate of distillate produced ($\dot{m}_d/\rho$) per unit of surface of the membrane.

$$\text{Distillate flux}\left(\frac{\text{l}}{\text{h}\cdot\text{m}^2}\right)=\frac{\dot{m}_d}{\rho_d\cdot\text{specific surface area}} \quad (1)$$

Recovery ratio (RR) is another parameter used in MD to measure the fraction of the feed water that is transformed into distillate:

$$\text{RR}(\%)=\frac{\dot{m}_d}{\dot{m}_f}\cdot 100 \quad (2)$$

where $\dot{m}_d$ (kg h^{-1}) is the distillate flow rate and $\dot{m}_f$ (kg h^{-1}) is the feed flow rate.

The energy efficiency of the process was calculated using the specific thermal energy consumption (STEC), which is the external thermal energy input required to produce a unit volume of distillate:

$$\text{STEC}\left(\frac{\text{kWh}}{\text{m}^3}\right)=\frac{\dot{m}_f\cdot C_p\cdot\left(T_{\text{evap in}}-T_{\text{cond out}}\right)}{\dot{V}_{\text{dist}}} \quad (3)$$

where $\dot{m}_f$ is the feed flow rate c_p(kg h^{-1}), is the heat capacity (kWh kg^{-1} °C^{-1}), $T_{evap\ in}$ is the evaporator inlet temperature (°C), $T_{cond\ out}$ is the condenser outlet temperature (°C) and $\dot{V}_{dist}$ is the distillate flow rate (m^3 h^{-1}).

For reference, another efficiency parameter was used, i.e., the gain output ratio (GOR), that is defined as the ratio between the latent heat necessary to evaporate all the mass of distillate produced and the total amount of heat supplied [13]:

$$\text{GOR}=\frac{\dot{m}_d\cdot\Delta h_v}{\dot{Q}} \quad (4)$$

where Δh_v is the enthalpy of vaporization (kJ kg^{-1}) and $\dot{Q}$ is the rate of thermal energy supplied to the system (kJ s^{-1}).

The quality of the distillate was evaluated by measuring its conductivity and calculating the salt rejection factor, defined as [6]:

$$\text{SRF}(\%)=\frac{\sigma_f-\sigma_d}{\sigma_f}\cdot 100 \quad (5)$$

where σ_f (µS cm^{-1}) is the conductivity of the feed and σ_d (µS cm^{-1}) is the conductivity of the distillate.

Results of distillate production and specific energy consumption were represented as a function of the logarithmic mean temperature difference. Due to the fact that the temperature inside the evaporation channel and the condenser channel was not constant, a more realistic approximation of the driving force of the process was to use this parameter:

$$\Delta T_m(°C) = \frac{\Delta T_{Evaporator} - \Delta T_{Condenser}}{LN\left(\frac{\Delta T_{Evaporator}}{\Delta T_{Condenser}}\right)} \quad (6)$$

where $\Delta T_{Evaporator}$ (°C) is the difference of temperature between the inlet and the outlet of the evaporator channel and $\Delta T_{Condenser}$ (°C) is the difference of temperature between the inlet and the outlet of the condenser channel.

3. Results and discussion

3.1. Production and energy consumption

Figs. 4–6 show the distillate production as a function of the logarithmic mean temperature difference between the hot and the cold channel. Fig. 4 shows the values of the distillate flux for the three modules for a feed flow rate of 400 l h^{-1}. For this feed flow rate, it can be seen that the production increased with the logarithmic mean temperature difference because the driving force of the process was enhanced. There is a clear difference between the productivity values obtained in the three modules. The maximum distillate fluxes were registered in the module Aquastill-1, reaching a top value of about 3 l h^{-1} m^{-2} for the maximum temperature difference used in this module (about 50 ºC). Values for the Solar Spring module were about 30% lower. The Aquastill-2 module had the lowest production of the three modules, more than 70% lower than the Aquastill-1. Figs. 5 and 6 show the distillate flux for the three modules at feed flow rates of 500 l h^{-1} and 600 l h^{-1} respectively. The results for all of these flow rates exhibited the same trend, with Aquastill-1 yielding the highest flux and Aquastill-2 the lowest. For feed flow rate of 500 l h^{-1}, the values of the distillate fluxes were between 16 and 23% higher than for 400 l h^{-1}. The increase of the productivity obtained when raising the feed flow rate from 500 to 600 l h^{-1} was more moderate. This increase in the amount of distillate when a higher feed flow rate was used, can be explained because when a higher volume of feed water enters the evaporator channel, the thermal energy input is higher and therefore the temperature difference across the membrane also

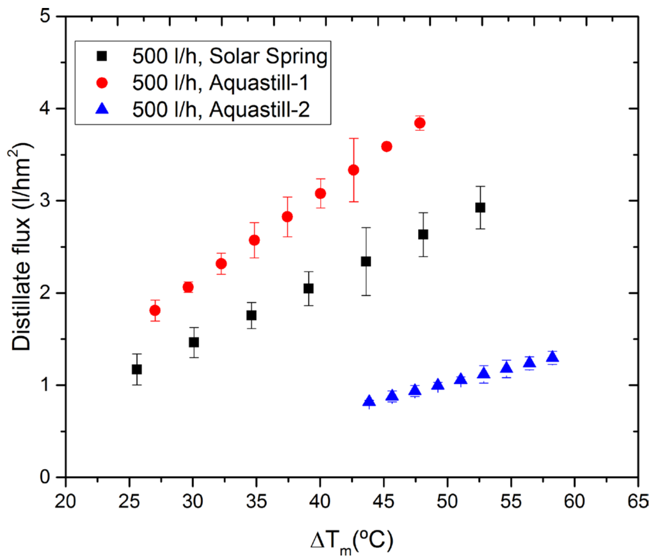

Fig. 5. Distillate flux as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 500 l h^{-1}.

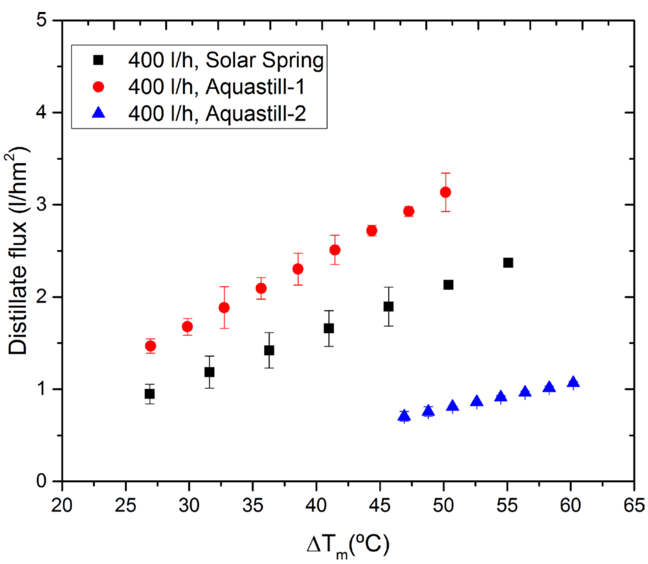

Fig. 4. Distillate flux as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 400 l h^{-1}.

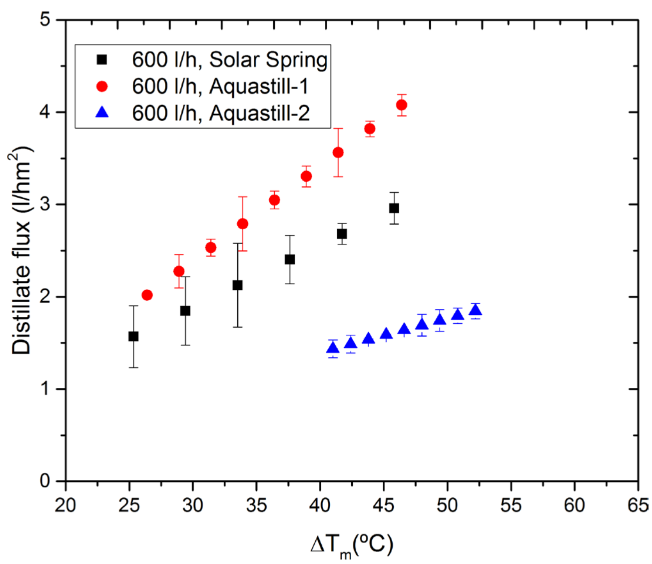

Fig. 6. Distillate flux (l h^{-1}.m^{-2}) as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 600 l h^{-1}.

increases, leading to a higher vapour transfer through the membrane. Moreover, working with a higher feed flow rate reduces the temperature polarization, which again results in a higher vapour flow. The same trend was obtained in different studies carried out by Fraunhofer ISE [14–16]. The corresponding recovery ratios ranged between 2 and 6%. These values are much lower than the typical values of a seawater RO plant, which can reach up to 50% [17].

The thermal efficiency was assessed by the specific thermal energy consumption (STEC), which is shown in Figs. 7–9 as a function of the logarithmic mean temperature difference and the feed flow rate. The maximum values registered were for the Aquastill-1 module. In this case, the highest value reached was 425 kWh m^{-3} (which corresponds to a GOR of 1.5) while the lowest was slightly above 250 kWh m^{-3}. The module with the lowest STEC and therefore the highest energy efficiency was the Aquastill-2, with STEC values between about 150 kWh m^{-3} and about 100 kWh m^{-3}, which correspond to a GOR of 4.3 and 6.5 respectively. Finally, the STEC values obtained for Solar Spring were between 180 and 325 kWh m^{-3} (GOR 3.5 and 2 respectively).

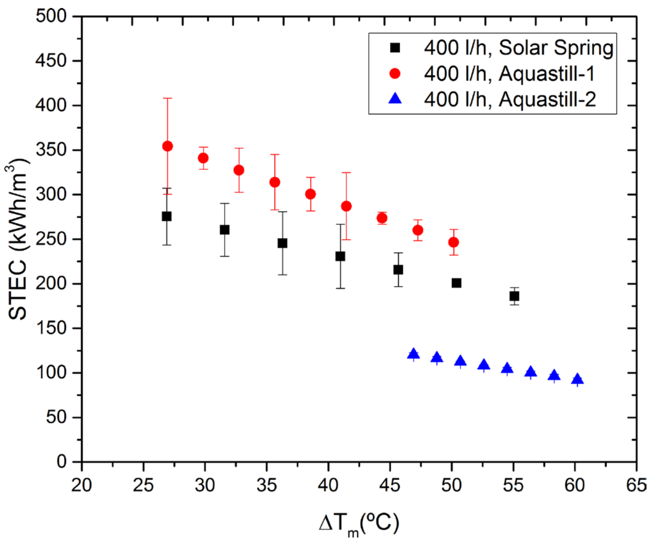

Fig. 7. Specific thermal energy consumption as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 400 l h^{-1}.

The STEC decreased with the logarithmic mean temperature difference, contrary to the distillate flux. This is because the higher driving force reached with a greater temperature difference means that more distillate was produced and more latent heat was passed to the condenser channel, reducing the external heat required. The effect of the feed flow rate in the energy efficiency was less important than in the productivity, but it followed an opposite trend. For higher feed flow rates, the STEC increased, so the energy efficiency was lower. Heat recovery in the spiral-wound modules takes place not only in the form of latent heat but also, and to a greater extent, in the form of sensible heat. The warm brine in the evaporation channel passes its sensible heat to the incoming cold feed water in the condenser channel, which is preheated as a result. This means that the driving force across the membrane is considerably reduced along the module. Therefore, a longer residence time inside the module leads to more heat recovery but also a reduced trasmembrane temperature difference. The reduction in the driving force of the process decreases the distillate production. This trade-off between the productivity and the energy efficiency has previously been identified for MD modules [10].

The existing difference in the productivity and energy efficiency among the different modules seems to be caused by the differences in internal design. While it is true that the PGMD configuration should promote more production and less energy efficiency, the differences between the lengths of the channels in the different modules seem large enough to overcome this effect. A longer channel means a longer residence time of the feed water inside the module for the

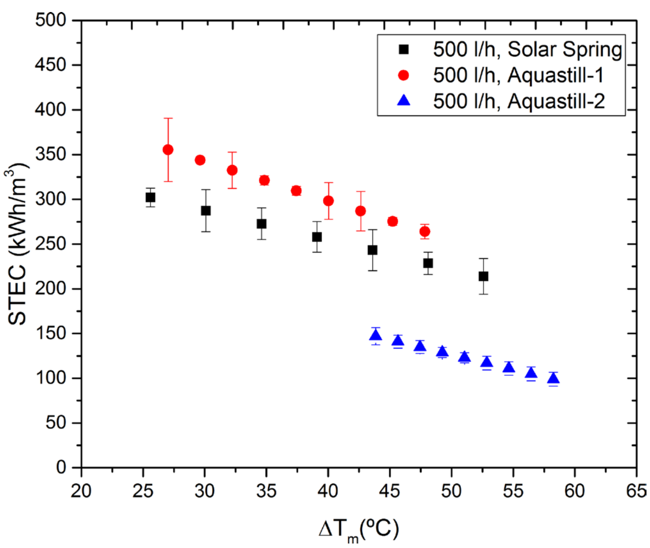

Fig. 8. Specific thermal energy consumption as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 500 l h^{-1}.

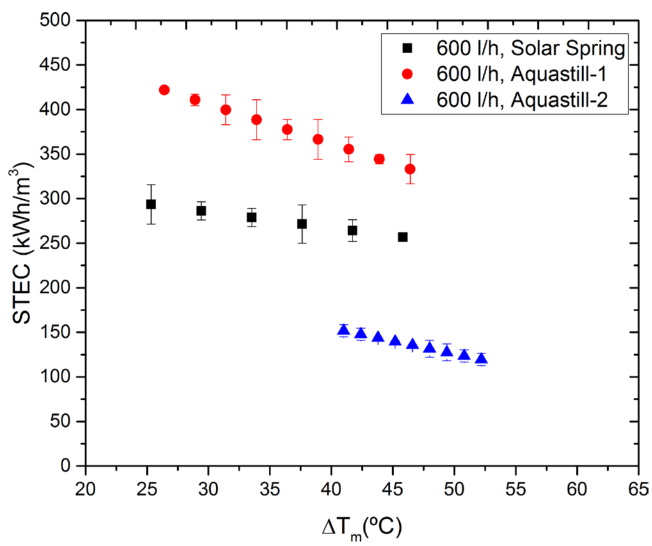

Fig. 9. Specific thermal energy consumption as a function of the logarithmic mean temperature difference for the three modules for feed flow rate of 600 l h^{-1}.

same feed flow rate, leading to more sensible heat transfer through the membrane, which reduces the transmembrane temperature difference. The reduction in the driving force of the process decreases the distillate production. A shorter length of the channel causes a short residence time, reducing internal heat recovery. The Aquastill-1 module has shorter channels than the Aquastill-2, which are more similar in length to the Solar Spring module. However, the feed flow in the Aquastill modules is split into 6 channels while in the Solar Spring module there is only one. As a result, the effective contact time of the feed with the membrane in the Aquastill-1 module was more comparable to that of Solar Spring (0.6 times shorter) than in the Aquastill-2 module (1.9 times longer than in Solar Spring). Therefore, the AGMD Aquastill-1 module gave results closer to the PGMD Solar Spring than the AGMD Aquastill-2. This latter was the most thermally efficient module, but also the one with the lowest production (i.e. the maximum distillate flux obtained was lower than 2 l h^{-1} m^{-2}).

3.2. Distillate quality

In Fig. 10, the conductivity of distillate obtained in the three modules is shown. For Solar Spring, the majority of the data showed values lower than 50 µS cm^{-1}, reaching values below 2 µS cm^{-1}. In the case of Aquastill-1, the minimum value was a little higher than 8 µS cm^{-1}, while the maximum was lower than 700 µS cm^{-1}. The distillate obtained in Aquastill-2 had a conductivity between 100 and 200 µS cm^{-1} in the majority of the cases. Considering the values obtained with the other two modules, these conductivities are very high. However, comparing with the feed conductivity, which is between 47,000 and 55,000 µS cm^{-1}, the obtained values were relatively low. As a matter of fact, the SRF vales in these cases were high, around 99.9 %.

According to the experiments, the quality of distillate was independent of operating conditions such as temperature and feed flow rate. However, in some cases the measured values of conductivity were very high, which reduced the SRF below acceptable values (lower than in RO, where SRF is greater than or equal to 99%).These measurements of

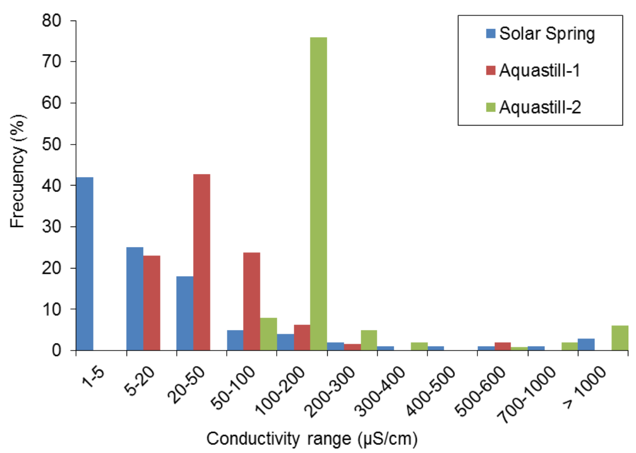

Fig. 10. Frequency distribution of the values of distillate conductivity measured for the Solar Spring, Aquastill-1 and Aquastill-2 modules.

conductivity corresponded to the beginning of the experiments. Salt deposition when the operation was stopped decreased the quality of the first distillate, which recovered normal values as the salt was washed out. This effect was discussed in Ruiz-Aguirre et al [10] and has been observed by other authors [14]. So, as mentioned before, although the operation conditions did not affect the quality, they could influence the velocity at which the salt depositions were washed from the membrane. This can explain that in Aquastill-2, the conductivity of distillate did not reach values of 8 µS cm^{-1} as in Aquastill-1.

On the other hand, the minimum conductivity obtained with Aquastill-1 module was approximately 6 µS cm^{-1} higher than that in the Solar Spring module. This could be due to differences in the membrane. The material of the Aquastill membrane is PE while the membrane of Solar Spring is PTFE, which is more hydrophobic than PE. Moreover, the mean pore size in Solar Spring is lower than in Aquastill. Both characteristics may increase the pass of liquid through the membrane, worsening the quality of distillate.

4. Conclusions

Two full-scale MD commercial systems with spiral wound modules were evaluated at PSA. In one of them, two different modules with an AGMD configuration (Aquastill) were used while in the other, the module evaluated had a PGMD configuration (Solar Spring). The performance was evaluated by measuring the distillate conductivity, distillate productivity and the energy efficiency. Distillate quality was very good in Aquastill-1 and Solar Spring (reaching 8 µS cm^{-1} and below 2 µS cm^{-1} respectively). In the case of Aquastill-2, values were higher, between 100 and 200 µS cm^{-1}, though still acceptable. Distillate production and thermal efficiency for the three modules as a function of different operation parameters were compared. The increase of the temperature difference between the hot and cold inlet of the module had a positive effect, enhancing the productivity and the energy efficiency. Higher feed flow rates caused larger production, however, the effect in the energy efficiency was not so visible because several effects were mixed. A higher feed flow rate led to more distillate production, however, it reduced the residence time inside the channel worsening the internal sensible heat recovery. A trade-off between the production and the thermal energy consumption was observed in these modules. In Aquastill-1 the maximum productivity of 4 l h^{-1} m^{-2} was registered, but with the worst energy efficiency (425 kWh m^{-3} of specific thermal consumption). The best results of energy efficiency were obtained for the Aquastill-2 module (150 kWh m^{-3}), but the distillate production did not surpass 2 l h^{-1} m^{-2}. The results for Solar Spring were between those of the other two modules, but closer to Aquastill-1. The existing difference among the three modules was due to the internal design of them. Although the configuration of the module influences the mass and heat transfer, in this study it was observed that the internal design, specifically the length of the channel, has a stronger effect than the gap. This means that it is important to find the optimal design of the module that balances both performance parameters, namely, distillate production and energy efficiency.

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