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Comparative evaluation of two membrane distillation modules

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ABSTRACT

Freshwater shortage difficulties make it necessary to find new sources of supply. Nowadays desalination is the solution adopted in many countries to solve this problem. All around the planet, regions with lack of freshwater match up with those with large amounts of available solar radiation. Therefore, solar desalination can be a suitable and sustainable option to tackle the water scarcity problems in those particular areas, especially in the coastal ones. Membrane distillation (MD) is a thermal membrane technology developed since late 60's which uses low exergy heat to drive a separation process in aqueous solutions. One of its applications is desalination where thanks to its separation principle, very high distillate quality can be obtained. MD is a thermally driven process that differs from other membrane technologies in that its driving force, rather than the total pressure, is the difference in water vapour pressure across the membrane, caused in turn by a temperature difference between the cold and the hot side of it. In comparison with other membrane-based desalination processes like reverse osmosis (RO), MD shows very high rejection rates and much lower operational pressures, also the nature of MD membranes (larger pore sizes than RO) makes them much less sensitive to fouling. Compared to conventional thermal desalination processes like MSF or MED, MD is less demanding regarding vapor space and building material's quality [1] leading to potential lower construction costs. Amongst its advantages, its low operating temperatures (ranging between 60–90°C [2]) make possible the use of low-grade heat, the kind of energy delivered by static solar collectors, as the only thermal supply. This, jointly with its low operational pressure and small footprint, make solar membrane distillation (SMD) in principle, a promising technology. Despite these advantages, SMD has been developed to a lesser extent, compared with other solar desalination technologies like PV-driven RO or solar stills, and although many encouraging laboratory experiences can be found in literature, large-scaling and module design is still an issue. It is precisely because of this preliminary state MD is in, that very preliminary, low energy efficiency and not commercial available MD prototypes are still found. In MD there is still a trade-off between efficiency (heat consumption) and production (distillate per square meter of membrane), as a result very high specific distillate fluxes can be attained (up to 80 kg h^{-1} m^{-2} of membrane [3]) but heat losses (mainly trough the membrane by conduction) are still substantial. Under the framework of an European project (MEDESOL: Seawater Desalination by Innovative Solar Powered Membrane Distillation) which main objective was to develop a stand-alone desalination system based on multi stage MD to supply decentralized rural areas [4], the status and future possibilities of currently developed MD have been evaluated. This paper presents the results obtained from the experiments realized with two different pre-commercial MD modules, coupled to a solar field comprised of

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static collectors. Both modules were tested in the same facility under the same conditions, in order to make a reliable comparison between them. Data on energy efficiency, production ratios and operational issues will be shown.

Keywords: Solar desalination; Membrane distillation; Experimental results

1. Introduction

Water scarcity problems are becoming a big issue especially in those isolated areas where a general lack of policies and governmental interests make the situation even worse. The special characteristics of these regions (decentralized services, scattered population, and lack of infrastructures jointly with hard climate conditions) make it difficult or at least not-cost effective to scale-down bigger desalination technologies such as RO or multi-stage flash distillation (MSF) designed for very big water productions. These regions which suffer from water scarcity have also another characteristic that is they normally also have plenty of available solar radiation. If we take all this into account and if we keep in mind that more than one third (2.4 billion people, FAO 2007) of the world population lives within the first 100 km of the sea, desalination driven with solar energy can be a suitable option to tackle these water scarcity problems in those particular areas.

When looking for alternative desalination processes which can be suitable for these special areas, some features are more than desirable. The chosen process must be robust in order to stand both hard climate conditions and for example varying conditions of raw water, should have advantageous attributes regarding the implementation of solar energy as driving force (unstable operation conditions) and stand-alone operating systems (practically maintenance-free). Membrane distillation which is a separation process that it is being worldwide investigated to be used for desalination purposes has some advantages regarding this specific application. Main reasons for that are:

- It shows promising results regarding the specific distillate production (up to 80 kg h^{-1} m^{-2} of membrane [3]) which can be found in lab-scale experiences.
- It is a low-demanding process i.e. can be run at atmospheric pressures and its operational temperatures are between 70–90°C therefore low-grade heat or renewable energies such as solar can be used.
- Its maintenance requirements are very low. Membranes used in MD are tested against fouling and as the process is not an absolute pressure driven one, the risk of clogging is much lower than for example in RO.

2. MD fundamentals

Membrane distillation is a thermal process in which a porous membrane is used to create a vapour–liquid interface in order to get the hot solution (in the case of seawater desalination, hot seawater is used) evaporated in one side of the membrane and to collect the condensate on the other side, free of salts. The driving force of the process is the difference of vapour pressure across the membrane. This is in turn created by a temperature difference of the two streams in contact with the membrane. So the greater the temperature difference across it is, the greater the pressure gradient, the driving force and so the distillate production. As the vapour pressure has an exponential relationship with increasing temperature (describe by Antoine's equation), theoretically the distillate production should follow that same tendency. In MD, mass and energy transfer processes occur simultaneously. The heat flux is related to the transport of energy from the hot stream to the cold one and can be in turn divided into three steps, which can be regarded as three resistances in parallel: 1) the heat transport from the hot bulk to the surface of the membrane, due to convection; 2) the heat transferred through the membrane which is both by conduction through the solid material of the membrane and the fluid filling its pores and by latent heat, due to the transportation of the water vapour flux produced and 3) the heat transferred from the membrane to the cold bulk due to convection. In MD, this heat transportation from the hot bulk to the surface of the membrane creates a transversely decreasing profile of temperatures (as shown in Fig. 1, dashed line represents the temperature gradient across the membrane and solid lines represent the consequently formed boundary layers). In the same way, the heat transferred by convection through the membrane contributes to this effect which final conse-

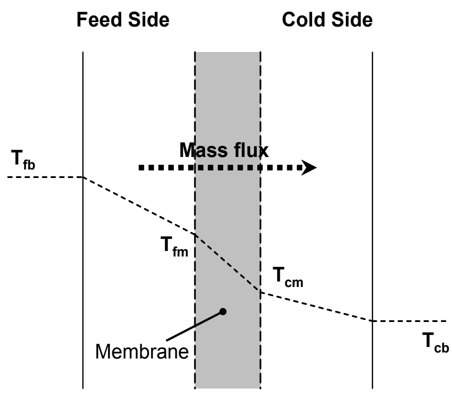

Fig. 1. Temperature profile and polarization effect in MD.

quence is a temperature drop in the surroundings of the hot side of the membrane and a resulting decrease in the available temperature gradient across the membrane, which is definitely the driving force of the process. This whole process is called "temperature polarization effect" and is one of the main reasons for the efficiency of the process to be lower than expected. This effect physically means that most part of the heat supplied to the process is directly transferred to the cold stream by conduction instead of being used to evaporate the water on the feed side and get distillate.

That is why in MD the heat transferred by conduction through the membrane is considered a net heat loss and many modifications of the process are focussed on reducing it. Temperature polarization effect must be taken into account when modelling the distillate production. For example, Schofield et al. found that the overestimation of distillate production can be as high as 40% for a feed inlet temperature of 60°C when polarization effect is ignored [5]. In MD, heat recovery is based partially on this phenomenon. The idea is to recover the heat transferred to the cold stream and use it as a pre-heated feed. Ideally, this heat should come only from the latent heat of the condensing vapour onto the cold side however; the heat transferred by conduction is also partially recovered in the same way.

3. Solar collectors for seawater thermal desalination

According to Garcia et al. the most suitable solar collectors for seawater thermal desalination are flat-plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collectors (CPC) and parabolic trough collectors (PTC). In the case of MD, operational temperatures are in the range of 50–80°C, a temperature level at which static solar collectors show a good performance. Also, in the case of this application (decentralized desalination systems) non-tracking collectors are preferred as economical and maintenance issues are important. Amongst static solar collectors, FPC collectors show the lowest performance specially when working at high temperatures. On the other hand, they are low-priced and vary cheap materials such as plastic can be used to manufacture them. ETC collectors show the best performance but they are also the most expensive ones. CPC collectors are low-concentration solar collectors that are designed to deliver more energy than a flat plate collector minimizing the heat losses by means of concentration. Their prices are in between FPC and ETC ones but they can deliver more energy per square meter reducing the number of collectors needed.

4. MD experience at PSA

Despite the many potential aforementioned advantages that SMD has, very few experimental systems have been erected compared to other mature technologies such as, PV-driven RO, wind driven RO and other solar thermally-driven distillation technologies (STD) like solar stills. The comparison between PV/wind systems and thermal ones, with respect to long-time performance and reliability, needs further research and therefore more information is needed in order to asses both types of technology.

The objective of the MEDESOL project, under which framework this work has been done, was to evaluate a desalination system based in MD and its coupling to a field of solar CPC collectors. For that purpose a set-up specifically designed was erected at the project coordinator's facility (Plataforma Solar de Almería) and was used as a pilot plant to evaluate different MD technologies. It consists of two independent loops which are interconnected by means of a heat exchanger. The solar loop that supplies the thermal energy to the system and operates with RO treated water in order to protect solar collectors from corrosion and scaling, and the desalination loop which is in turn divided into two circuits (Fig. 2). The solar loop was installed and designed for a previous project and is composed of 252 stationary solar collectors (CPC 3E+ AoSol) [6], with a total area of approximately 500 m^2 arranged in four rows (35° tilted) and has a 24 m^2 thermal storage system based on water. Only half of the solar field is used in the case of the membrane distillation plant (250 m^2 of solar collector field).

The heat output of the solar field can be regulated. The desalination loop consists of two 2 m^3 polypropylene tanks (PP-H) used as hot and cold water reservoirs. Feed solution, prepared with deionised water and marine salt is heated up through the heat exchanger and pumped into the air gap membrane distillation (AGMD) modules. Likewise, the same solution is used as refrigerant and can be cooled down if necessary, using an air cooler. After AGMD process, both cold and hot water are returned to their corresponding tanks thus closing both circuits while distillate is discarded. Set-up was designed to be flexible and easy to adapt to the needs of the operation.

5. MD modules evaluated

Two different commercial and pre-commercial MD technologies have been evaluated. Both of them use AGMD and a configuration based on flat sheet membranes. First module evaluated was the one manufactured by the Swedish company Scarab Development AB. This module was in the beginning of the MEDESOL project the chosen one to test the multi-stage concept. Therefore, three of those modules were used in the experimentation. Only two of them could be finally used for the purpose of this investigation because of the many leakage problems faced. These modules have a membrane made of 100% expanded PTFE spun-bonded with a polypropylene support (GoreTM MicroFiltration Media) with a porosity of

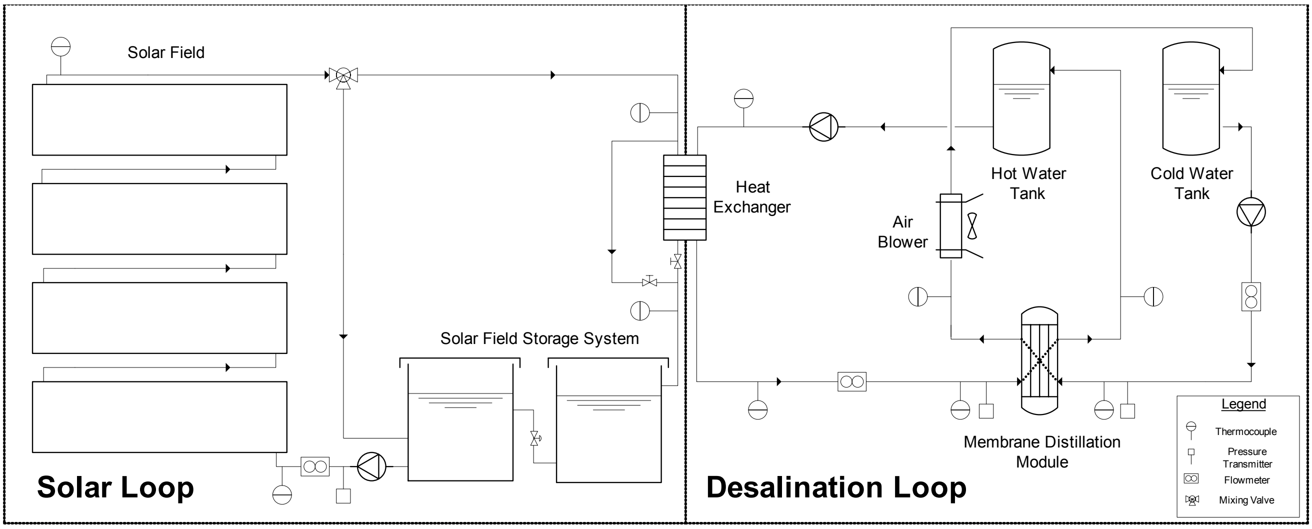

Fig. 2. Experimental set-up for MD evaluation at PSA facilities.

80%; 0.2 mm pore diameter and 0.28 mm thickness. Each module has twenty membranes (a total membrane area of 2.8 m^2) and an air gap width of 1 mm. The membranes are supported onto injected polypropylene cassettes. Each of them contains the inlet and outlet channels for the hot water and two condensing walls. By piling up the cassettes, channels for the cooling water are formed between the condensing walls of adjacent cassettes enclosed. The module is sandwiched by two stainless steel covers of approximately 100 kg each. The operational conditions of these modules are the ones shown in Table 1.

The second module evaluated was the one manufactured by the Singaporean company Keppel Seghers. This module was a prototype and therefore only few data about its construction were shared by the company. It is also a module based in AGMD and has a membrane surface of 9 m^2. In this case, the set-up had to be slightly modified to connect the module. A cartridge filter and a degasser were installed on line and upstream the modules and only one of the tanks was used (only one closed circuit). Operational conditions of this module are shown in Table 2.

The routine for the experiments was the same for both MD modules: 6 h of continuous operation, shut-down (modules were drained) until the next day of operation. All the experiments were carried out with a water solution of NaCl and two different salt concentrations (35 g L^{-1} and 1 g L^{-1}) to check the effect (if any) of the salt content. The circuit was closed but the distillate is discarded. Therefore, salt concentration got higher throughout the experiment (around 1–2 mS cm^{-1} higher, depending on the production) and had to be restored with fresh water for the next day. The operational conditions were intended to stay as stable as possible not to introduce too many uncertainties into the experiment. Temperatures, flow rates, conductivities and pressures were monitored and recorded every minute through the SCADA system. Also manual samples (distillate flow rates measurements) were taken every five minutes during approximately one hour (after stable conditions were reached) and in order of

Table 1
Operational conditions of Scarab MD modules tested at PSA

Operational parameter	Specification	Recommended by manufacturer
Warm water flow, one module, nominal	Range (5–20 L min^{-1})	Recommended 15–20 L min^{-1}
Cold water flow, one module, nominal		Range (5–20 L min^{-1})
Pressure limit for the feed and cooling water	Max. 0.3 bar (gage)	Recommended 0.2 bar (gage)
Warm water operation temperature	40–85°C	Recommended > 60°C
Cold water operation temperature		20–40°C
Temperature drop per pass		3.5–10°C (temperature and flow rate dependant)
Recommended temperature difference	20°C	Temperature difference between feed and cooling inlets
Pressure drop per module per pass	0.02–0.1 (bar)	Tested value 0.02–0.04 (bar)

Table 2
Operational conditions of Keppel Seghers MD module tested at PSA

Operational parameter	Specification	Recommended by manufacturer
Warm and cold water flow, nominal	To compare Scarab and KS modules, 20 L min^{-1} was used.	Range (10–26 L min^{-1})
Pressure limit for the feed and cooling water	1.3 bar (feed)/0.8 bar (condenser)	
Warm water operation temperature	60–80°C	Recommended > 60°C
Cold water operation temperature	20–40°C	Recommended 20°C
Temperature drop per pass		5–20°C (temperature and flow rate dependent)
Temperature difference		20°C
Pressure drop per module per pass		0.15–0.3 (bar)

increasing temperature and flow rate to avoid possible thermal inertia of the system. Based on experimental data the analyses carried out and the operational parameters varied were the following:

- Distillate production [L h^{-1}; L h^{-1} m^{-2} and % of recovery ratio] assessed by direct sampling as a function of temperature (both hot and cold temperatures) and feed flow rate.
- Thermal efficiency, evaluated by means of:
  - Specific heat consumption [kWh m^{-3}]: calculated based on direct sampling. As a function of feed temperature ranges, feed salt concentration and feed flow rate.
  - Performance ratio of the module [PR]: calculated based on direct sampling as a function of feed temperature ranges and feed salt concentration, using the formula specified below:

$$PR = \frac{2326\,\frac{\text{kJ}}{\text{kg}}\left(q_{\text{dist}} \cdot \left(\text{dens}W\left[T_{\text{dist}}, 1\,\text{bar}\right]\right)\right)}{Q_{hot}} \quad (1)$$

where q_{dist} and T_{dist} are the distillate volumetric flow rate and temperature respectively; dens$W$ is water density as a function of temperature and pressure of the distillate stream (considered as 1 bar); and Q_{hot} which is the energy input, considered as the enthalpy difference between the membrane inlet and outlet streams for the corresponding temperatures.

There are many ways to evaluate the PR of a desalination system. In this case the PR of the membrane here estimated evaluates the way energy is used inside the membrane, namely, how much energy is employed in the evaporation of the feed water and turned into distillate. Also help us to comparatively assess different modules and to identify possible enhancements. Of course, this approach does not consider the possible heat recovery and therefore the results can be different from the ones shown here.

- Quality (conductivity) of the distillate [µS cm^{-1}] was evaluated by direct sampling with a conductivity probe equipped with temperature adjustment. Also some extra measurements were done in the laboratory to confirm the right performance of the conductivity probes. It was evaluated as a function of temperatures, feed flow rate and salt concentration of the feed.

6. Experimental results

6.1. Distillate production

As an example of a normal day of operation and the temperatures that can be reached during it; Figs. 3a and 3b show average values of distillate production as a function of feed temperature of a representative number of experiments, carried out with the two evaluated MD modules under the same conditions (35 g L^{-1} salt solution and 20 L min^{-1} as feed and 30°C as refrigeration). The distillate production has been represented as specific production (per 1 m^2 of membrane).

In the case of the Keppel Seghers module, these figures mean a total maximum distillate production reached of 20 L h^{-1} per module and a maximum recovery ratio (RR) per module of around 2%. For Scarab MD module, the maximum production per module reached was around 10 L h^{-1} and a maximum RR per module of <1%.

6.2. Thermal efficiency

Figs. 4a and 4b show data on PR for both modules as a function of feed hot temperature. Average values of a representative number of experiments, carried out under the same operational conditions (20 L min^{-1} as feed flow rate and 30°C as refrigeration) have been represented. The figures also show the differences found when working with the two different salt concentrations: 1 g L^{-1} of marine salts (F 20 in the figure) and 35 g L^{-1} (S 20 in the figure).

PR values can be translated into specific heat consumption. The best registered value (working with 35 g L^{-1}) was 0.58 working with Scarab's module at a feed

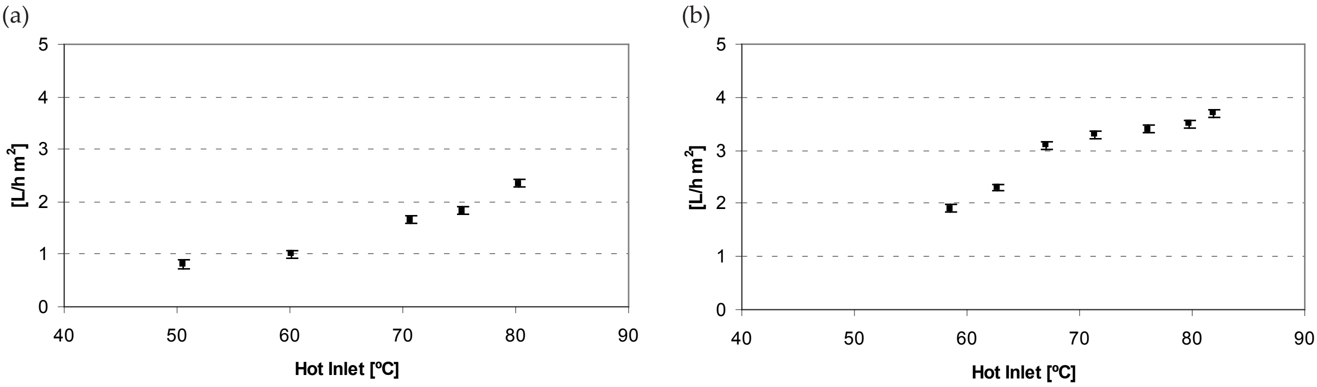

Fig. 3. Specific distillate production as a function of hot feed temperature, for a feed flow rate of 20 L min^{-1} and a refrigeration temperature of 30°C. Average values and their standard deviations are represented. (a) Keppel Seghers module results; (b) Scarab module results.

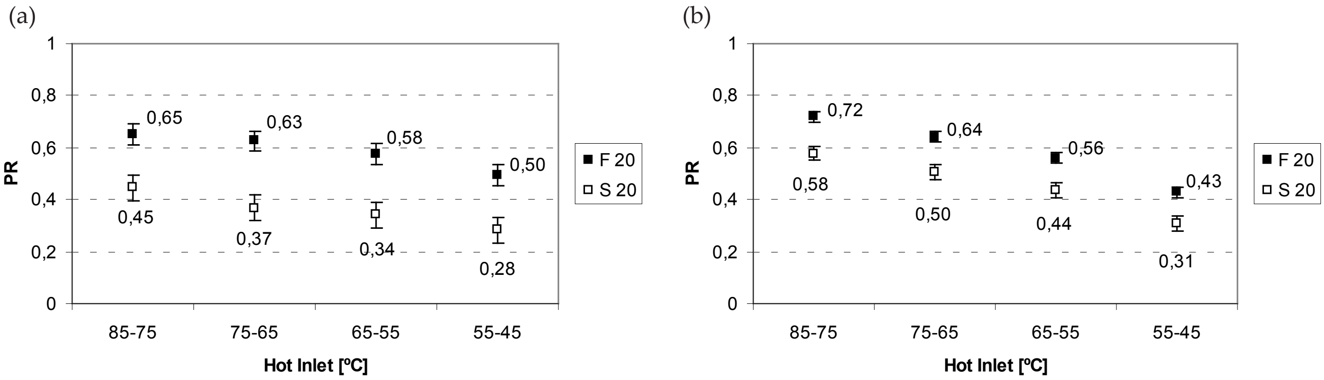

Fig. 4. Performance ratio as a function of hot feed temperature and salt concentration for a feed flow rate of 20 L min^{-1}and a refrigeration temperature of 30°C. Average values and their σ are represented. Black points represent results found working with 1 g L^{-1} feed solution and white ones represent those corresponding to 35 g L^{-1}. (a) Keppel Seghers module results; (b) Scarab module results.

temperature of 82°C. This PR value matches up with a specific heat consumption of around 1100 kWh m^{-3}. In the case of Keppel Seghers module, the best value obtained was 0.45 (80°C and 35 g L^{-1}) which corresponds to 1400 kWh m^{-3}. In the case of Keppel Seghers module, the observed reduction of the distillate production working with the 35 g L^{-1} salt solution is about 33% hence the PR is also affected. In the case of the Scarab's one, the differences are not as noticeable, but a decline in distillate production by about 23% was also observed.

In the case of Keppel Seghers module, its configuration and performance made it possible to evaluate the effect that feed flow rate would have on the thermal performance. Fig. 5 shows the result obtained for different feed flow rates.

In these experiments, refrigeration was kept constant around 30°C and feed fluxes were varied between 15/20/26 L min^{-1} to evaluate if the thermal efficiency was affected by feed flow rates. The results obtained also show that for this module, PR gets better at low temperatures working with 20 L min^{-1} of feed. But for greater temperatures, greater feed flow rates are desirable. The maximum specific flow rates for these feed flow rates (15; 20 and 26 L min^{-1}) were: 1.3, 2.3 and 2.6 L h^{-1} m^{-2} respectively.

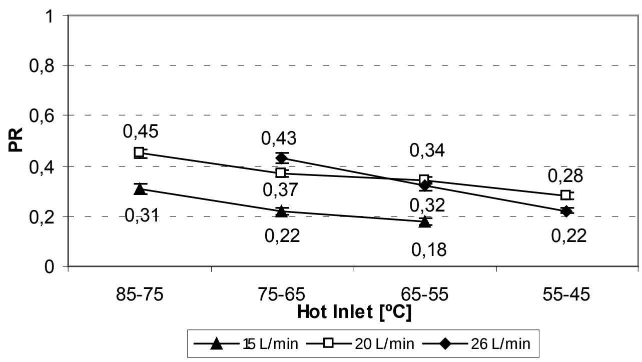

Fig. 5. Performance ratio values for Keppel Seghers module as a function of hot feed temperature and feed flow rate, for a feed salt concentration of 35 g L^{-1}and a refrigeration temperature of 30°C. Average values and their σ are represented.

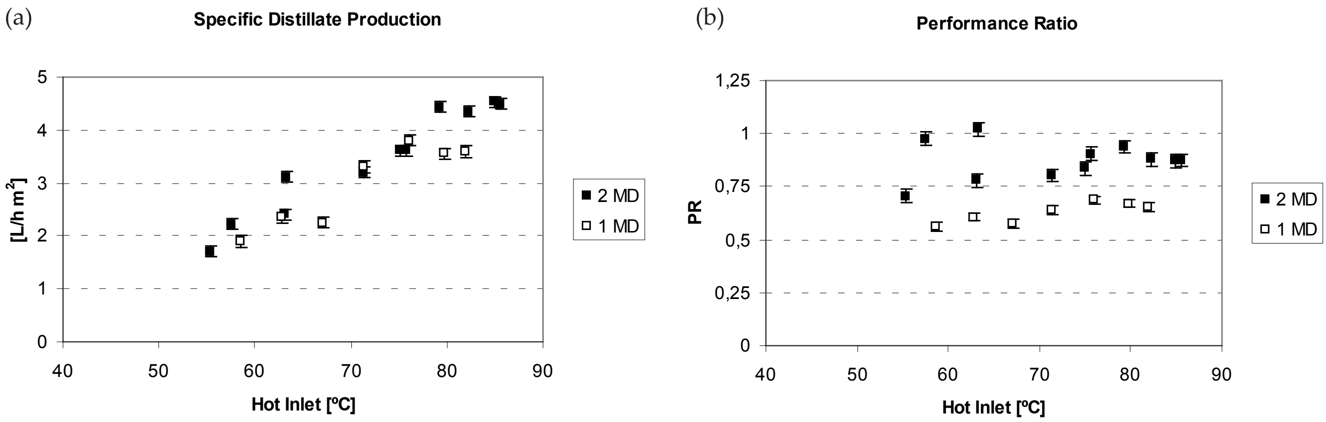

Fig. 6. Specific distillate production (a) and PR values (b) for Scarab's modules as a function of hot feed temperature for a feed salt concentration of 35 g L^{-1} a refrigeration temperature of 30°C and feed flow rate 20 L min^{-1}. 2 MD stands for the results obtained working with two modules in series and 1 MD stands for the ones obtained working with one module.

In the case of Scarab module, the feed flow rate could not be varied because of the conductivity problems that appeared when lower fluxes were employed (see next section: quality of the distillate) but the specific flow rate and the PR could be enhanced by the multi-stage concept. In the figures below, some preliminary results of an experiment working with two Scarab's modules in series (2 MD in the figures) are shown and confronted to the results obtained for the same experiment but working with one module (1 MD in the figures).

Although distillate production was at most a 15% greater which is in holistic terms not very significant (means less than 1 L h^{-1} m^{-2} more) PR was enhanced by a 32% which means that thermal consumption can be reduced around 300 kWh per m^3 of distillate produced.

6.3. Quality of the distillate

Figs. 7a and 7b show distillate conductivity values registered throughout different experiments as a function of feed hot temperature for both modules. In the case of Scarab module (Fig. 7b) in which only experiments carried out at a feed flow rate of 20 L min^{-1} are represented, a big difference in the quality of the distillate when working with 1 and 35 g L^{-1} of marine salts in the feed, was observed. Namely the conductivity worsened greatly and very high values (from an average value of 3.9 µS cm^{-1} to values > 12 µS cm^{-1} with an average value of 60 µS cm^{-1}) were registered. Also, an even higher raise in conductivity (> 500 µS cm^{-1}) was registered when working with lower flow rates than the nominal one (< 20 L min^{-1})[1].

In the case of the Keppel Seghers module, the quality of the distillate was excellent (average value around 3 µS cm–1) and remained constant throughout the experimental campaign of almost continuous operation during

[1] That fact jointly with the leakage problems we had working with this module, were the reason why it was decided to evaluate the performance of the Scarab's module working with nominal feed flow rate (20 L min^{-1}) and thus the effect of different flow rates could not be evaluated in the case of this module.

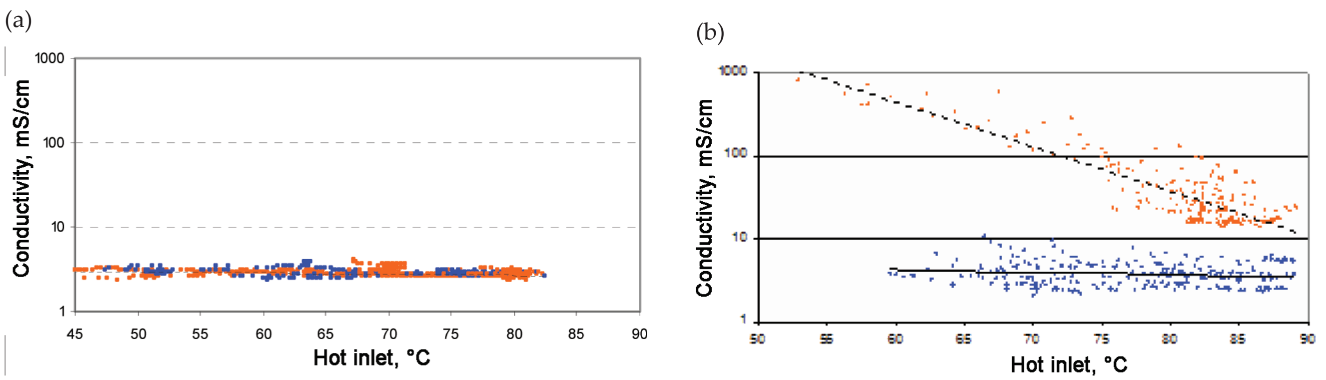

Fig. 7. Distillate conductivity as a function of hot feed temperature, for different feed flow rates (5b) and a refrigeration temperature of 30°C. Blue points represent results found working with 1 g L^{-1} feed solution and orange ones represent those corresponding to 35 g L^{-1}. (a) Keppel Seghers module results; (b) Scarab module results.

three months. Also, the quality of the distillate was not worsened by the concentration of the feed nor by the temperatures or the flow rates employed.

A second prototype of Keppel Seghers is being tested at PSA and the preliminary results are encouraging, as the performance ratio, the thermal consumption and the specific distillate production of the whole system have been more than significantly improved with the multi-stage concept. In this case, the new prototype consists of three modules in series. Therefore the PR can be evaluated taking into account the heat recovery through the condenser stream. The values so reach obtained (1.70 at 80°C) mean a heat consumption of around 380 kWh m^{-3}.

7. Final remarks and conclusions

The reliability and standalone characteristics of the Keppel Seghers module have been satisfactory. No leakage or operational problems were found throughout the whole experimental campaign. And the performance of the module did not change or worsen during the whole period of experimentation. It has even endured intermittent operation, high hot inlet temperatures and small delta T (between hot and cold side) without any problem. The distillate's conductivity remained low, constant and not affected by temperature or feed flow rate and salt concentration.

This was not the case for Scarab modules. Apart from the numerous leakage problems faced during the experimentation period, the conductivity of the distillate rose when feed salt concentration was 35 g L^{-1} and even got worse when lower flow rates than the nominal ones were employed.

Both modules distillate production was lower when higher salt concentration was used and that affected their general performance. This could be explained by the fact that salt concentration reduces the partial vapour pressure of the solutions employed; therefore the driving force and consequently the distillate are diminished. On the other hand and generally speaking, their performances got better when higher feed flow rates and temperatures were employed.

The multistage concept for MD can reduce noticeably heat consumption, but still the specific production is very low (compared to other thermal desalination systems). This was proven only for Scarab modules due to the available number of modules and preliminary assessed for the second Keppel–Seghers prototype.

The use of higher feed flow rates can improve MD modules performance, but in order to compensate the still low distillate production, heat consumption needs to be reduced.

MD technology has proven to be suitable for being coupled with solar energy but is still in its first steps. Thermal efficiency is the key factor to be improved. The more efficient the technology is the less solar collector's area will be needed and therefore the technology could compete with PV–RO or humidification–dehumidification, as MD is still less demanding regarding operational issues and easier and cheaper to be set up and operated.

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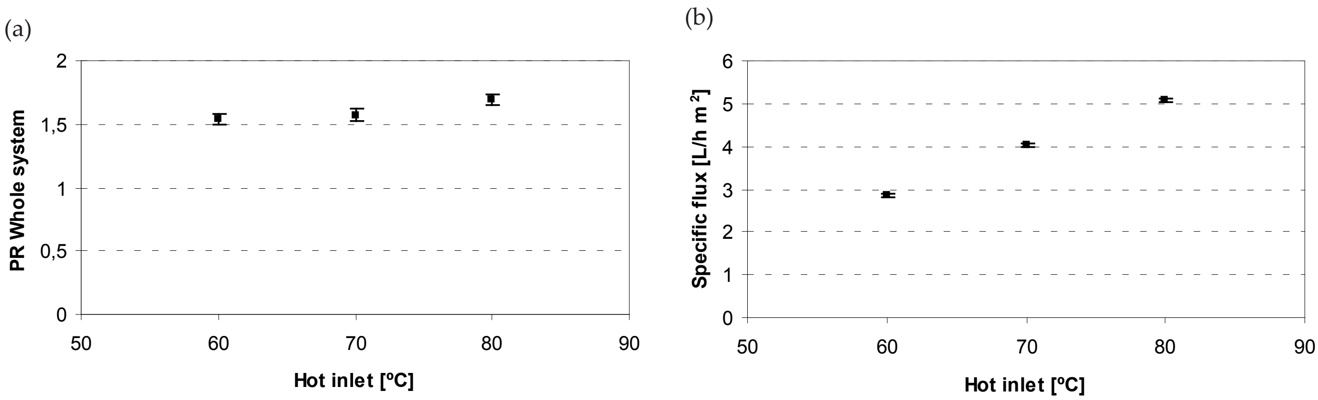

Fig. 8. Performance ratio (a) and specific distillate flux (b) of the whole system (3 MD in series) values for Keppel Seghers 2nd prototype as a function of hot feed temperature for feed flow rate of 19 L min^{-1} and salt concentration of 35 g L^{-1} and a refrigeration temperature of 30°C. Average values and their σ are represented.

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