Renewable water: direct contact membrane distillation coupled with solar ponds

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29 **Abstract**

30 Desalination powered by renewable energy sources is an attractive solution to address the
31 worldwide water-shortage problem without contributing significant to greenhouse gas emissions. A
32 promising system for renewable energy desalination is the utilization of low-temperature direct
33 contact membrane distillation (DCMD) driven by a thermal solar energy system, such as a salt-
34 gradient solar pond (SGSP). This investigation presents the first experimental study of fresh water
35 production in a coupled DCMD/SGSP system. The objectives of this work are to determine the
36 experimental fresh water production rates and the energetic requirements of the different
37 components of the system. From the laboratory results, it was found that the coupled DCMD/SGSP
38 system treats approximately six times the water flow treated by a similar system that consisted of an
39 air-gap membrane distillation unit driven by an SGSP. In terms of the energetic requirements,
40 approximately 70% of the heat extracted from the SGSP was utilized to drive thermal desalination
41 and the rest was lost in different locations of the system. In the membrane module, only half of the
42 useful heat was actually used to transport water across the membrane and the remainder was lost by
43 conduction in the membrane. It was also found that by reducing heat losses throughout the system
44 would yield higher water fluxes, pointing out the need to improve the efficiency throughout the
45 DCMD/SGSP coupled system. Therefore, further investigation of membrane properties, insulation
46 of the system, or optimal design of the solar pond must be addressed in the future.

47 **1 Introduction**

48 Global population growth and higher standards of living are significantly increasing the
49 demand for energy and water [[1]]. Fossil fuels have been used to meet the energy needs, but are
50 not sustainable due to the environmental impacts of combustion and the rapid depletion of fossil
51 fuel reserves [2-4]. Thus, renewable energy sources are needed to reduce fossil fuels consumption
52 and to increase fresh water production.

53 One way to create new sources of fresh water is to desalinate seawater or brines. Reverse
54 osmosis (RO) has been the most common method for desalination, especially since the cost of
55 membranes has decreased over the years [5]. However, RO requires significant quantities of energy
56 [6]. Desalination powered by renewable energy sources is an attractive solution, because it has
57 lower environmental impacts and lower greenhouse gas emissions [7-9]. In fact, novel temperature-
58 driven membrane techniques can produce fresh water at a competitive cost, and can be very
59 effective to desalinate brackish water, seawater, or even brines [10,11].

60 A promising approach to desalination is low-temperature membrane distillation (MD) driven
61 by thermal solar energy [12]. This approach may be especially well-suited to arid regions, where
62 there is a fresh water shortage, a salt water surplus, and high availability of solar energy [13]. MD is
63 a temperature-driven membrane separation process that has the potential to become a viable tool for
64 water desalination [14-17].

65 An ideal, renewable source of heat for MD systems is a salt-gradient solar pond (SGSP). An
66 SGSP is a body of water that collects solar radiation and utilizes a salt gradient in order to store this
67 collected solar radiation as thermal energy [18]. Most common SGSPs consist of three distinct
68 layers: the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective
69 zone (LCZ). The UCZ consists of the least saline water and is located in the uppermost section of
70 the solar pond. The NCZ consists of an increasing saline solution with increasing depth and is
71 located below the UCZ. The salinity gradient present in the NCZ suppresses any mixing between
72 the three layers while still allowing solar radiation to penetrate through the solar pond into the LCZ.
73 The LCZ consists of the most saline, and thus, most dense solution and is located below the NCZ,
74 making up the bottom of the solar pond. As the LCZ collects solar radiation and rises in
75 temperature, the high salinity solution remains trapped below the NCZ due to its density. This
76 salinity (or density) gradient allows the LCZ to collect and store solar energy for long periods of
77 time [19]. Temperatures higher than 80 °C have been observed in previous studies [20-22], while
78 temperatures as high as 110 °C have been observed in an outdoor solar pond, with a temperature

difference between the UCZ and LCZ of nearly 70 °C [23]. A major advantage of using a solar pond for energy collection and storage are low costs of construction and operation, especially when compared to photovoltaic cells [24].

When a solar pond is exposed to solar radiation, energy is collected and stored in the LCZ. This stored energy, or heat, can be easily extracted from the solar pond through heat exchangers and utilized for applications such as thermal desalination by direct contact membrane distillation (DCMD) [25]. DCMD is the simplest configuration of MD where the warmer feed solution and cooler distillate solution are in direct contact with both sides of the membrane [14]. The driving force is the vapor pressure gradient that is induced across the membrane from contact of the warmer and cooler streams. Previous studies have shown that DCMD is advantageous for obtaining high fluxes [26] but does suffer from heat losses due to conduction through the membrane surface [24]. The simplicity of DCMD, requiring only a membrane module, low-grade heat source, and two low-pressure pumps, makes it very suitable to be coupled with an SGSP for solar powered thermal desalination.

Solar ponds have been previously used to provide heat for various forms of desalination. A 3,000 m² solar pond in El Paso, Texas was used to deliver heat for both a multi-stage flash distillation (MSF) unit and an air-gap MD (AGMD) unit [20]. The MSF unit was able to produce water at 3.3 L min⁻¹, or 1.6 x 10⁻³ m³ d⁻¹ per m² of SGSP, while the AGMD unit was able to produce water at 6.7 L m⁻² h⁻¹, or 0.158 x 10⁻³ m³ d⁻¹ per m² of SGSP. The desalination research performed at the El Paso Solar Pond demonstrated that desalination driven by solar ponds on a large scale is feasible and competitive with other desalination techniques [22]. However, most of the investigations where solar ponds deliver heat for thermal desalination correspond to performance analysis [25,27,28]. Suárez et al. [25] studied a coupled DCMD/SGSP system that has potential to produce four times the expected water fluxes in an AGMD/SGSP system. Saleh et al. [27] studied the coupling of a solar pond with an MSF desalination unit. Mericq et al. [28] investigated the coupling of vacuum MD with solar ponds and solar collectors. These investigations only studied the

105 previous configurations by means of theoretical models and no experimental validation was
106 performed.

107 The objective of this study is to experimentally evaluate, for the first time, the performance
108 of a synergetic DCMD/SGSP system to achieve solar-powered thermal desalination. The specific
109 objectives of this work are to determine: 1) the experimental fresh water production rates; and 2)
110 the energetic requirements of the different components of the DCMD/SGSP system. An SGSP is a
111 promising renewable energy system that can deliver low-grade heat to desalination systems.
112 Coupling an SGSP with a simplistic desalination system such as DCMD allows for remote
113 desalination with very little electrical input; thus, reducing fossil fuels consumption and increasing
114 fresh water production in a sustainable way.

115 **2 Materials and methods**

116 **2.1 Solar pond**

117 This study used the laboratory-scale solar pond constructed by Suárez et al. [29]. Complete
118 details on the pond's instrumentation are presented in previous works [29,30]. For this investigation,
119 the pond was modified to allow heat extraction (Figure 1). Two sets of diffusers were installed at
120 ~0.5 m depth at both sides of the pond. This depth was selected because it was intended to be just
121 below the interface between the NCZ and LCZ. Brine was recirculated at a rate of 3.00 L min⁻¹
122 using a gear pump (Cole-Parmer® Gear Pump Systems, Cole-Parmer Instrument Company, Vernon
123 Hills, IL). The hot brine was taken from one side of the pond, passed through a plumbing system
124 that was connected to a custom-made heat exchanger (used to extract the collected heat), and then
125 the cooler brine was returned to the other side of the pond. The plumbing outside the solar pond is
126 comprised of 1.27-cm (½-inch) diameter polyvinyl chloride (PVC) pipes. The pipes were insulated
127 using self-seal polyethylene foam pipe insulation (Tubolit®, Armacell, Mebane, NC). The heat
128 exchanger was used to extract heat from the solar pond to warm the feed solution of the DCMD test

unit. The heat exchanger consisted of approximately twenty 0.64-cm ($\frac{1}{4}$ -inch) stainless steel tubes inside a 5.1-cm (2-inch) diameter PVC pipe. The heat exchanger was also insulated with self-seal polyethylene foam pipe insulation.

2.2 DCMD test unit

The DCMD module used in this study (MD 020 CP 2N, Microdyn, Wiesbaden, Germany) contained 40 capillary membranes of 1.8 and 2.8 mm inner and outer diameter, respectively, an active length of 460 mm, a surface area of 0.1 m^2 , and a free flow area of 1 cm^2 . The polypropylene membrane has an average pore size of $0.2 \text{ }\mu\text{m}$, a porosity of 70%, a tortuosity of 1.43 [31], and an average effective thermal conductivity of $0.046 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ [32].

Fresh water was used as the feed solution and was continuously pumped at a rate of 1.25 L min^{-1} from a feed reservoir through the heat exchanger (that is connected to the solar pond), across the membrane module and back to the feed reservoir (Figure 1). The fresh water feed allows evaluating the best-case scenario for membrane flux. The assessment of fouling mitigation (e.g., evaluation of feed water pretreatment, selection of the most appropriate membrane for the solution chemistry, optimization of the flow conditions to minimize deposition of foulant material) is outside the scope of this study. Distilled deionized water was used as the distillate solution and was recirculated at a rate of 2 L min^{-1} in the distillate loop in the same way as the feed loop (Figure 1). The distillate solution was cooled to the desired temperature with a heat exchanger fed by a water chiller (ISOTEMP 1023S, Fisher Scientific, Pittsburg, PA). The distillate reservoir was a 2 L filtration flask that allows overflow of excess permeating water into a collecting flask. The overflow was continuously weighed on an analytical balance (PGL 8001, Nova-Tech International, Houston, TX), which allowed estimation of the water fluxes across the membrane.

Electrical conductivity (EC) and temperature (T) in different locations of the DCMD test unit (Figure 1) were measured using EC electrodes (SK23T, Van London-pHoenix Company, Houston, TX). A modular multi-channel datalogger (D230, Consort, Turnhout, Belgium) was used

154 to record these data at 5-min intervals. Pressure within the DCMD system was not measured since it
155 operated at near atmospheric pressure (approximately 0.9 atm). Acrylic flowmeters (FR4000, Key
156 Instruments, Trevose, PA) were installed after each pump (Cole-Parmer® Gear Pump Systems,
157 Cole-Parmer Instrument Company, Vernon Hills, IL) to control the flow rates of the DCMD feed
158 and permeate streams.

159 **2.3 Thermal desalination driven by solar ponds**

160 For the experiment, the lights over the laboratory-scale solar pond were turned on 24 hours
161 per day, with an average radiation at the water surface of $240 \pm 3 \text{ W m}^{-2}$. Temperature within the
162 solar pond was monitored throughout the experiment using a vertical high-resolution distributed
163 temperature sensing (DTS) system [29,33]. This DTS system achieves a temperature resolution of
164 $\pm 0.06 \text{ }^{\circ}\text{C}$ when data were integrated over 30 s. The thermal desalination experiment began when
165 thermal quasi steady-state conditions were achieved inside the solar pond. Heat was extracted for
166 45 hours at $\sim 0.5 \text{ m}$ depth (by the two sets of diffusers).

167 An energy balance was carried out on the solar pond-powered desalination system to
168 determine the energy used in each component of the system. The heat extracted from the solar
169 pond, q_{USE}'' , was estimated using the heat content inside the solar pond [34]. The heat used in the
170 membrane module, q_m , was estimated using a previously developed heat and mass transfer model
171 for DCMD [25] (This model is briefly described below). Conductive heat losses in the solar pond
172 plumbing, $q_{\text{SGSP}}^{\text{cond}}$, were calculated using the temperature at the extraction depth inside the solar pond
173 as an approximate temperature for the bulk temperature within the pipes and the temperature of the
174 laboratory as the ambient temperature. The thermal properties of the PVC pipes and the self-seal
175 foam pipe insulation were used to determine the radial conductive flow through this part of the
176 system. Other heat losses throughout the system, $q_{\text{SYST}}^{\text{other}}$, were estimated by subtracting $q_{\text{SGSP}}^{\text{cond}}$ and q_m
177 from the heat extracted from the solar pond.

178 The DCMD heat and mass transfer model developed previously allows determining the heat
 179 used in the membrane module and the water flux across the membrane. In this model, the water
 180 flux, J , across the membrane is estimated by [35]:

$$181 \quad J = C_m [p_{fm}(T_{fm}, S_{fm}) - p_{dm}(T_{dm})] \quad (1)$$

182 where C_m is the distillation coefficient of the membrane, p is the vapor pressure, T is the
 183 temperature, and S is the feed concentration. The subscripts "fm" and "dm" represent the feed and
 184 distillate sides of the membrane surface, respectively. At steady-state conditions, a heat transfer
 185 analysis yields:

$$186 \quad q_f = q_m = q_d \quad (2)$$

187 where q_f and q_d are the convective heat transfer in the feed and distillate, respectively; and q_m is the
 188 heat transferred across the membrane. These heat fluxes are given by:

$$189 \quad q_f = h_f (T_f - T_{fm}) \quad (3)$$

$$190 \quad q_d = h_d (T_{dm} - T_d) \quad (4)$$

$$191 \quad q_m = q_m^c + q_m^v = \left[k_m \frac{dT}{dx} \right] + [JH_v(T)] \quad (5)$$

192 where h_f and h_d are the heat transfer coefficients in the feed and distillate, respectively; T_f and T_d are
 193 the bulk temperatures in the feed and distillate, respectively; q_m^c is the conductive heat flux through
 194 the membrane; q_m^v is the enthalpy heat flux through the membrane; k_m is the effective thermal
 195 conductivity of the membrane; x is the distance in the mass flux direction; and $H_v(T)$ is the vapor
 196 enthalpy (latent heat of vaporization) at temperature T . A detailed description of the model is
 197 presented elsewhere [25,36]. The input parameters of the mathematical model were based on the
 198 properties of the membrane (described above), and the operating conditions monitored during the
 199 experiments. Table 1 presents a summary of the values of the input parameters that were used in the
 200 numerical simulations. Note that the mathematical model allows disaggregating the heat fluxes that
 201 govern the physics of the DCMD unit. Hence, model results give insights on the parts of the system

202 that require improvement and the parts of the system that are working properly. Also, it is important
203 to mention that assessing the effect of fouling on the energetic aspects of the DCMD/SGSP system
204 is out of the scope of this work.

205 Monte Carlo simulations were performed to quantitatively estimate the uncertainty of the
206 water flux across the membrane and the energy used in each component of the system, i.e., to
207 analyze how the uncertainty of the operating parameters and membrane properties affect the water
208 and heat fluxes in the coupled system. These simulations were based on the energy balance
209 explained above. Table 1 shows the probability distribution of the input parameters used in the
210 Monte Carlo simulations. The input parameters of the Monte Carlo simulations were based on the
211 experimental measurements and on values obtained from the literature [31,32].

212 **3 Results and discussion**

213 **3.1 Heat extraction in the solar pond**

214 The thermal behavior of the solar pond before, during, and after the desalination experiment
215 is shown in Figure 2. Data collected from the vertical high-resolution DTS system [29] were
216 integrated over 30 s intervals to achieve a temperature resolution of 0.06 °C. Before the desalination
217 experiment began, thermal quasi-steady state and a temperature of ~45 °C were reached in the LCZ.
218 Heat extraction started at 12:12 p.m. on January 19, 2010. Figure 2 clearly shows pond cooling in
219 the lower depths during heat extraction and pond warming in the lower depths soon after heat
220 extraction stopped. Figure 3 (a) shows the temperature profile before heat extraction (black line),
221 after approximately 1 and 2.5 hours of experimentation (blue and red lines, respectively), and at
222 approximately 45 hours, which is the end of the heat extraction period (green line). The time period
223 between 1 and 2.5 hours was plotted because during this timeframe the desalination system
224 achieved steady-state conditions. This steady-state allowed estimation of the heat used in the
225 desalination process (discussed below). After 60 min of extracting heat, the temperature profile

226 already showed the existence of different layers inside the solar pond (Figure 2). Initially, the NCZ-
227 LCZ interface was intended to be at a depth of ~ 0.5 m. However, the interface actually occurred at a
228 depth more deep than 0.5 m. During the first 2.5 hours of the desalination experiment, it is likely
229 that heat was extracted from the NCZ rather than from the LCZ (Figure 3 (a)). After 45 hours of
230 heat extraction, the thermal structure inside the solar pond (green line) reveals that even though
231 energy is being extracted from the NCZ, there is energy likely coming from the LCZ. When the
232 temperatures at the extraction depth are cooler than some threshold, the fluid at this depth become
233 heavier and thus, sinks into the bottom of the pond, which has been shown to produce a rise of the
234 warmer brine [37].

235 The temperature profiles measured inside the solar pond were used to determine the heat
236 content throughout the pond. Figure 3 (b) presents the temporal evolution of the heat content, which
237 has an error of 0.2 MJ (due to the temperature resolution of the DTS system). The slope of this
238 curve represents the heat extracted from the solar pond. An average of 139 ± 12 W was extracted
239 from the solar pond during the 45 hours of operation. This corresponds to an efficiency of 29%.
240 Efficiencies between 4 and 35% have been reported in other solar ponds studies [38-40]. During the
241 first 2.5 hours of experimentation, an average of 230 ± 20 W (efficiency of 48%) was extracted from
242 the pond (Figure 3 (b) inset). In calculating heat extraction, only the heat content below 0.20 m
243 depth was considered as heat used for extraction. Changes in the heat content at shallower depths
244 could have been the result of changes at the surface of the pond, e.g., due to evaporation or to fresh
245 water injection to account for evaporation. It has also been found that operation of the solar pond at
246 lower temperatures decreases conductive heat losses throughout the NCZ, which results in more
247 useful energy that can be used in the desalination system [25]. In this experiment, 6% of the
248 incoming energy was lost due to conductive heat losses when the LCZ of the solar pond was at 45
249 °C. When the LCZ was at 39 °C, a 56% reduction of the conductive heat losses was estimated.
250 Although this additional energy is relatively small, reduced conductive heat losses are an advantage
251 of this system compared to systems that operate at higher temperatures.

The results presented in Figure 3 suggest that the solar pond is far from reaching steady-state conditions when heat is being extracted from the system. As discussed by Suárez et al. [25], to operate a DCMD/SGSP system under thermal steady-state conditions, the surface area of the solar pond must be on the order of 1,000 times the membrane surface area. In this experimental system, a solar pond with surface area of 2 m² is being used to provide energy to a DCMD module with 0.1 m² of membrane surface area, and thus the surface area of the solar pond is only 20 times that of the membrane. As can be seen in Figures 2 and 3, by the inability of the pond to maintain steady-state conditions, the solar pond essentially cannot keep up with the MD system. The desalination system would thus have to be operated intermittently to maintain a viable thermal structure in the solar pond. Because it is not efficient to have a larger membrane area operating intermittently, use of a smaller membrane area is desired not only for continuous operation but also for lower capital costs.

3.2 Thermal desalination driven by solar ponds

Figure 4 (a) shows water flux through the membrane and cumulative distillate throughout the experiment. The experimental errors associated to the water flux and to the cumulative distillate were estimated on 0.01 L hr⁻¹ per m² of membrane and on 1×10⁻⁴ L, respectively. A maximum water flux of ~1.1 L hr⁻¹ per m² of membrane was observed during the first 8 hours of the experiment. After this, the water flux decreased most likely due to a reduction in the feed temperature caused by a decrease in the solar pond temperature (as explained in section 3.1 and as seen in Figure 2). Flux decline due to fouling or scaling is not likely because the membrane module was operated with fresh water as the feed solution. Also, electrical conductivity in the distillate reservoir did not change significantly over time, thus wetting of the membrane pores was not observed.

A total of 3.3 L of water were produced during the first 34 hours of the experiment. After this time, the analytical balance turned off and no record of treated water was available. This water production corresponds to an average water flux of 0.97±0.09 L hr⁻¹ per m² of membrane, which is

equivalent to $\sim 1.16 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond. However, this water flux is not sustainable over time because the coupled system was not optimized to operate at steady-state conditions. It was found that the solar pond required approximately 10 days to recover its initial thermal structure after heat extraction was stopped (data not shown). This results in an actual flow rate of $\sim 0.12 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond, which is actually on the same order as the maximum treated flow rate obtained by an AGMD unit tested at the 3,000- m^2 El Paso Solar Pond [41]. A maximum treated flow of $\sim 0.16 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond (6.7 L hr^{-1} per m^2 of membrane) was obtained by the AGMD system. This water production was obtained using clean water as the feed solution and with feed and distillate temperatures of 69.6 and 28.5 °C, respectively, i.e., at a temperature difference across the membrane of 41.1 °C. The average temperature difference across the membrane in the current work is approximately 10°C (Figure 4 (b)) with feed and distillate average temperatures of 34.3 ± 0.1 and 24.0 ± 0.1 °C, respectively (feed and distillate average temperatures were calculated using the inlet and outlet temperature of each stream). When the temperature difference in the AGMD system decreased to approximately 10°C [41], the AGMD system treated approximately 6 times less water than that treated by the DCMD system presented in this work. No information was found regarding temperature reduction inside the El Paso Solar Pond while the AGMD system was operating. To our knowledge, no other experimental studies of membrane distillation driven by solar ponds exist except El Paso's AGMD/SGSP [20,22,41]. Although, it should be noted that the El Paso's system used an outdoor large-scale solar pond and a membrane distillation unit that was approximately 30 times larger than that used in this work.

Figure 4 (b) also presents the water flux of the DCMD module during the first 2.5 hours of experimentation, where steady-state conditions were observed. At the beginning of the experiment, the temperatures in the desalination system increased until steady state was reached. A water flux of $1.08 \pm 0.01 \text{ L hr}^{-1}$ per m^2 of membrane was obtained in this steady-state time period. The heat and mass transfer model for the DCMD module [25] was used to estimate the theoretical water flux and

energy requirements of the desalination system. The results of the heat and mass transfer model are presented in Figure 4 (b). It can be seen that the water fluxes obtained using the heat and mass transfer model agree fairly well with the experimental data, with differences less than 6%.

The results of the Monte Carlo simulations are shown in Figure 5 and Table 2. Figure 5 presents the histogram of the water flux across the membrane and provides further confirmation of the agreement between the modeled and experimental water fluxes. Table 2 presents the results of the energy budget of the DCMD/SGSP system. As shown in Table 2, approximately 70% of the energy extracted from the solar pond was used to drive thermal desalination, i.e., $q_m = 0.7 q_{USE}''$, approximately half of this energy is used to transport water across the membrane (the enthalpy flow, q_m^v), and the remainder is lost by conduction in the membrane (q_m^c). Therefore, improvement of DCMD membranes and modules to reduce conductive heat losses would yield higher water fluxes. From the energy that is not used to drive thermal desalination, approximately 20% was lost in the plumbing system of the solar pond, and the rest was lost in other parts of the system (e.g., heat exchanger, feed reservoir, feed side plumbing, or from the membrane module to the ambient). By having better insulation throughout the system more heat would be available for the desalination process, and thus, more water could be treated. For example, if 90% of the energy extracted from the solar pond is used to drive this desalination system, i.e., $q_m = 0.9 q_{USE}''$, the water flux could increase from 1.08 to 1.43 L hr⁻¹ per m² of membrane, i.e., a water production of 0.37×10^{-3} m³ d⁻¹ per m² of solar pond, which corresponds to a 33% increase in the water flux. This points out the need to improve the efficiency throughout the DCMD/SGSP coupled system. Therefore, further investigation of membrane properties, insulation of the system, and optimal design of the solar pond must be addressed in the future.

It is important to note that the laboratory-scale solar pond used in this work is also subject to other energetic inefficiencies [30] that reduce the efficiency of this system; and ultimately have an impact on the energy that can be extracted and subsequent water that can be treated. For instance,

the pond is heated with artificial lights that yield lower radiation intensities than the sun. Thus, outdoor operation of the solar pond is expected to result in higher values of treated water than those achieved with the indoor solar pond presented here. Also, the pond has a sloped wall that has two main drawbacks: (1) radiation is absorbed at shallower depths inside the pond, resulting in lower temperatures at the bottom of the pond compared to those expected in large-scale operation; and (2) the energy storage volume is reduced when compared to a large-scale solar pond where boundary effects can be neglected. Therefore, a maximum temperature of only 45 °C was achieved in the laboratory-scale solar pond, whereas temperatures higher than 80 °C have been observed in the majority of large-scale solar ponds [20-22,41-43]. Even more, temperatures as high as 110 °C were observed when the brine of a solar pond was boiling [23]. Hence, even when the pond could be subject to other heat losses, e.g., due to meteorological conditions, more energy could be collected and higher water production values than those reported in this work could be achieved.

In addition to the energetic inefficiencies observed in the laboratory-scale system [30], it is important to address other issues that also reduce the overall efficiency. For instance, in a recent investigation, Ruskowitz [44] used the same solar pond of this study to evaluate the effect of evaporation suppression on both the energy collected by the solar pond and the freshwater production rates. Ruskowitz [44] obtained a maximum water production rate of $\sim 2.89 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond when 88% of the pond surface was covered with transparent floating discs [44,45]. This water production rate is 2.5 times larger than that obtained in this work. Therefore, from the work of Ruskowitz [44] two conclusions can be drawn: 1) his water production rates demonstrate the reproducibility of the experimental values presented in this work; and 2) evaporation suppression at the pond surface increase both the energy collected by the solar pond and the water production rates in the DCMD module. Thus, more research should be carried out to improve the performance of the DCMD/SGSP coupled system.

351 4 Conclusions

352 The performance of an experimental DCMD/SGSP system to achieve solar-powered thermal
353 desalination was investigated for the first time and the following conclusions can be drawn:

354 An average fresh water flux of $\sim 1.0 \text{ L hr}^{-1}$ per m^2 of membrane was obtained. This water
355 production is equivalent to $\sim 1.16 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond. However, in our
356 experiments, the SGSP was far from reaching steady-state conditions while providing energy to
357 the desalination system. Therefore, the desalination system would have to be operated
358 intermittently. This is not cost-effective because it is more expensive to have larger membrane
359 areas that will not be operating continuously. For this reason, smaller membrane areas should be
360 used to reduce capital costs and to enable continuous operation.

361 When considering that the DCMD/SGSP produces a sustainable water flux over time, an
362 average water flux of $\sim 0.12 \times 10^{-3} \text{ m}^3 \text{ d}^{-1}$ per m^2 of solar pond was obtained. This water
363 production was achieved with a temperature difference of 10°C between the feed and distillate
364 solutions, and it is approximately six times greater than the water production of an
365 AGMD/SGSP system operating under similar conditions.

366 Although $\sim 70\%$ of the energy extracted from the SGSP was used to drive thermal desalination,
367 only half of this energy was effectively used to transport water across the membrane (enthalpy
368 flow), and the remainder was lost by conduction in the membrane. Thus, improvements of
369 DCMD membranes and modules are a research line that could improve the performance of this
370 coupled system. In addition, by having better insulation throughout the system more energy
371 should be available for fresh water production. Thus, further investigation of membrane
372 properties, insulation of the system, or optimal design of the solar pond must be addressed in the
373 future.

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382

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493

503 **Table 2. Water fluxes in the desalination system and energy budget in the coupled system for the first 2.5 hours**
 504 **of experimentation. $T_f = 34.3\text{ }^\circ\text{C}$; $T_p = 24.0^\circ\text{C}$; $v_f = 0.21\text{ m s}^{-1}$; $v_p = 0.33\text{ m s}^{-1}$; $S_f = 0$; $p_a = 86\text{ kPa}$; $\tau = 1.43$; $k_m =$**
 505 **$0.046\text{ W m}^{-1}\text{ }^\circ\text{C}^{-1}$.**

J (L m ⁻² hr ⁻¹)	q_{USE}'' (W)	q_{m} (W)	q_{m}^{v} (W)	q_{m}^{c} (W)	$q_{\text{SGSP}}^{\text{cond}}$ (W)	$q_{\text{SYST}}^{\text{other}}$ (W)
1.14 ± 0.12	231.3 ± 21.7	157.7 ± 10.8	80.9 ± 8.8	76.8 ± 7.8	43.7 ± 1.1	29.9 ± 24.3

506 Average value ± standard deviation.
 507
 508

Figure captions

509

510 **Figure 1. Diagram of the experimental setup. The symbols P, EC, F, and T represent pumps, electrical**
511 **conductivity probes, flow meters, and temperature sensors, respectively; UCZ, NCZ and LCZ are upper**
512 **convective zone, non-convective zone, and lower convective zone, respectively.**

513

514 **Figure 2. Thermal behavior inside the solar pond. Temperature was measured using a vertical high-resolution**
515 **DTS system with a spatial resolution of 1.1 cm. A temperature resolution of 0.06 °C was achieved when the data**
516 **were collected using integration intervals of 30 seconds. The desalination experiment started after thermal quasi-**
517 **steady state was achieved and continued for 45 hours. Heat was extracted at a depth of ~0.5 m.**

518

519 **Figure 3. Thermal behavior inside the solar pond during the desalination experiment: (a) temperature profile**
520 **inside the solar pond at different times. The depth of the UCZ-NCZ and NCZ-LCZ interfaces are shown at the**
521 **right side of the graph, and the depth where heat was extracted is shown at the left side of the graph; (b)**
522 **temporal evolution of the heat content inside the solar pond. The inset shows a zoom of the first 2.5 hours of the**
523 **desalination experiment.**

524

525 **Figure 4. Thermal desalination experiment: (a) water flux and cumulative distillate in the desalination system;**
526 **(b) water flux and temperatures in the desalination system when steady-state conditions were observed.**

527

528 **Figure 5. Monte Carlo simulations ($n = 10^6$) show that experimental water fluxes ($J_{\text{exp}} \pm \sigma_{\text{exp}}$) are within the range**
529 **of the modeled water fluxes ($J_{\text{mod}} \pm \sigma_{\text{mod}}$).**

Figure 1

Figure 1. Diagram of the experimental setup. The symbols P, EC, F, and T represent pumps, electrical conductivity probes, flow meters, and temperature sensors, respectively; UCZ, NCZ and LCZ are upper convective zone, non-convective zone, and lower convective zone, respectively.

Figure 2

Figure 2. Thermal behavior inside the solar pond. Temperature was measured using a vertical high-resolution DTS system with a spatial resolution of 1.1 cm. A temperature resolution of 0.06 °C was achieved when the data were collected using integration intervals of 30 seconds. The desalination experiment started after thermal quasi-steady state was achieved and continued for 45 hours. Heat was extracted at a depth of ~0.5 m.

Figure 3. Thermal behavior inside the solar pond during the desalination experiment: (a) temperature profile inside the solar pond at different times. The actual depth of the UCZ-NCZ and NCZ-LCZ interfaces are shown at the right side of the graph, and the depth where heat was extracted is shown at the left side of the graph; (b) temporal evolution of the heat content inside the solar pond. The inset shows a zoom of the first 2.5 hours of the desalination experiment.

Figure 4. Thermal desalination experiment: (a) water flux and cumulative distillate in the desalination system; (b) water flux and temperatures in the desalination system when steady-state conditions were observed.

Figure 5

Figure 5. Monte Carlo simulations ($n = 10^6$) show that experimental water fluxes ($J_{\text{exp}} \pm \sigma_{\text{exp}}$) are within the range of the modeled water fluxes ($J_{\text{mod}} \pm \sigma_{\text{mod}}$).