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Distilled and drinkable water quality produced by solar membrane distillation technology

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ABSTRACT

Scarcity of water for human consumption in many places such as arid and semi-arid regions is well known. This situation has become even more complicated in those areas where there are virtually no energy sources or the electrical grid is too weak or has not been provided. In these cases, the solar membrane distillation (MD) technology is an emerging and promising solution to small distributed desalination systems. Regardless of the technology used for desalination, the water produced the desalination plant has to fulfil the local requirements on water quality for human consumption. In this work, the main physico-chemical and microbiological characteristics of water produced by two types of solar MD technologies are presented. The necessity to fulfil the European requirements on disinfection and remineralization post-treatment is also considered.

Keywords: Water quality; Membrane distillation

1. Introduction

The water need for human composition is a special problem that should be addressed, especially in the arid and semi-arid areas lacking fresh natural sources. Almost one-fifth of the world population live in areas where water is physically scarce [1]. This problem is aggravated in the small settlements of remote areas without any hydraulical or electrical infrastructure. In such circumstances desalination technologies driven by renewable energy, mainly solar power or wind energy, can be a solution to cater to the water supply needs of the population. The lack of conventional energy sources as well as missing or weak and unreliable connections to the electricity grid complicates the use of standard desalination techniques in such areas. Besides, some desalination technologies are not easy to be scaled down to processing a small quantity of water.

The possible combinations of the main renewable energies with desalination techniques can give us 24 different systems or combination possibilities [2]. More recently, a comprehensive review of the com-

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mercial desalination products powered by renewable energy was developed under the frame work of the Prodes project (www.prodes-project-org), showing us that solar photovoltaic (PV) or wind energy coupled with reverse osmosis (RO) desalination plants is the most popularly installed technology for water supply on a small scale.

Membrane distillation (MD) is an emerging technology for water supply, which was investigated in the past few years with respect to solar thermal and PV energy supply [3,4]. The results demonstrate that MD is most suitable for small distributed desalination system as the technology is very robust against different raw water and ambient conditions. The MD modules can be directly connected to a corrosion-free solar thermal collector without any heat storage tank; owing to its low thermal capacity, the feed volume flow and operation temperature can be changed very quickly without causing any instability to in the MD process. Another advantage of the MD process compared to the RO is that the product's water conductivity is low, thus making it also suitable for other applications such as in industrial sector or in medical field.

Some very promising developments on a solar thermally driven MD have been shown from the laboratory up to pilot scale in the past years. Recently, Saffarini and co-workers [5] compiled the demonstration projects of a distillation process using solar energy. There were four main configurations, being air gap (AGMD) being the most used one and employed on a pilot scale.

Despite the technology employed to produce or treat water for human consumption, this facility should be provided to consumers devoid of any health risk. According to the European Council Directive No. 98/83 [6] or the WHO recommendations for drinking water, the water intended for human consumption shall be wholesome and clean if it is free from any micro-organism or parasite and from any substance which, in number or concentration, constitutes a potential threat to human health.

The technological developments made in the field of membrane desalination technologies have paid more attention to energy consumption, material qualities, and cost and to the recovery rate volume of water produced, rather than the quality of it. This paper presents some quality parameters for the water produced by two MD systems powered by solar thermal energy, contributing to the few investigations on desalinated water quality from small-scale RES-desalination technologies. Also, the requirement to fulfill the European-Spanish regulations on potable water is discussed.

2. Materials and methods

2.1. Description of MD system—plant no. 1

The solar MD experimental compact system (see Fig. 1) was developed by the MEMDIS project coordinator—Fraunhofer ISE (Institute for Solar Energy Systems) [4].

The MD system has a nominal capacity to produce 150 l/day of distilled water. Seawater is pretreated with a 10 μm cartridge filter and stored in a 500 l feed tank that is connected to a seawater well by a refilling pump. Cold seawater is pumped by a PV (one module of 80 Wp) supplied pump to the MD module. The volume flow in the system is controlled by solar radiation on the PV module. The membrane used, a hydrophobic PTFE of 0.2 μm pore size, has an effective surface area between 8.5 and 10 m^2, and is configured as the permeate gap. A solar field area of 6.96 m^2 (three plane collectors in parallel) was employed. The brine rejected by the module was recycled to the feed storage which was then refilled automatically when a trash hold was reached. The nominal pressure is 1 bar and the operations hours vary from 6 h in winter to 9 h in summer.

2.2. Description of MD system—plant no. 2

The experimental MD plant (see Fig. 2) was developed by Memsys, using the Vaccum-Multi-Effect Membrane Distillation V-MEMD system and Agbar has been operating it since 2011. The distillation system has a recovery rate of 45%, producing 150 l/day of distillate water with a conductivity below 10 μS/cm. Seawater was pretreated with two cartridge filters (10 and 20 μm) and stored in a 1,000 l stratified thermal tank. The heating energy was provided by 12 solar collectors of 2.27 m^2 each. A two-step module membrane configuration, with a total hydrophobic membrane area of 4.16 m^2, was used. The flows, temperatures and other parameters were registered to study the system's efficiency.

2.3. Analytical methods

To evaluate the quality of distillate water and system performance, some physical, chemical and microbiological parameters were monitored.

The parameters recorded were pH, conductivity, temperature (T^a), alkalinity (Alk), boron (B), calcium (Ca), magnesium (Mg), chloride (Cl), sodium (Na), potassium (K), nitrate (NO_3), sulphate (SO_4) and aerobic micro-organisms (22 and 37°C). All the methods

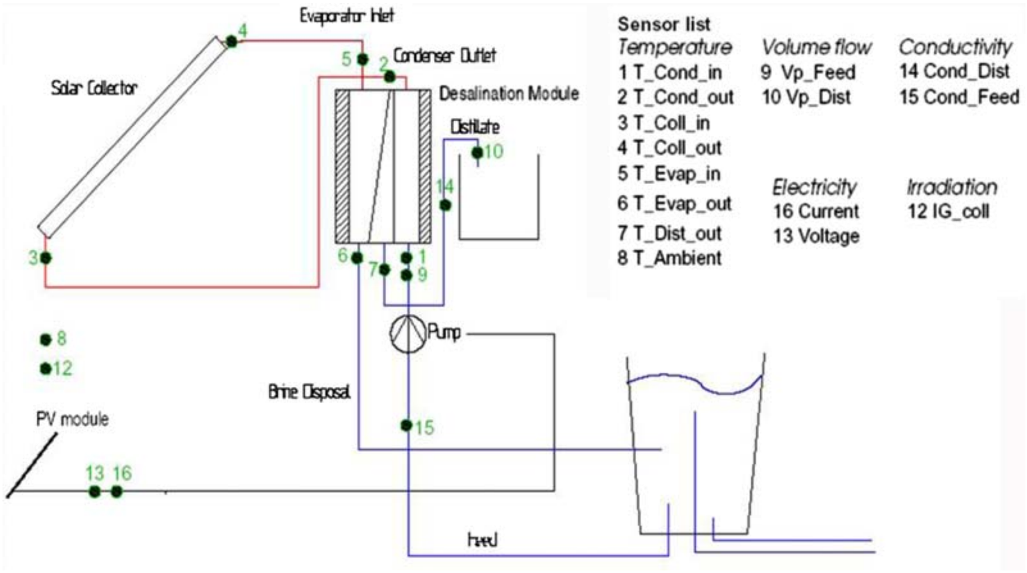

Fig. 1. Diagram of the distillation membrane unit—plant no. 1.

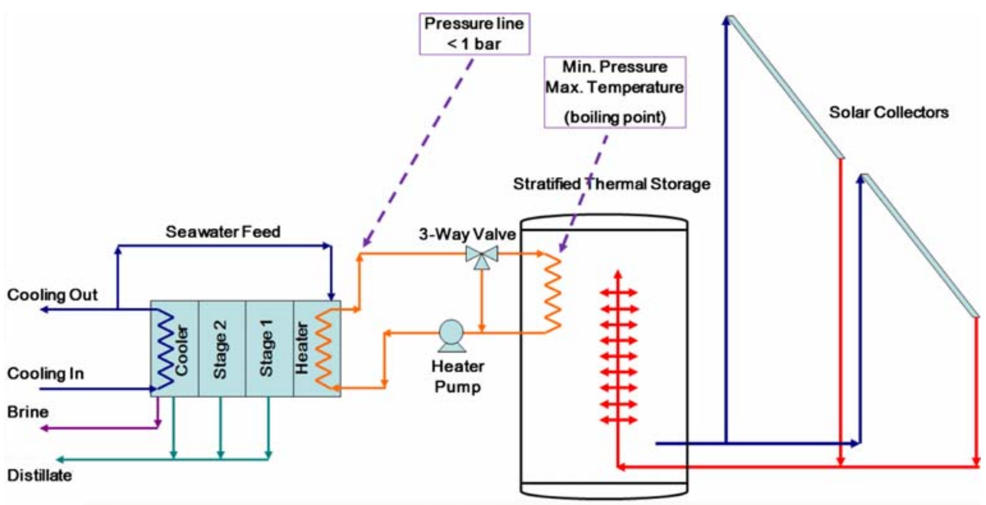

Fig. 2. Diagram of the distillation membrane unit—plant no. 2.

employed for evaluating the distilled water were tested according to the ISO standard for water quality, with some remarks according to the characteristics of this type of water, to assure us of the precision of the results.

For conductivity measurement of the distillate, the sensor was calibrated periodically with a 84 μS/cm NIST traceable solution. The pH sensor was calibrated daily, also with traceable calibration solution. Alkalinity was measured according to ISO9963 employing a 10 ml microburette and titrated with 0.01 N HCl solution. The boron content was measured using the azomethine-H spectrophotometric method. Anions were measured by ionic chromatography. Metals and cations in low concentration, lower than 1 mg/l, were measured by inductively coupled plasma optical emission spectrometry (ICP-OES). For microbiological analysis, the spread-plate method (ISO 6222) was used to enumerate the count of aerobic micro-organisms. All chemical and products used were the highest quality according to each method.

Langelier Saturation Index (LSI) was calculated as follows

$$LSI = pH - pHsat$$

$$pHs = (9.3 + A + B) - (C + D)$$

$$A = 1/10\times(\log[TDS] - 1); \quad TDS = Cond\times 0.55\ (mg/l)$$

$$B = -13.12\times\log(T\ [^{\circ}K]) + 34.55$$

$$C = \log[Ca\ as\ CaCO_3] - 0.4$$

$$D = \log[Alkalinity\ as\ CaCO_3]$$

Samples of the distillate were re-collected when the major production process of the system was at its peak and when this was not possible, the samples were collected at noon (12:00 h or later).

3. Results and discussion

3.1. Distilled water characterization—plant no. 1

The distillate produced by the MD module was analysed weekly for five months, to evaluate the system's water quality. The conductivity and pH variation of the distillate during the sampling period are shown in Fig. 3. The water produced by the MD module was characterized by very low conductivity, with a mean value of 29.3 μs/cm, and hence with a very low salt content, which was about 7.5 mg/l considering a factor of 0.55 to obtain an approximation of the TDS content from a mean conductivity value.

The pH of the water was slightly acidic, with a mean value of 5.5, and did not undergo any drastic change during the sampling period. The mean distillate temperature was approximately 23°C, ranging from 23°C registered during spring to the maximum of 29.9°C, registered in August the same year.

The alkalinity values as well as the calcium concentration were very low, with concentrations below 20 mg/l $CaCO_3$ for alkalinity and 5 mg/l $CaCO_3$ for calcium hardness, respectively, for all the samples analysed. Considering a minimum measurable alkalinity of 20 mg/l, distillate The LSI values were calculated. LSI values were always negative with a maximum LSI of −4.0, which means that this water was very corrosive and aggressive to cement and metallic materials that were used in storage and distribution. European regulations establish that water for human consumption should be neither aggressive nor corrosive. Spanish regulations [7] measure this characteristic through the LSI, which should be fall within the range (−0.5, +0.5). Stabilization of the distillate to a level that is non-aggressive, non-corrosive and palatable to consumers is therefore mandatory. Post-treatment by remineralization or recarbonation should be conducted prior supply to the population.

The respective bacteria content in the distillate was observed from the beginning of the analytical phase that colony counts (aerobic microorganisms) were very high, above 300 cfu/ml, for all the samples analysed even for colony counts at 22 and 37°C. Colony counts is a parameter indicating the effectiveness of water treatment processes, thus it is used as an indirect indication of pathogen removal and as a measure of the numbers of regrowth organisms that may or may not have sanitary significance [8]. In fact, the currently recommended European microbiological standards include colony counts' limits for water supply, with no significant increase over the normal levels when incubated at 22 and 37°C. So these values should be kept as minimum as possible to avoid any human infection. Considering the above factors, the water produced by the MD distillation system, without any treatment, does not fulfil the quality criteria for drinking water and has to be disinfected prior consumption. Subsequent investigations were conducted to identify the genus of bacteria that appeared in the culture plates. Using the isolation techniques and biochemical tests, it was determined that many of the growing bacteria belonged to the genera *Pseudomonas* and *Aeromonas*.

3.2. Distilled water characterization—plant no. 2

The conductivity variation of MD System 2 of the distillate, during the sampling period is shown in Fig. 4.

As it can be shown, the conductivity values were very low. The pH mean value was 6.2 and temperature 28.7°C. The alkalinity and calcium hardness values obtained for plant no. 1 were very low, with concentrations below 20 mg/l $CaCO_3$ for alkalinity and 5 mg/l $CaCO_3$ for calcium hardness, which are the cunatification limits of both methods respectively. The LSI for the distillate was calculated considering these minimum measurable values. The values obtained were always negative with an LSI mean

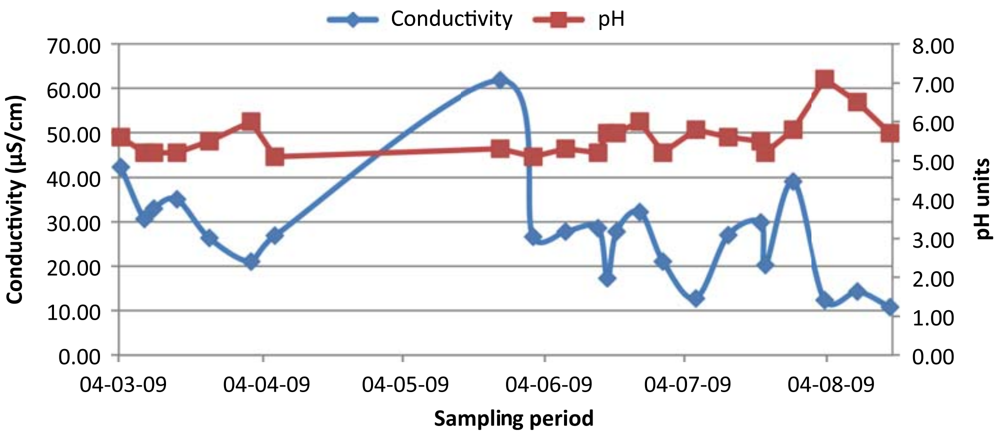

Fig. 3. Variation in pH and conductivity during the sampling period—plant no. 1.

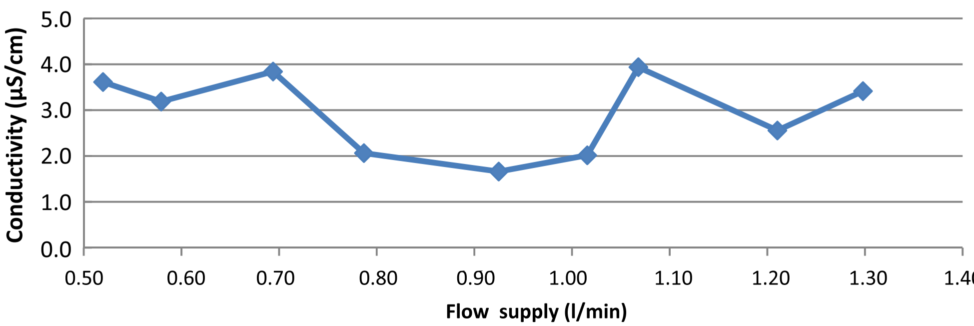

Fig. 4. Conductivity values vs. flow supply—plant no. 2.

value of −3.9, confirming the corrosiveness and aggressiveness of water.

The respective bacteria content in the distillate was observed in all the analysed samples, that colony counts were very high, above 300 cfu/ml, even for colony counts at 22 and 37°C.

4. General considerations for potabilization

Waters produced by the MD technology are not suitable for human consumption due to the low mineral content, low buffer capacity, which makes them, highly aggressive and corrosive, besides the high bacterial content. So remineralization and disinfection post-treatment should be applied prior distribution.

Several remineralization–recarbonation systems have been reviewed and proposed mainly for large-scale desalination plants, to increase and adjust the LSI value. The main methods that are being applied in large scale are: chemical addition, carbon dioxide addition followed by limestone or dolomite dissolution; carbon dioxide addition followed by lime dosing; blending with water containing a high mineral content [9,10].

Selection of the most suitable remineralization technique, to the described distillation units, should take into account the following considerations:

- The remineralization system should increase the calcium content and alkalinity value (buffering capacity) of treated water, to reach a value of appropriate LSI.
- The system must be easy to use, low maintenance, low cost and without or very low-energy demand.
- Besides the technical considerations, remineralization methods based on calcium and magnesium addition are more desirable, because they contribute to these nutrient minerals, especially in such areas with a deficient food intake [11]. Based on these criteria and with the information compiled, a remineralization system based on calcium carbonate dissolution seems to be the most suitable.

It would be desirable that for an isolated drinkable water production system, the post-treatment process

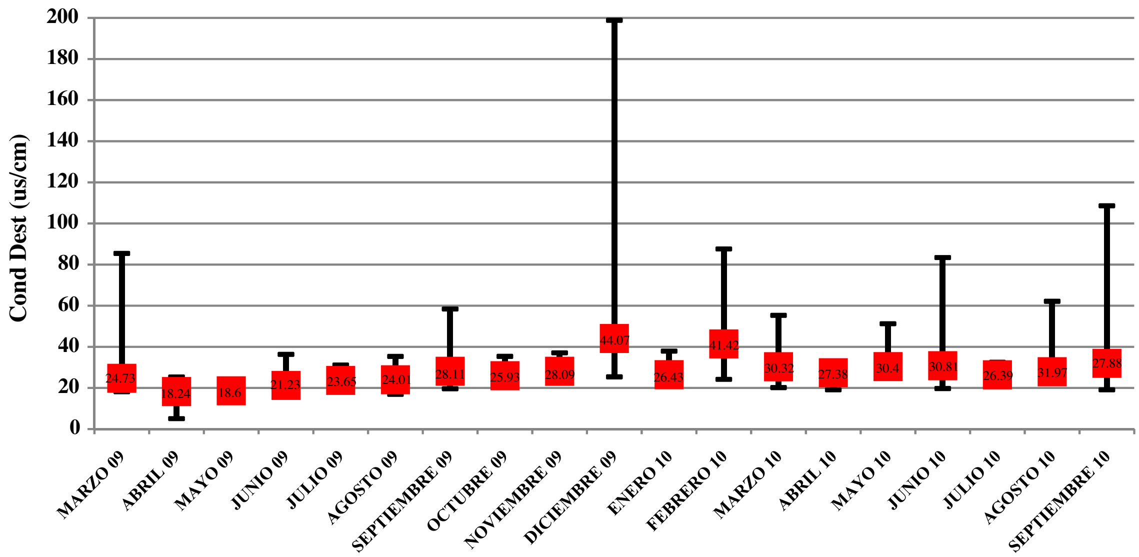

Fig. 5. Maximum and monthly average distillate conductivity of the MD system no. 1, from 9 February to July 2010.

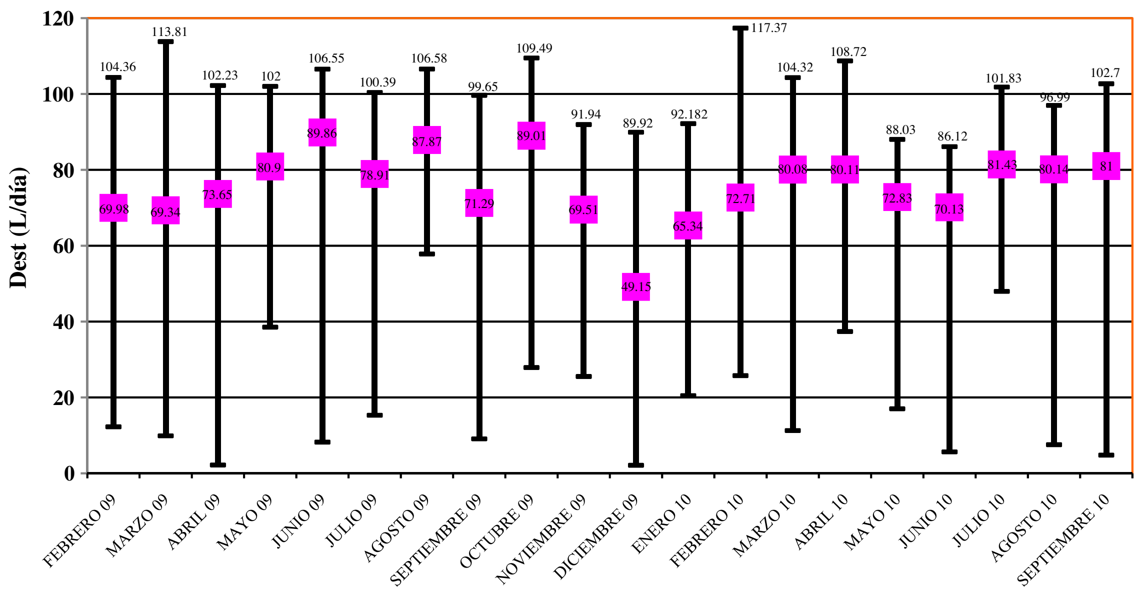

Fig. 6. Maximum and monthly average production (l/day) of the MD system no. 1, from 9 February to July 2010.

should be autonomous and robust. Any manual intervention should be avoided to prevent any chemical or microbiological contamination and the quality of the treated water should always be the same, or within a proper range. In this context, the MD technology presents some drawbacks.

The distillate water chemical characteristics also fluctuate, during the day and all through the year. The mean conductivity value of the distillates, and per month are illustrated in Fig. 5. Automatization of the remineralization system requires that some parameters should be fixed and build up the remineralization process under these circumstances. Presumably fluctuations in LSI values will also be obtained.

The wide water flow fluctuations. Solar MD is a technology which depends on the solar irradiation level. The monthly average and the variation of distillate produced by plant no. 1 are shown in Fig. 6. This water flow variation makes the post-treatment process more complicated. More equipment and accessories are needed, and hence more energy consumption would be necessary.

Table 1
The removing capacity of MD technology (Plant no. 1) for several metals

Parameters	Distillate	Seawater	Rejection efficiency
	Mean	Mean	%
Boron (mg/l)	0.08	4.7	98.297
Stronium (μg/l)	<55	11,164.0	>99.507
Sodium (mg/l)	1.9	1,445.5	99.868
Magnesium (mg/l)	<0.2	1,441.9	99.998
Potassium (mg/l)	<0.2	427.4	99.995
Calcium (mg/l)	<0.2	583.6	99.965

The complementary post-treatment for proper disinfection of the waters does not have as many complexities as remineralization. For this experience, UV disinfection was considered. A UV lamp (19–15 l/min; 230 V) was installed and tested. The UV lamp was connected to the electrical grid and the control system started through a relay only when the distillate production took place. After installation, colony counts were always below 30 cfu/ml. The main inconvenience of this technology is that it has a bactericidal effect limited to 48 h, for which reason a recirculation of the treated water was considered.

4.1. Solar MD technology efficiency

During the sampling period, feed water (seawater from beach well) was analyzed to know about the removing capacity for certain chemical compounds, and hence the efficiency of this technology. Table 1 shows the parameters analyzed and its concentration, even if seawater is in the distillate. The MD technology is highly efficient in removing some metals such us boron and strontium, the rejection efficiency being higher than those obtained by RO.

Fluoride and nitrate concentrations in feed water were determined to be mean values of 1.7 and 3.8 mg/l, respectively. All the distilled samples showed a value below the detection limit for both methods which was set up at 0.1 mg/l. According to these considerations, the MD has a minimum removal capacity for fluorides of 94.186 and 97.403% for nitrates.

5. Conclusions

Stand-alone desalination plants that are based on the MD technology serve as a solution to provide drinking water to remote areas using high solar radiation. However, low conductivity obtained in the distillate and the quality of water produced are not suitable for human consumption without treatment.

Remineralization is needed to remove the aggressiveness and corrosiveness of the distillate and to increase the mineral content for public health reasons. The bacterial content in the distillate is high, with the presence of bacterial genera, *Pseudomonas* and *Aeromonas*, which could affect the human health, so disinfection has to be done prior distribution.

Considering the high efficiency of this technology for remove Boron, make it considered as an alternative for treat waters with high boron content.

References

[1] World Health Organization, Safe drinking-water from desalination. Guidance on risk assessment and risk management procedures to ensure the safety of desalinated drinking-water. (2011) WHO/HSE/WSH/11.03.
[2] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: Review and the state of art, Desalination 203 (2007) 346–365.
[3] J. Koschikowski, M. Wieghaus, M. Rommel, Solar thermal-driven desalination plants based on membrane distillation, Desalination 156 (2003) 295–304.
[4] J. Koschikowski, M. Wieghaus, V. Subiela, B. Peñate, J.R. Betancort, Experimental investigations on solar driven stand-alone membrane distillation systems for remotes areas, Desalination 248 (2009) 125–131.
[5] R. Saffarini, E. Summers, H. Arafat, J. Leinhard, Technical evaluation of stand-alone solar powered membrane distillation systems, Desalination 286 (2012) 332–341.
[6] Directiva 98/83/CE del Consejo de 3 noviembre de 1998 relativa a la calidad de las aguas destinadas al consumo humano. Diario Oficial de las Comunidades Europeas. L 330/32.
[7] Real Decreto 140/2003, de 7 de febrero, por el que se establecen los criterios sanitarios de la calidad del agua de consumo humano. BOE no. 45, 2003.
[8] World Health Organization, Heterotrophic plate counts and drinking water safety (2003).
[9] A. Whiters. Options for recarbonation, remineralisation and disinfection for desalination plants. Desalination (2005) 11–24.
[10] L. Birnhack, N. Voutchkov, O. Lahav, Fundamental chemistry and engineering aspects of post-treatment processes for desalinated water—a review, Desalination 273 (2011) 6–22.
[11] J.A. Cotruvo, Health aspects of calcium and magnesium in drinking water, Water conditioning & Purification 48(6) (2006) 40–44.