Experimental characterization of a solar thermal desalination system: MED coupled to a flat plate solar collector field

Autores: Patricia Palenzuela (Project researcher at the Solar Desalination Unit, CIEMAT-Plataforma Solar de Almería, Crta de Senés s/n, 04200, Tabernas, Almería, patricia.palenzuela@psa.es), Aicha Chorak (Ph.Dstudent, Abdelmalek Essaâdi University, Faculty of Science and Technology of Tangier, Ziaten. BP: 416, Tangier, Morocco/ International University of Rabat, Morocco, chorakaicha@gmail.com), Diego-César Alarcón-Padilla (Head of the Solar Desalination Unit, CIEMAT-Plataforma Solar de Almería, Crta de Senés s/n, 04200, Tabernas, Almería, diego.alarcon@psa.es)

Abstract

This research work presents the experimental characterization of a solar Multi-effect Distillation (MED) system located at the Plataforma Solar de Almería. Firstly, the assessment of the efficiency of anew large-aperture flat plate solar field has been carried out at several temperature levels for different climate conditions. Secondly, an experimental characterization of the solar MED plant working at off-design conditions has been addressed in terms of the distillate production and performance ratio (PR).

From the results obtained, it was found a maximum experimental overall collector field efficiency close to 56% at a temperature level of 70 °C. The solar field efficiency showed some differences before and after solar noon due to the influence of the incidence angle which varies along the day due to the static nature of the solar collector. Regarding the thermal desalination plant, it was observed that the distillate production increases with the hot water temperature at the inlet of the MED first effect, and with the feed water flow rate. The maximum distillate production (3 m^3/h) was achieved at 74 °C and 9 m^3/h. The PR was normally lower the higher the inlet hot water temperature and it increased with the rise in the feed water flow rate from 5 to 8 m^3/h, decreasing at higher flow rates. The most pronounced rise was found at 68 °C where the maximum PR was obtained (11.1). Also, when the vapor temperature in the condenser is varied from 25 °C to 35 °C, the highest distillate production was found to be 3.22 m^3/h when the inlet hot water temperature is 74 °C, and the vapor temperature in the condenser was 25 °C. Besides, the maximum PR earned was 9.80 at a hot water inlet temperature of 66 °C when the vapor temperature in the condenser was 33 °C.

1 INTRODUCTION

Due to the usual geographic and seasonal coincidence of regions that present water stress and have high levels of solar irradiation, seawater desalination processes driven by solar energy seem to be the most promising option to solve the fresh water problems in these zones. For large-scale desalination systems, the best option is indirect desalination systems, which consist on the coupling of a conventional desalination system with the most suitable solar conversion system according to the energy form required by the desalination process. Among the distillation methods more frequently used in indirect solar desalination plants, multi-effect distillation (MED) is being preferred due to its low top brine temperature (TBT) and its higher thermodynamic efficiency compared with the rest of thermal distillation processes. In 2006, a unique experimental facility for the evaluation of solar MED systems was erected within the framework of the AQUASOL Project with the aim of developing an improved-cost and energy-efficient solar MED system [1]. A solar field composed of static compound parabolic concentrators (CPC) with a water-base thermal storage system was the solar thermal system that provided the required energy by the MED plant. The solar field and the thermal storage system have been recently replaced by a new one, consisting on large-aperture flat plate collectors' solar field with theoretically higher efficiency at the operating temperature of the MED plant, and a doubled-size water tank.

The experimental characterization of solar MED processes under design and off-design conditions can be a benchmark for the energy and cost optimization task together with the research of the most suitable control strategies. The literature related to the experimental characterization of solar MED plants is scarce (Blanco et al. [1], El-Nashar and Samad[2], Fernández-Izquierdo et al.[3]), and most of the studies focused on modeling and single optimization of MED systems have not been supported by experimental data.

This paper presents the experimental characterization of a solar MED system located at the PSA. Firstly, the assessment of the efficiency of a new large-aperture flat plate solar field has been carried out at several temperature levels for different climate conditions. Secondly, the analysis of the coupling of a pilot-scale MED plant to this solar field through a water storage system has been performed. Thirdly, an experimental characterization of the solar MED plant working at off-design conditions has been addressed in terms of the distillate production and performance ratio (PR) and, finally, some conclusions from this experimental work are given.

2 MATERIAL AND METHODS

Figure 1.1 depicts the general layout of how the components of the experimental facility are integrated. The coupling of the MED plant with the solar field is as follows: the water is heated through the solar field and directly after provides its thermal energy to the thermal storage circuit (which has a total storage capacity of 40 m^3) through a plate heat exchanger. Then, the hot water from the hot storage tank enters the first effect of the MED desalination plant, being the temperature controlled by the three-way valve (V1).

The static solar field (see Figure 1.1), manufactured by Wagner & Co. is composed of 56 flat plate collectors (FPC) type LBM10 with a total aperture area of 565.6 m^2. It consists of 4 loops with 14 large-aperture flat plate collectors each (two rows connected in series per loop with 7 collectors in parallel per row), all of them titled 35° south orientation. In the experiments for the evaluation of the solar field efficiency, the outlet water temperature T_{out_SF} of the solar field was kept constant at a certain value by means of an air cooler and the process parameters were measured every second. The efficiency was measured at different outlet water temperatures, from 70 °C to 90 °C, keeping the water flow rate in each loop constant and equal to the design value (37 L/min).

On the other hand, the characterization of the MED plant was carried out by the study of the influence of the variation of some parameters that control the operation of the MED system on the distillate production and the performance ratio. The latter is a parameter that determines the thermal efficiency of an MED plant and it is defined as the ratio between the mass of distillate (in kg) and the thermal energy supplied to the process normalized to 2,326 kJ (1,000 Btu) that is the latent heat of vaporization of water at 73 °C. It is expressed by the following equation:

$$PR = \frac{\dot{m}_d \times 2326}{Q_h} \quad (1)$$

where $\dot{m}_d$ is the distillate production and Q_h is the thermal energy consumption of the MED plant. The latter is calculated using the enthalpy difference at the inlet (h_{in_MED}) and outlet (h_{out_MED}) of the hot water in the first tube bundle of the MED unit at the temperatures T_{in} and T_{out}, respectively, and the hot water flow rate($\dot{m}_{hot}$) through this tube bundle, as follows:

$$Q_h = \dot{m}_{hot}(h_{in\_MED} - h_{out\_MED}) \quad (2)$$

Two experimental campaigns were carried out for the characterization of the solar MED pilot plant, which are detailed below:

- Case study 1: the feed water mass flow rate of the MED plant was varied between 5m^3/h and 9m^3/h for every hot water inlet temperature in the first effect, from 62 °C to 74 °C. In these experiments, the hot water flow rate in the first effect and the condenser vapour temperature were kept constant at 12 L/s and at 35 °C, respectively.
- Case study 2: the vapour temperature in the condenser was varied between 25 °C and 35 °C for every hot water inlet temperature, from 60 °C to 74 °C. In these experiments, the hot water flow rate and the feed water mass flow rate were remained fixed at 12 L/s and 8 m^3/h, respectively.

The measurements were taken after steady state conditions were reached in the solar desalination system and the average value of each variable was determined.

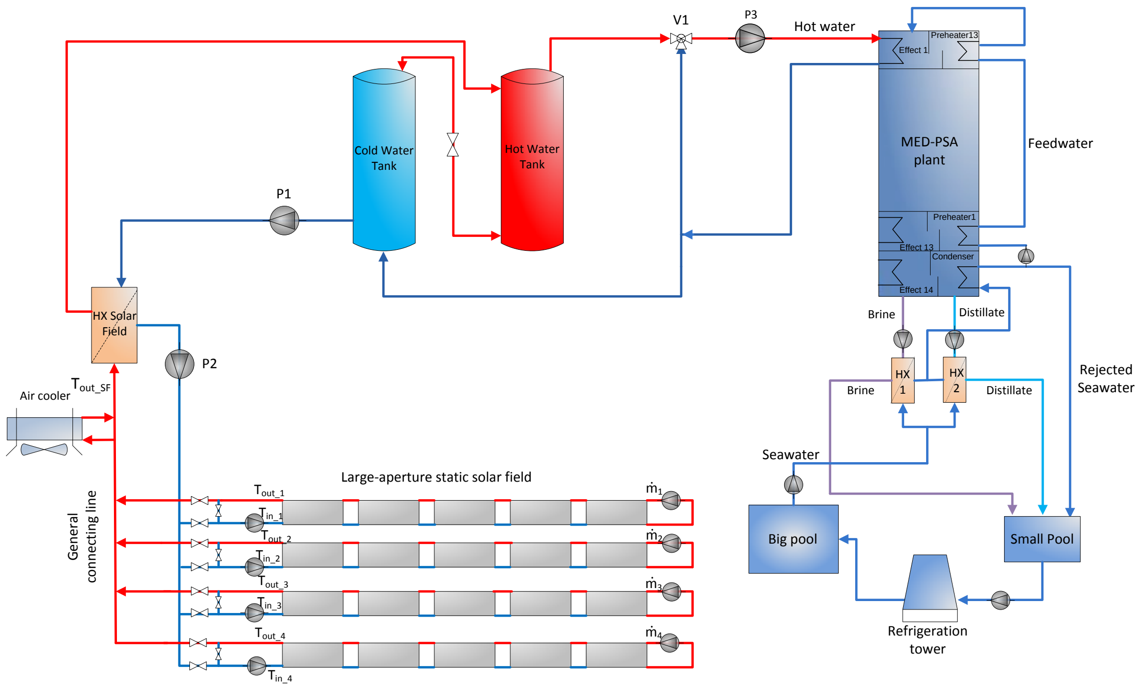

Figure 1.1 Layout of the experimental facility at the PSA

3 RESULTS AND DISCUSSION

3.1 Solar field efficiency

Figure 1.2 shows different experiments carried out to evaluate the experimental and theoretical efficiency of the FPC solar field along the daylight hours, keeping the solar field outlet temperature ($T_{out,SF}$) at 70 °C, 75 °C, 80 °C, 85 °C and 90 °C. As it is observed, the experimental and theoretical efficiencies of FPCs were close to each other, being more different early in the morning and after solar noon because of the influence of the incidence angle modifier, which varies along the day due to the static nature of the solar collectors. The maximum experimental efficiency of the FPC solar field was found at a $T_{out,SF}$ of 70 °C at 12:25:16 (when the global solar radiation reached the highest value) and it had a value about 55.78%. The respective minimum and maximum experimental mean efficiency of the FPCs solar field was 41.26% in August at $T_{out,SF}$ of 90 °C and 50.18% in November at 70 °C. Similarly, the minimum and maximum theoretical mean efficiency was 43.61 % and 52.15%, respectively.

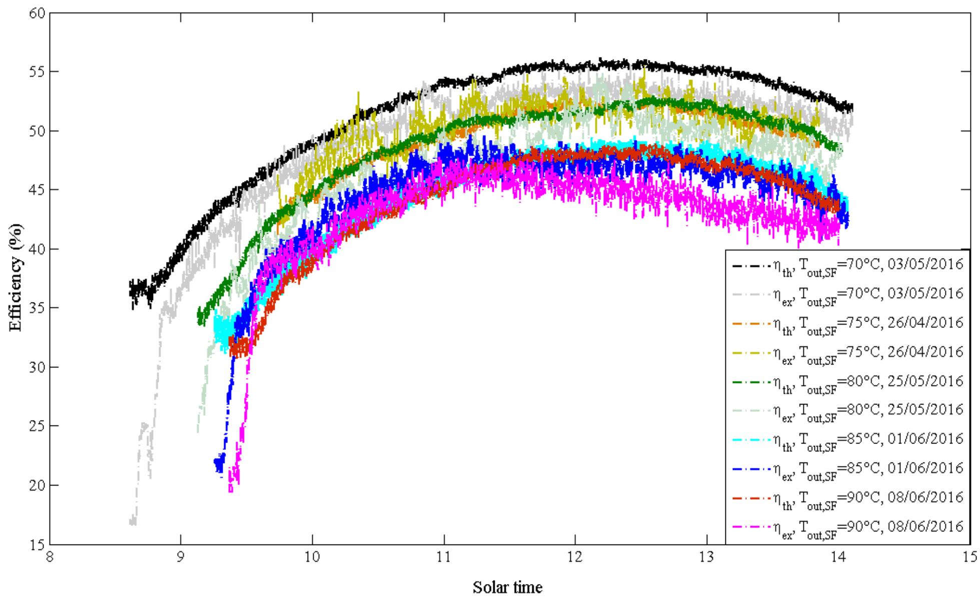

Figure 1.2 Theoretical and experimental solar field efficiency at different hot water outlet temperature and at several days (03/05/2016, 26/04/2016, 25/05/2016, 01/06/2016, 08/06/2016)

Figure 1.3 shows the operation of the solar field for two tests at different $T_{out,SF}$ in order to have an idea of the thermal power that can be delivered by the solar field to the desalination process. As it is seen, at 75 °C the solar field delivers an average of 230.4kW$_{th}$of thermal power, which is quite more than that needed by the MED plant at nominal conditions (190kW$_{th}$), so this positive difference is used to increase the energy in the storage tanks. As the global solar radiation reaches 818.80W/m^2 at 12:00:46 solar time at 95 °C, the solar field supplies its maximum value about 224.73 kW$_{th}$, so the remaining 34.73 kW$_{th}$ are stored in the water tanks. On the other hand, results revealed that the solar field supplies its maximum value at75°C about 282.04kW$_{th}$, so the remaining 92.04kW$_{th}$are stored in the water tanks.

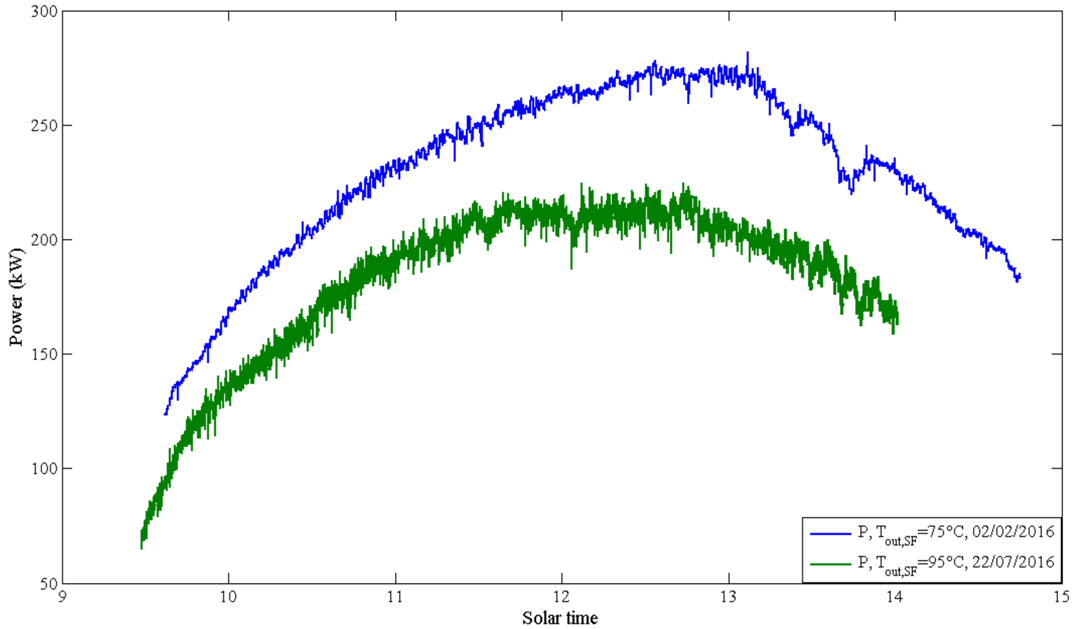

Figure 1.3 Power provided by the solar collector field for several days and at different solar field outlet temperature vs the solar time

3.2 Steady-state characterization of the MED plant

3.2.1 Influence of the variation of the feed water flow rate on the water production and the PR

Figures 1.4 and 1.5 show the distillate production and PR obtained for different feed water flow rates and different hot water inlet temperatures.

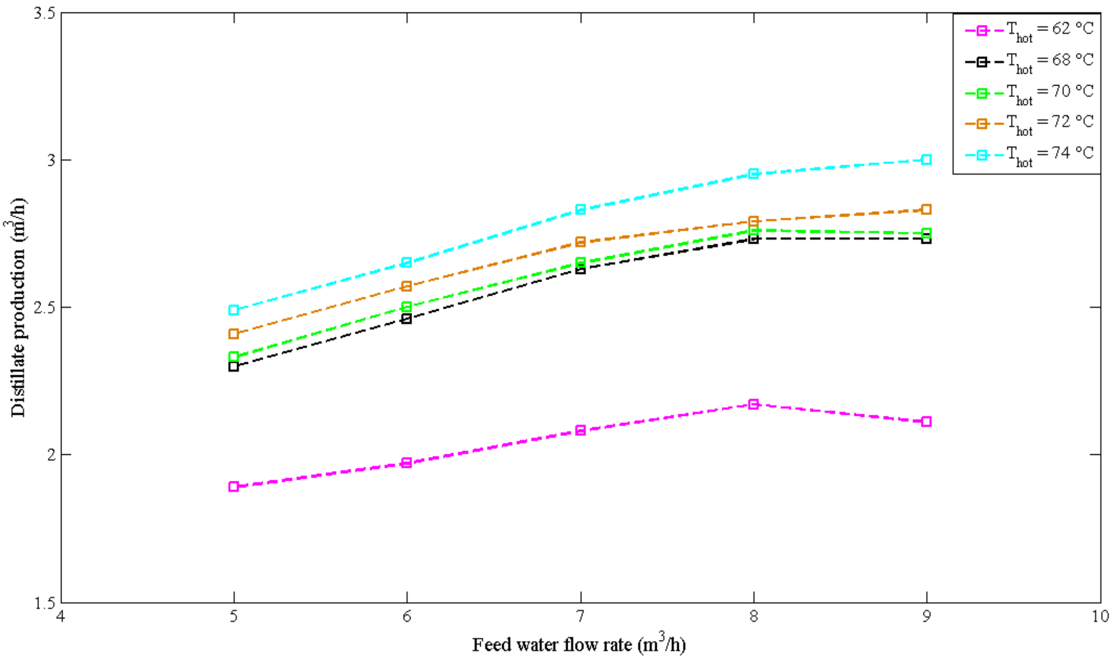

Figure 1.4 Variation of the distillate production from the MED-PSA plant with different feed water flow rates (5-9 m^3/h) for several hot water inlet temperatures (62-74 °C)

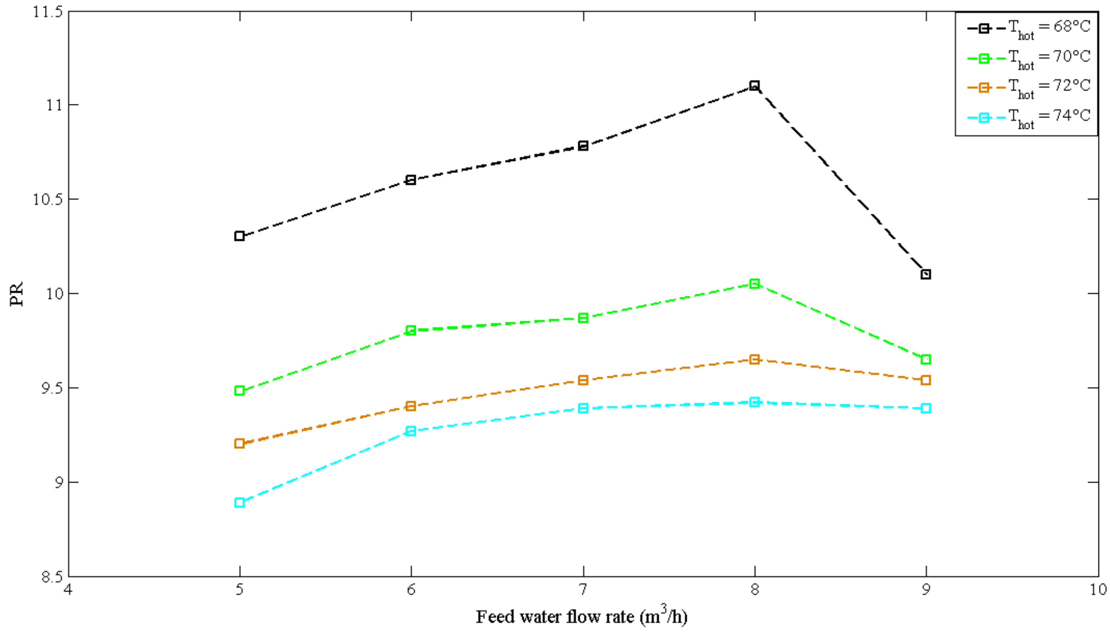

Figure 1.5 Variation of the Performance Ratio of the MED-PSA plant with different feed water flow rates (5-9 m^3/h) for several hot water inlet temperatures (68-74 °C)

In Fig. 1.4, it can be observed that, as expected, the distillate production rises with the hot water inlet temperature in all cases. It also increases with the rise of feed water flow rate from 5m^3/h to 8 m^3/h. This rise is different depending on the hot water inlet temperature. In this way, the distillate production increased with a percentage of 15.99% and 18.40% at an inlet hot water temperature of 72 °C and 70 °C, respectively, and with a percentage of 14.87% at an inlet hot water temperature of 62 °C. The maximum rate of growth in the distillate production (19.08%) is reached at hot water inlet temperature of 68 °C. It can be also seen that the rate of growth in the distillate production decreases for almost all the hot water inlet temperatures at feed water flow rates above 8 m^3/h, except to for hot water inlet temperatures of 72 °C and 74 °C. For example, at 62 °C it decreases 2.74%. This decrease could be caused by the shorter contact time in this case between the feed and the heating surface of the horizontal tube, which decreases the quantity of heat absorbed by the saturated feed water in the falling film evaporation process. Moreover, the maximum amount of distillate (3 m^3/h) is reached when the feedwater flow rate is 9 m^3/h and the hot water inlet temperature the one at nominal conditions of the MED plant (74 °C). According to the results, it can be stated that even at higher feed water flow rates, the production of the MED plant does increase significantly.

Regarding the PR, it should be highlighted that the accuracy of the performance ratio is strongly dependent on the accuracy of hot water temperatures and flow measurements, so a small error in these measurements yields a much higher error in the performance ratio calculation. In Figure 1.5, it can be observed that the PR decreases with the increase of the hot water inlet temperature, which is in agreement with the work published in [4]. For example, in the case of 5 m^3/h of feed water flow rate, the PR at 74 °C was a 1.16% lower than at 68 °C. Also, it can be seen that the PR increases with the rise of the feed water flow rate from 5 to 8m^3/h with a percentage of 5.98% for high hot water inlet temperature (74 °C) and with a percentage of 7.77 % for low hot water inlet temperature (68 °C), which is in agreement with other works of the literature [5]. However, the PR starts decreasing at higher feed water flow rates, being this decrease more pronounced at low hot water inlet temperatures. Concretely, at a hot water inlet temperature of 68 °C, it was observed that the PR decreased strongly a percentage of 11.8% when the feed water flow rate increased above 8 m^3/h while at a hot water inlet temperature of 74 °C the percentage of decrease was only 0.37% at the same flow rate. The maximum PR obtained was 11.1 with the plant operating at a feed water flow rate of 8 m^3/h and at a hot water temperature of 68 °C.

The significant increase observed in both parameters, the distillate production and the PR, with the feed water flow rate from 5 m^3/h to 8 m^3/h can be due to the fact that the increment of feed water flow rate is helping to strengthen the convective heat transfer of external falling film evaporation, increasing then the overall heat transfer coefficient and therefore the distillate produced and the PR.

3.2.2 Influence of the variation of the vapor temperature in the condenser on water production and PR

The influence of the variation of the condenser vapor temperature on the distillate production and the PR are shown in Figure 1.6 and Figure 1.7, respectively.

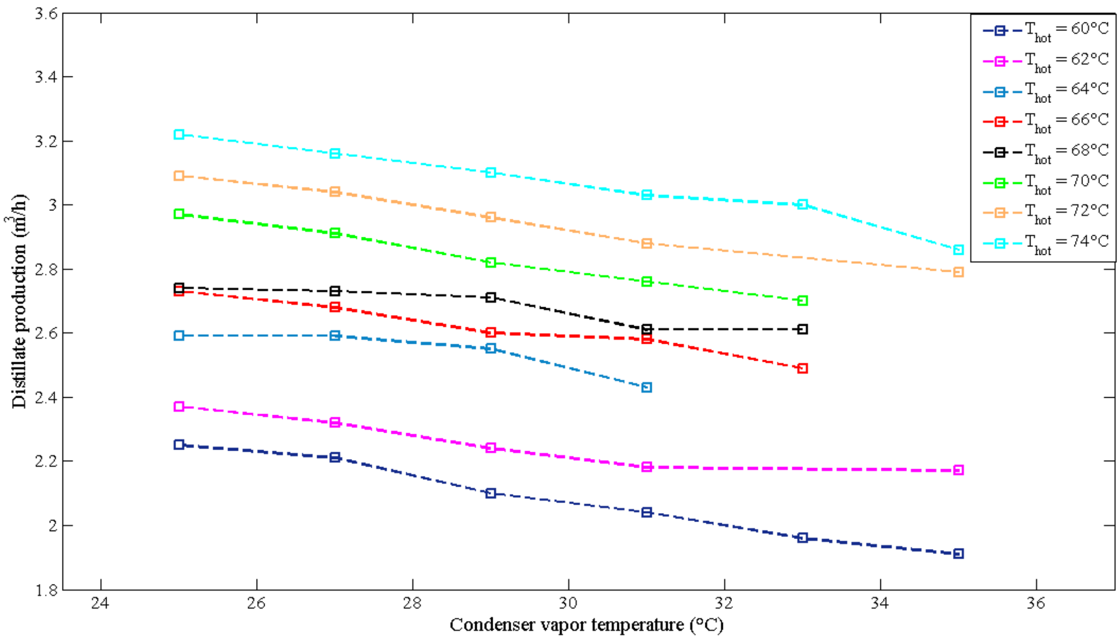

Figure 1.6 Distillate production of the MED-PSA plant at different condenser vapor temperatures (25-35°C) and different hot water inlet temperatures (60-74°C)

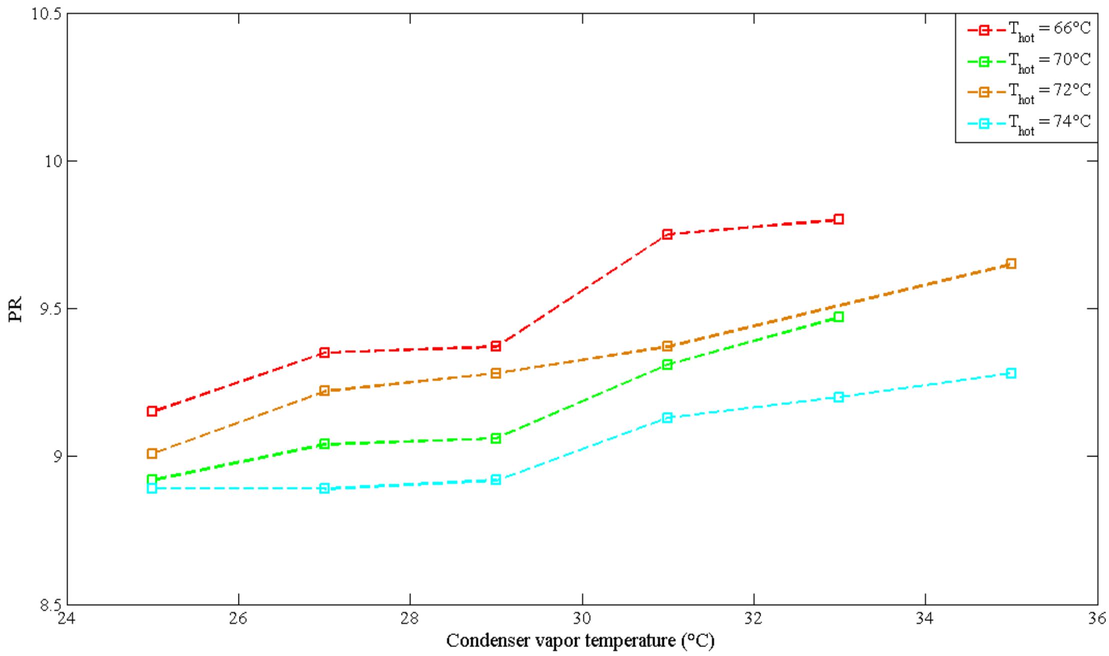

Figure 1.7 Variation of the Performance Ratio of the MED-PSA plant with the condenser vapor temperature (25-35 °C) for several hot water inlet temperatures (60-74 °C)

Regarding the distillate production, Figure 1.6 shows that it decreases with the increase in the condenser vapor temperature between 25 °C and 35 °C. The increase in the condenser vapor temperature while the vapor temperature of the first effect is fixed (by maintaining the hot water inlet temperature constant) makes the temperature difference between effects smaller. This temperature difference is the driving force of the process so its decrease leads to a lower evaporative capacity between effects giving place to a lower distillate production. From the results, it was observed a decrease in the distillate production of 17.97 % and 9.35% for low hot water inlet temperature (60 °C and62 °C, respectively), and of 10.71% for high hot water temperatures (72 °C) when the condenser vapor temperature increased from 25°C to 35°C. The maximum distillate production was reached in the case when the condenser vapor temperature was25 °C and the hot water inlet temperature the one at nominal conditions of the MED plant (74 °C).

Regarding the tendency of the PR, Figure 1.7 shows that it increases with the rise in the condenser vapor temperature, which is in agreement with other works of the literature[6, 7]. This rise is due to several factors: the rise in the condenser vapor temperature results in a higher feed water temperature at the outlet of the last preheater (located next to the first effect), which leads to a lower thermal consumption and therefore to a higher thermal efficiency of the MED plant. Furthermore, as mentioned before, the temperature difference between the adjacent effects become smaller and this makes the process more thermodynamically reversible and therefore more efficient. From the results, it was observed that the PR increased a percentage of 9.57% with the increase in the condenser vapor temperature from 25 °C to 33 °C, for low hot water inlet temperatures (66 °C),and a percentage of 7.10% and 4.43% in the case of high hot water inlet temperatures (72 °C and 74 °C, respectively). The maximum PR (9.80) was obtained when the condenser vapor temperature was 33 °C at a hot water inlet temperature of 66 °C.

From a comparison between these results and those ones obtained in the previous test campaign, it can be seen that the rise in the condenser vapor temperature has more impact on the PR than the increase in the feed water flow rate for the same hot water temperatures. In this way, the rise in the PR with the increase in the condenser vapor temperature was 2.24% more than with the increase in the feedwater flow rate, in the case of a hot water inlet temperature of 72 °C. The highest increase in the PR was obtained at a hot water temperature of 70 °C, at which the PR increased with a percentage of 6.15% with a rise in the condenser vapor temperature from 25 to 33°C.

The rise of feed water flow rate has more influence on the production of distillate that decreasing the condenser vapor temperature considering the same hot water temperature. As an example, the rise in distillation production with the increase of the feed water flow rate was 6.34% and 5.52% more than with the decrease in the condenser vapor temperature, in the case of hot water temperatures of 74 °C and 62 °C, respectively. The highest rise was obtained at a hot water temperature of 68°C, at which the distillate production increased a percentage of 19.08% with a rise in the feedwater flow rate from 5 to 8m^3/h.

4 CONCLUSIONS AND RECOMMENDATIONS

The target of this work is to perform an experimental characterization of a solar MED plant in a wide range of operating conditions. Firstly, the assessment of the efficiency of a large-aperture FPC solar field has been realized at several temperature levels for different climate conditions on the basis of meteorological data, the incidence angle calculated in Matlab and collected data from SCADA. The experimental and theoretical efficiency were close to each other, showing consistent results. Besides, the power curves of the FPC solar field revealed that the solar field is able to produce more thermal power than needed by the MED plant (especially at lower operation temperatures), addressing the remaining thermal energy to a storage system to enlarge the operation of the solar desalination system during the transient periods in which the solar radiation is not available.

In order to study the impact of several key parameters on the MED plant performance, two different cases have been examined and valuable quantitative conclusions have been summarized in Table1. This table shows the optimum operation points that should be selected in function of the goal to be achieved: either the maximization of the distillate production or the minimization of the energetic consumption of the MED plant. According to the results, when the MED plant is operated at a fixed condenser vapor temperature (35 °C), the highest amount of distillate (3 m^3/h) is reached when the feedwater flow rate is 9 m^3/h and the hot water inlet temperature is 74 °C. In the case of the PR, the optimum (11.1) is reached for a feed water flow rate of 8 m^3/h and a hot temperature of 68 °C. In the case that the MED plant is operated at a fixed feed water flow rate (8 m^3/h), the maximum distillate production (3.22 m^3/h) is obtained at the lowest condenser vapour temperature (25 °C) and the highest hot water inlet temperature (74 °C). Regarding the PR, the best thermal efficiency of the MED plant is achieved (PR of 9.80) for a hot water temperature of66 °C and a vapour temperature in the condenser of 33 °C.

This study also revealed that the influence of the variation of the feed water mass flow rate and the temperature in the condenser on the distillate production and on the PR is different. In other words, the rise in the condenser vapor temperature has more impact in the thermal efficiency of the MED plant than the rise in the feed water flow rate (around an increase of 2.24% more is observed with the variation of the condenser vapor temperature), which make this parameter as one of the main ones in the optimization of the operation of the MED plant.

Table 1
Comparison of the optimum results of key parameters of the MED for the two study cases

Study cases	Hot water flow rate (L/s)	Feed water mass flow rate (m^3/h)	Condenser vapor temperature (°C)	Distillate production (m^3/h)	Hot water inlet temperature (°C)	PR
Case study 1	12	8	35	2.95	74	9.42
	12	9	35	3.00	74	9.39
	12	8	35	2.73	68	11.10
Case study 2	12	8	35	2.49	66	9.80
	12	8	25	3.09	72	9.01
	12	8	25	3.22	74	8.89

Acknowledgments

This work has been funded by the National R+D+i Plan Project DPI2014-56364-C2-1-R of the Spanish Ministry of Economy and Competitiveness, ERDF funds and the 7th Framework Programme of the EU (SFERA 2 Grant Agreement n. 312643)".Likewise, the authors would like also to express their appreciation to "IRESEN" for providing financial support to perform this research under "Seawater desalination using solar energy project", InnoTherm II Solar thermal applications and solar technologies support.

References

[1]J. Blanco, D. Alarcón, E. Guillén, W. Gernjak, The AQUASOL system: solar collector field efficiency and solar-only mode performance, JSEE133(2011) 011009-1.

[2] A.M. El-Nashar and M. Samad, The solar desalination plant in Abu Dhabi: 13 years of performance and operation history, Renewable Energy 14 (1998), 263-274

[3] P. Fernández-Izquierdo, L. García-Rodríguez, D.C. Alarcón-Padilla, P. Palenzuela, I. Martín-Mateos, Experimental analysis of a MED unit operated out of nominal conditions, Desalination 284 (2012) 233-237.

[4] T. El-Dessouky, M. Ettouney, Multiple-effect evaporation desalination systems: thermal analysis, Desalination 125 (1999) 259-276.

[5] L. Yang, S. Shen, H. Hu, Thermodynamic performance of a low temperature multi-effect distillation experimental unit with horizontal-tube falling film evaporation, Desalination & Water Treatment 33 (2011) 1-3, 202-208.

[6] D. Zhao, J.L. Xue, S. Li ,Theoretical analyses of thermal and economical aspects of multi-effect distillation desalination dealing with high-salinity wastewater, Desalination 273 (2011) (2/3), 292-298.

[7] A.M. El-Nashar, Predicting part load performance of small MED evaporators - a simple simulation program and its experimental verification, Desalination 130 (2000) 217-34.