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Solar membrane distillation: theoretical assessment of multi-stage concept

Juan Carlos Vega-Beltrán[a], Lourdes García-Rodríguez[b,*], Isabel Martín-Mateos[a], Julián Blanco-Gálvez[c]

[a]*Dpto. Física Fundamental y Experimental, Electrónica y Sistemas, Universidad de La Laguna, Avda. Astrofísico Francisco Sánchez s/n. 38205- La Laguna, Tenerife, Spain*
Tel.: +34 922 318102; Fax : +34 922 318228; email: jcvega@ull.es, itmartin@ull.es
[b]*Dpto. Ingeniería Energética, Universidad de Sevilla, Escuela Técnica Superior de Ingenieros, Camino de los Descubrimientos, s/n. 41092- Sevilla, Spain*
Tel.: +34 95 4487231; Fax: +34 95 4487133; email: lourdesg@esi.us.es, diego.alarcon@psa.es
[c]*CIEMAT-Plataforma Solar de Almería, Ctra. de Senés s/n, 04200- Tabernas, Almería, Spain*
Tel.: +34 950387939; Fax: +34 950365015; email: julian.blanco@psa.es

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ABSTRACT

This paper deals with a project entitled "Seawater Desalination by Innovative Solar-Powered Membrane-Distillation System", MEDESOL (FP6-2005-Global-4, FP6-036986). The main project objective is the development and experimental assessment of solar multi-stage MD concept in order to obtain a high-efficiency and cost-effective system for stand-alone seawater desalination. This concept is based on the use of some MD modules connected with a particular design arrangement to minimize both, main and auxiliary energy consumptions. The selection of the system configuration is based on a generic membrane distillation module. This paper selects the configuration of the MD system among different candidate designs, set the prospects of solar MD technology as function of available MD modules and assess the influence on system efficiency of main operational parameters of an individual module: temperature gradient across the membranes and maximum working temperature.

Keywords: Membrane distillation; Solar desalination; Seawater desalination

1. Introduction

The status of Membrane Distillation (MD) technology and of solar desalination have been reported by the authors [1,2]. Although there are many commercial membranes [3] suitable to membrane distillation (MD) of seawater, there are very few commercial or pre-commercial MD modules [4–6]. Moreover, experimental data published about such systems exhibit specific energy consumptions and recovery rate much lower [5,6] than conventional solar distillation systems based on industrial distillation processes—multistage flash distillation and multi-effect distillation. Both parameters are especially important in stand-alone solar systems since they determine the sizes of solar thermal and photovoltaic fields required to supply main and auxiliary energy consumption, respectively.

MD process has significant advantages compared to aforementioned processes, as technical simplicity, long maintenance-free operation periods and ability of operating with high concentrate brine. Moreover, due to its modularity there is no practical limitation of capacity. Hence, to develop membrane distillation technology in

*Corresponding author.

order to achieve energy consumptions similar to those of conventional distillation technologies is of major interest.

This paper deals with a project entitled "Seawater Desalination by Innovative Solar-Powered Membrane-Distillation System", MEDESOL (FP6-2005-Global-4, FP6-036986) [1,7], partially supported by the European Commission under the Horizontal Programme "Global Change and Ecosystems (Global 4)". CIEMAT, Spain, coordinates the project and other ten partners take part in the project consortium from different European countries and Mexico. The main project objective is the development and experimental assessment of solar multi-stage MD concept in order to obtain a high-efficiency and cost-effective system for stand-alone seawater desalination. This concept is based on the use of some MD modules connected with a particular design arrangement, suitable for stand-alone solar desalination systems, suitable to minimise both, main and auxiliary energy consumptions.

The selection of the system configuration is one objective of the MEDESOL project. It is based on a generic membrane distillation module. This paper selects the configuration of the MD system among different candidate designs, set the prospects of solar MD technology as function of available MD modules and assess the influence on system efficiency of main operational parameters of an individual module:

- Temperature gradient across the membranes.
- Maximum working temperature.

2. Selection of system configuration for a stand-alone solar system

The analysis of capital costs of a stand-alone solar system points out that two main parameters have to be minimised in order to obtain the most suitable design for stand-alone solar distillation systems:

- Main energy consumption, which is the most important parameter of the solar collector area required.
- Auxiliary energy consumption, mainly dependent on the recovery rate of the desalination process as a whole, which mainly determines the area of the photovoltaic field required.

Figure 1 shows the influence of the above mentioned parameters. In order to estimate the cost of the thermal and photovoltaic solar field the following assumptions were used:

- Photovoltaic solar field required for the seawater intake: 6 €/Wp installed, 2.5 Wp installed per W required, 0.5 kW per 1 m3/h of seawater [8].

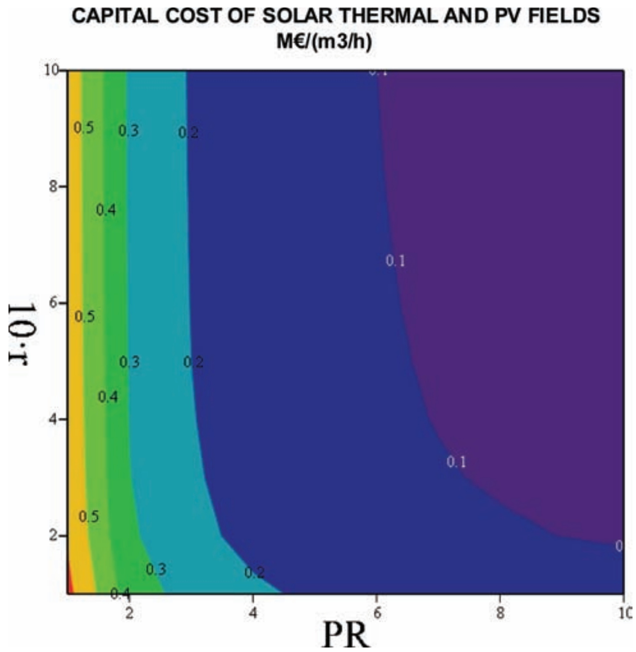

Fig. 1. Capital cost of solar thermal and photovoltaic fields per m^3/h of nominal production for a stand-alone solar system as function of Performance.

- Solar Thermal field: 300 €/m^2, solar irradiance at design point 700W/m^2.

Figure 1 shows that low recovery rates should be avoided in efficient systems in order to achieve reasonable capital costs. Auxiliary energy required to pump the cooling seawater is not included since its required mass flow rate depends on the particular temperatures of a given case study. It will increase the influence of the recovery rate of the process (r), especially for systems with low PR.

3. System configuration

Taking account Figure 1, three candidate designs were analysed:

1. *Configuration 1.* A single MD module.
2. *Configuration 2.* A multistage concept in which saline water used as cooling water to condense steam generated in one of the membrane modules (and therefore heated) is used as feed water by the following module, while cold brine from same module is used as cooling water by the following. This design is repeated in the following modules.
3. *Configuration 3.* A multistage design arrangement proposed by Hanbury and Hodgkiess [9], the same as a conventional Multi-Stage Flash (MSF) distillation system.

Configuration 1 is a particular case of configuration 2. The analysis of these designs is based on the use of a given number of generic MD modules in which the following parameters are set:

1. Temperature, pressure and mass flow rate of the feed water input of the first MD module.
2. Temperature, pressure, salinity and mass flow rate of the cooling water input of the first MD module.
3. Mass flow rate recycled in the desalination process as a whole.
4. Temperature gradient mean across the membrane, ΔT, which depend on the available technology of the modules used to construct the system.

Atmospheric pressure is assumed for feed and cooling channels. Pressure losses are assumed to have negligible effect. A maximum top temperature of 90ºC is considered to fit the objectives defined within the framework of the MEDESOL project.

Different number of modules and different points of connecting the recycling stream(s) were analysed. Finally, the design arrangement shown in Figure 2, which consists of 4 membrane modules for top temperatures about 80ºC–90ºC was selected.

The mathematical models of the module configurations presented in this paper use basic material and energy balance equations and physical properties of water and saline waters.

MATLAB software was used to perform the analysis and to carry out the best configuration for the modules arrangement. MATLAB® is a commercial “Matrix Laboratory” package which operates as an interactive programming environment. It is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation.

Two assumptions were used in the analysis: the first assumes the system at steady state conditions and the second assumes salt-free distillate. The second assumption implies negligible entrainment of the brine droplets by the steam generated. Other features of the developed mathematical models include the following:

- Physical properties of saline water dependent on temperature and salinity.
- No thermal losses are considered in this first approach.

Results are reported in terms of performance ratio, distillate production and recovery rate. Other data include profiles of the effect temperature, pressure, flow rate, and salinity.

The mathematical model for the MEDESOL configuration includes the material and energy balance equations as well as the heat transfer equations for each module (evaporation and condensation). Correlations used for thermodynamic properties are given by El-Dessouky et al. [10]. The model includes the following equations:

- Total balance in module i

$$q_{F_i} = q_{B_i} + q_{P_i}$$

- Salt balance effect in module i

$$X_{F_i} \cdot q_{F_i} = X_{B_i} \cdot q_{B_i}$$

- Energy balances on module i, lead to the following equations:

1. Evaporation:

$$\int_{T_{Hio}}^{T_{Hif}} \int_{s_{io}}^{s_{if}} \frac{C_p(T,s)}{\lambda(T)} ds dT = \int_0^{q_{Pi}} \frac{1}{q_{H_i} - q_{P_i}} dq_P = \ln \frac{q_{H_i}}{q_{H_i} - q_{P_i}}$$

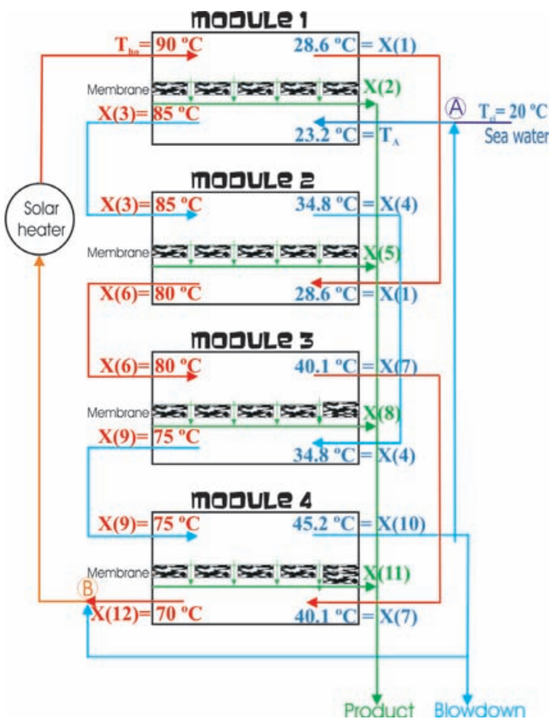

Fig. 2. Selected design arrangement for a stand-alone solar system with top temperature around 80ºC–90ºC. The cooling system is not shown in the figure since its connection depends on the particular behaviour of the MD modules.

2. Condensation:

$$q_{C_i}\int_{T_{C_{io}}}^{T_{C_{if}}} C_p(T,s_i)dT = \frac{q_{P_i}}{T_{C_{if}}-T_{C_{io}}}\int_{T_{C_{io}}}^{T_{C_{if}}} \lambda(T)dT$$

Finally, configuration 3 for a MD system was proposed by Hanbury and Hodgkiess [9] similar to the standard design of a multistage flash distillation plant (see Fig. 3): the plant consists of two different sections (1: heat recovery section; 2: heat rejection section), in which several stages are connected in series.

4. Results

Some useful results are presented in this section for the selected system configuration reported in the previous section. One of the objectives of MEDESOL project is the development of a stationary solar collector with low concentration, able to achieve top temperatures of about 90ºC. Hence, 90ºC is selected to operate the MD system.

4.1. Configurations 1 and 2

Initially, configuration 2 was studied. The corresponding results are applicable to configuration 1 since it is the particular case of a single module.

It was analysed the influence of the available technology of MD modules. One of the most influent parameters is the temperature gradient mean across the membrane (ΔT). A given value of ΔT may be achieved with a proper selection of membrane and MD module design. For a given feasible value of ΔT, the membrane area required in every MD module depends on the production required in every module and the achievable permeate fluxes for a given membrane. Once the membrane area required is calculated, a rough cost estimation of the system could be done. However the accurancy of cost estimations is strongly limited by the status of development of MD market. For system configuration 2, shown in Fig. 2, Fig. 4 shows the influence of ΔT on:

- Performance Ratio (PR) of the desalination system as a whole.
- Required production of every module.
- Recovery rate of the desalination system as a whole.

A second point of the analysis is the influence of the maximum working temperature on:

- Performance Ratio (PR) of the desalination system as a whole.
- Required production of every module.
- Recovery rate of the desalination system as a whole.

For a system design based on configuration 2, shown in Fig.2 under the assumption of a temperature gradient mean across the membrane of 5ºC. Results are shown in Figure 5.

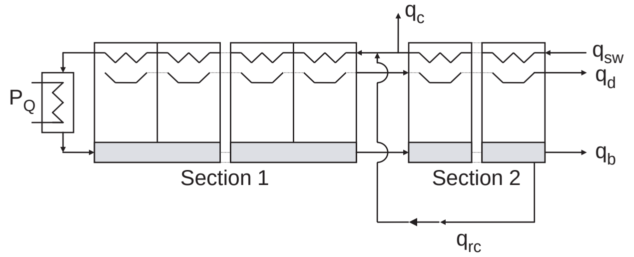

Fig. 3. Conceptual design of a multistage flash distillation plant. Thermal power input, PQ; mass flow rate, q; subscripts: blowdown, bd, cooling, c, distillate, d, recycling, rc, seawater, sw.

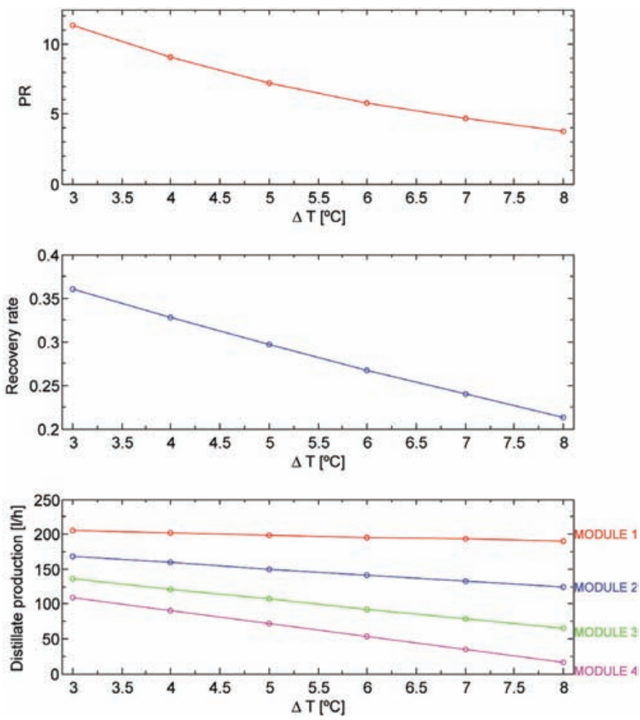

Fig. 4. Results obtained for configuration 2: Influence of the temperature gradient mean across the membranes on the performance ratio and recovery rate of the desalination system as a whole (fig. 2) and the corresponding production of every module.

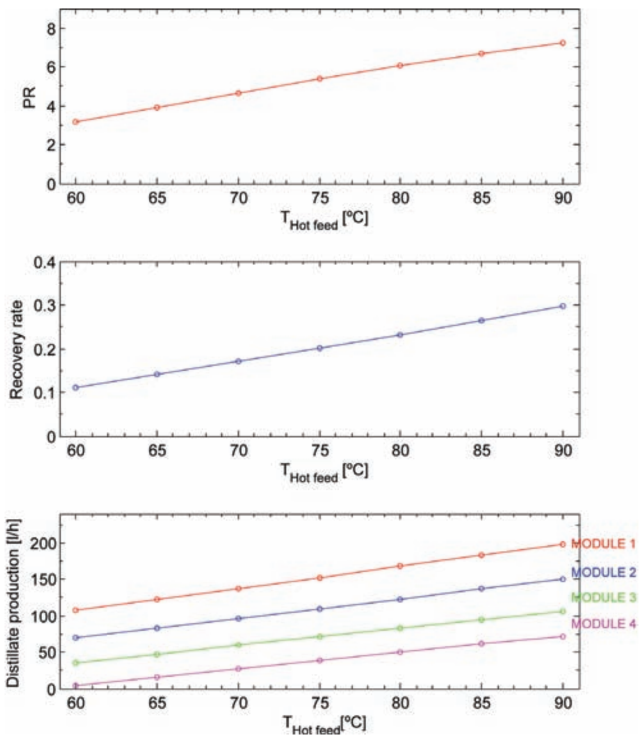

Fig. 5. Results obtained for configuration 2: Influence of the maximum temperature on the performance ratio and recovery rate of the desalination system as a whole (fig. 2) and the corresponding production of every module for a temperature gradient mean across the membranes of 5ºC.

Results obtained for the particular case of a single module (design 1) were worse than those provided in Figures 4–5, related to design 2. If ΔT = 5ºC, the particular case of single MD module (configuration 1) achieves a PR of 10.6 with low recovery rate, 0.1. Besides that, for the same value of ΔT, the multistage configuration 2 (see Fig. 2) achieves a PR of 7.3 and recovery rate 0.3. Respective capital cost of the thermal and PV solar fields per m3/h of nominal capacity are the following:

- *Configuration 1.* PV field: 75 k€/(m^3/h); Solar thermal field (stationary collectors): 52.4 k€/(m^3/h). Total: 127.4 k€/(m^3/h).
- *Configuration 2.* PV field: 38.8 k€/(m^3/h) (cooling seawater included); Solar thermal field (stationary collectors): 76.5 k€/(m^3/h). Total: 115.4 k€/(m^3/h).

4.2. Configuration 3

Figure 6 shows the PR achieved with the multi-stage configuration proposed by Hanbury and Hodgkiess [9] (configuration 3) vs. the temperature of the outlet cooling stream of the first module (Tc,o) [1]. Different maximum temperatures (Th,i) are shown from 55ºC to 100ºC. The difference Th,i – Tc,o is ΔT at the first module inlet. Figure 6 shows that PR higher than 10 can be achieved if ΔT is 5ºC and maximum temperature is 90ºC with configuration 3, which is able to obtain recovery rates higher than configuration 2. Therefore, capital costs of the solar fields for configuration 3 are about 52.4 k€/(m^3/h) for a stationary solar thermal field and less than 38.8 k€/(m^3/h) for the PV field, thus resulting in a total amount less than 90.2 k€/(m^3/h).

Regarding the membrane area required, in configurations 2 and 3 membranes operate at similar working conditions. Therefore, configuration 2 and 3 require approximately the same membrane area per unit of distillate production. Nevertheless, in configuration 2, membranes in second module, and the following operate at less favourable working conditions. Then, configuration 2 requires higher membrane area than configuration 1 and 3.

Qualitative results obtained are also applicable to different maximum temperatures and ΔT.

5. Conclusions

The analysed performed is based on generic membrane distillation (MD) modules connected with different system configurations in order to find the most

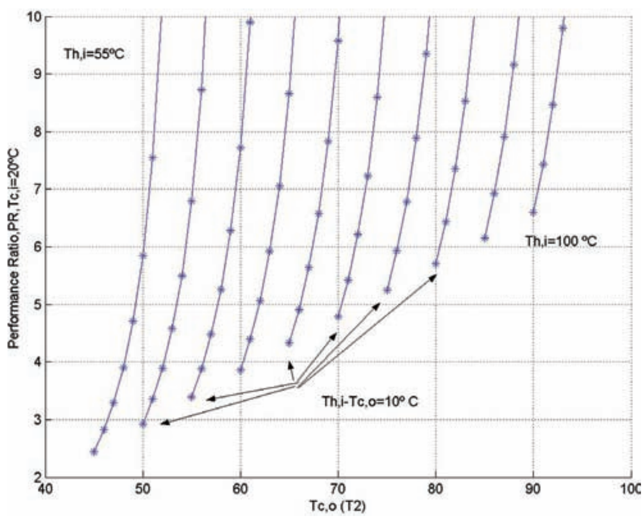

Fig. 6. PR that could be achieved with configuration 3, proposed by Hanbury and Hodgkiess [9]. Maximum temperature, Th,i; Th,i – Tc,o is ΔT at the first module inlet [1].

suitable design for stand-alone solar distillation. Then, the main objective is to minimise both, main energy consumption and auxiliary energy consumption, and thus the recovery rate. Configurations analysed are based on connecting different MD (multistage concept). The following conclusions could be pointed out from the analysis performed about stand-alone solar MD:

1. A multi-stage configuration of MD modules based on the conventional multi-stage flash distillation process is the most suitable design.
2. If maximum temperature is 90ºC and the temperature gradient mean across the membrane is 5ºC, capital costs of the solar subsystem per m3/h of nominal distillate production are: about 52.4 k€/(m3/h) for a stationary solar thermal field and less than 38.8 k€/(m3/h) for the PV field, thus resulting in a total amount less than 90.2 k€/(m3/h).
3. An estimation of capital cost of the solar subsystem (thermal and PV fields) could be obtained from Figure 1, as function of recovery rate (r) and performance ratio (PR) of the desalination system as a whole. Besides that, the dependence on the PR of maximum temperature and temperature gradient across the membrane is provided by Figure 5.

Acknowledgments

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Nomenclature

C_p Mass heat capacity at constant pressure, kJ/(kg·K).
q mass flow rate, kg/sec.
s Salinity, mg/kg.
T Temperature, ºC.
X salt concentration, ppm.

Greek symbols

λ Mass enthalpy of phase change, kJ/kg.

Subscripts

B Brine
C Cooling
F Feed
f Final value
H Hot feed
i Module number
o Initial value
P Permeate

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