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Optimal operating conditions analysis of a multi-effect distillation plant

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ABSTRACT

A study which aims to determine the optimal operating conditions and the effects that the operational parameter variations produce on the experimental solar thermal desalination system at CIEMAT-Plataforma Solar de Almería (PSA) AQUASOL has been performed. A mathematical model of the experimental MED plant, previously developed, has been used to provide the information required for the analysis of the performance and improve the operation strategies in this plant. The mathematical model was implemented using the equation-based object-oriented modeling language Modelica and was validated using experimental data measured in the real facility. In this paper, a genetic optimization algorithm with three objectives and five decision variables has been considered and the results are shown and discussed.

Keywords: Optimal operation; Energy consumption; Multicriteria optimization; Desalination; Modelica

1. Introduction

Water has a very important role in society development. Recent history shows that unsustainable development and wrong policies can produced an immense pressure on water resources affecting their quality and availability. The main water consumption sources are industrial, human, agriculture and energy. Industrial water demand is expected to increase in all productive sectors [1]. Furthermore, it should be noted that the world's population is growing by about 80 million people per year and could reach 9.1 billion by 2050, with 2.4 billion people living in Sub-Saharan Africa, the region with the most heterogeneously distributed water resources [2]. Also, waste water from agriculture and fresh water required for energy production, which are 15% and 70% of the total, respectively, can further exacerbate water scarcity in both sectors. With these predictions, United Nations expect that between 2 and 7 billion people will be facing water scarcity by the middle of the century [3].

Therefore, in the next decades, water problems are even expected in regions currently fresh water rich. Shortage of fresh water resources, salinization and contamination of the sources are some of the major problems to be tackled by humanity in the coming decades [4]. Considering that 50% of the population is living in coastal territories, water desalination could be very useful. For example, some countries of the Middle East make use of desalination of sea water as a vital source of fresh water.

Currently one of the main technologies used for

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desalination is thermal distillation [5]. The advantages of thermal distillation processes are their ability to be driven by a low energy thermal source, their reliability, easier operation and maintenance, high purity fresh water and their capability to deal with harsh feed waters of high temperature and salinity or even with contaminated water. In thermal distillation, multi-stage flash (MSF), multi-effect distillation (MED) and mechanical or thermal vapor compression (MVC-TVC) can be considered the main techniques.

However, these techniques are energy inefficient as in any thermal distillation process the energy cost is 50% of the total fresh water cost. Thermal distillation processes demand two different forms of energy: thermal energy, which represents most of the energy consumed, and can come from different sources (fossil fuels, waste energy [6], solar energy [7], etc.), and electric power that is consumed for driving actuators and pumping systems (feeding, cooling, vacuum and removing system). Table 1 [8] summarizes the energy consumption of the three main thermal distillation techniques.

One way to reduce the energy inefficiency of both the existing and future plants is to study the influences of operational parameter, find the optimal operational conditions according to different criteria and develop efficient operational strategies, as shown by the several operational conditions studies [9].

There are operational conditions studies of the thermal distillation plants based on mathematical models and experimental data [10–17] that used the mathematical model to simulate the behavior of the plant and the experimental data to validate the results. These studies trying to find the best setting for the desalination process according to different criteria through optimization algorithms. In the case of the Plataforma Solar de Almería (PSA) MED plant specifically, there are mathematical models [18,19], that show a good agreement between the simulated and experimental results, and experimental studies of the optimal operational conditions of the PSA MED plant [20,21]. In the last one, an experimental study of out of its nominal working conditions concludes that influences of operational parameter are different for the criteria selected and show an irregular behavior over the range study. Although, there are mathematical models and experimental studies, there is no a study of the operational conditions based on the mathematical model and optimization algorithms for the PSA MED plant.

Table 1
Thermal distillation energy consumption [8]

	MSF	MED	MVC
Electrical energy consumption (kWh/m^3)	4–6	1.5–2.5	7–12
Thermal energy consumption (kJ/kg)	190–390	230–390	None
Total equivalent energy consumption (kWh/m^3)	13.5–25.5	6.5–11	7–12

2. PSA MED plant and model

The studied plant in the present paper is a forward feed MED unit manufactured by ENTROPIE in 1987 consisting of 14 effects in a vertical arrangement with decreasing pressure from the 1st to the 14th effect. Originally, a low pressure boiler produced saturated steam at 70°C and 0.31 bar which was sent to the first effect, where the steam was condensed thus delivering thermal energy. Under the framework of AQUASOL project, whose main objective was the development of a hybrid solar-gas desalination system which met at the same time the requirements of low-cost, high efficiency and zero liquid discharge [20,22] the MED plant was modified. The current configuration allows for a 24-h plant operation and the system is flexible regarding the heat source in the first effect. Nowadays, at the AQUASOL facility a flat-plate collector solar field and a double-effect absorption heat pump (DEAHP) (which can be fed with a gas boiler or with a solar field composed by parabolic trough collectors, PTCs [23]), can provide the required heat. The DEAHP is coupled with the last effect of the MED plant recovering part of the wasted energy and can be connected to the MED plant directly or indirectly through the tanks [20]. In this indirect mode, the thermal energy can come from the DEAHP and the solar field at the same time.

In the PSA MED plant (see Fig. 1 [24]), each effect is composed by two heat exchangers, the first is called tube bundle evaporator or heater and it is employed to evaporate the feed water. The second one is called tube bundle cooled or preheater and it is employed to condensate the vapor by the feed water. Hot water flows inside the heater and delivers heat flow (q) to the feed water that is sprayed over it, hot water flows from heater inlet (H_0) to heater outlet (H_1). The thermal energy released evaporates part of the feed water that comes from the preheaters of the effects

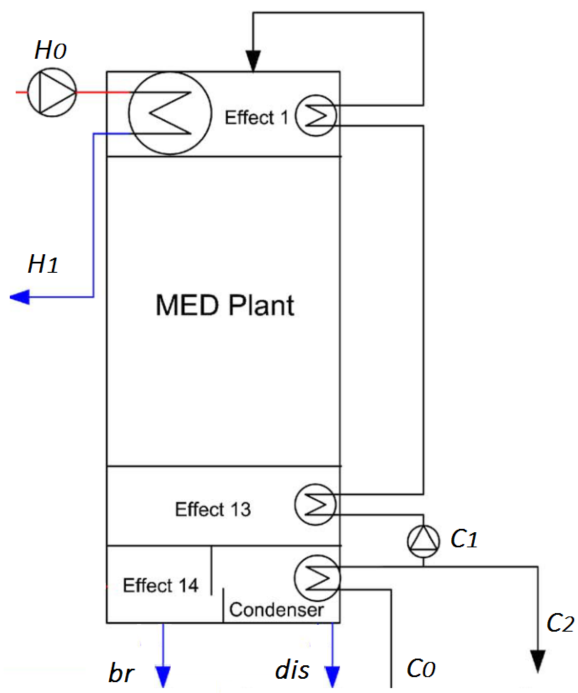

Fig. 1. MED plant unit scheme.

successively, (C_1) and previously from the condenser inlet (C_0). The vapor generated is partially condensed in the preheater, which is located next to the evaporator, and then the remaining vapor that has not been condensed is transported to the next heater in order to release its latent heat to the feed water which has not been evaporated (called brine) in the previous effect. This process is repeated successively in the next effects. Water condensed is collected in each effect and goes out of the MED unit through the distillate output (*dis*), feed water that has not been evaporated falls by gravity from one effect to the following one, and finally leaves the plant through the brine output (*br*). The pumping system is composed by four pumps (sea water, heater, vacuum, brine and distillate pump) and represent the main electric energy consumer ($\dot{e}$). Three hydro-ejectors connected to the 2nd effect, 7th effect and the condenser, do the vacuum to the MED plant and remove the non-condensable gases during the whole operation.

All these phenomena can be simulated by mathematical models that predict the behavior of the MED in different operating conditions, saving time, costs and preventing critical situations. A dynamic model developed by de la Calle et al. [19] is the most suitable to perform this study. This model predicts the steady-state and transient behavior of the PSA MED plant in the whole operating range using as inputs the natural inputs of the system, i.e., the inlet heater water flow rate and temperature, the inlet condenser seawater flow rate and temperature, the preheater seawater flow rate and the ambient temperature, and using as outputs of the system the natural outputs i.e., distilled and brine rate and performance parameters. It was developed with the non-proprietary object-oriented modeling language Modelica [25] which allows formulating the problems in an acausal way, being very suited for representing physical systems. The MED model is an index-1 differential algebraic equations (DAEs) system with 4,474 equations, of which 57 are continuous time states. In order to handle this system of equations, the model follows a modular and hierarchical arrangement of sub models where there are three levels of abstraction. The low level describes the main heat and mass transfer phenomena of the plant, the medium level describes each physical element such as effects and preheaters and the high level composes the complete model of the plant.

Even though the model has a low number of inputs, it predicts the heat and mass processes which happen inside the plant with a high level of detail. This model assumes that the fluids inside the MED plant are in thermodynamic equilibrium and only water vapor is considered inside the effect. This vapor is completely condensed at the tube bundles, and although heat losses to the environment are considered, the thermal capacity of the metal structure of the plant is neglected. The Nusselt film condensation theory is used to model the condensation of the vapor inside and outside the tube bundle. The evaporation of the steam from the seawater is calculated according to mass and energy balances where a Nusselt number correlation adjusted with real data of the plant, characterizes the heat transfer at the falling film evaporators. The pressure inside the effects is calculated with the ideal gases law. A simple model of the pipes with a single control volume calculates the sensible heat transfer inside the tubes of the preheaters.

Dymola 2015 [26] and DASSL [27] were the tool and the numerical solver selected for performing the simulations, respectively. The calibration and validation showed a good agreement between simulated results and experimental data. The average errors of some of the most relevant variables like the outlet temperatures were lower than the uncertainty range of the measurement instruments. In the case of the distillate mass flow rate, the value predicted resulted in absolute average error lower than 0.045 kg/s of for one day of simulation.

3. Optimization

The present work has employed the Optimization library included in Dymola [28]. The optimization problem in this library is formulated as follows:

$$\min_{p\in B} f(diag(d_1)^{-1} c_1(p)),$$

$$c_2(p) \le d_2, \quad c_3(p) = d_{3,}$$

$$c = \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix}, \quad d = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}$$

$$f = \begin{cases} \max & \text{maximum criteria values,} \\ ||\cdot||^2 & \text{sum of squared criteria value,} \\ ||\cdot|| & \text{sum of absolute criteria values.} \end{cases} \tag{1}$$

Here, p represents an editable parameter vector, in which the parameters are varied during the optimization process (tuner parameters) and belong to the decision space B. C_1 represents the objectives vector of the optimization calculated by means of the objective function. Equality and inequality constrains vectors (C_2, C_3), which enable some criteria restriction if needed, are optional. d_1 vector serves as a reciprocal scaling factor of the criteria and they enable different weights for each criteria. d_2 and d_3 vectors contain the restrictions values. The goal is to minimize all these objectives (C_1) with their respective weights (d_1) subjected to the imposed optional constrains (d_2 and d_3).

These multi-criteria optimization formulation is transformed into a scalar optimization problem by means of the scalar objective function, *f*. This function can be configured in the library in three different ways, minimize the maximum, the sum of the square or the sum of the absolute values of the objectives.

Algorithms commonly used to solve this kind of energy system optimization problems are evolutionary programming, evolutionary strategies and genetic algorithm [11]. The latter, already implemented in the Optimization library, has been used to perform the optimizations.

In genetic algorithms, a population of individuals, which represents the potential solution space, is evaluated for each iteration. The performance of an individual is evaluated according to the scalar fittest function, also called scalar objective function (*f*). The initial population evolves successively a number of specific generation to best regions in the search space selecting the fittest individuals in the population and modifying them by recombination or mutation.

In order to provide information required for the analysis of the performance and operation strategies in the MED plant, it is necessary to find the optimal operational conditions according to different criteria, even more after all the modifications carried out in the MED plant. This study contributes to develop new designs and operational methodologies. There are some performance indices useful to find a trade-off between cost reduction and performance improvement, in other words decrease the energy consumption and the maximize the fresh water production. Performance ratio (PR), the gain output ratio (GOR) and the specific water cooling consumption (SFWC) are the most relevant performance indices used in thermal desalination plants related with energy consumption and fresh water production. GOR is the most extended PR and shows the ratio between the mass of the produced distilled water and the mass of steam delivered to the plant, but it is referred only for steam-fed plants. PR 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 (see Table 2). Finally, SFWC is the ratio between distilled water flow rate and the feed water flow rate.

Another useful performance index is the specific energy consumption ($\bar{E}$), which is the relation between the total inlet energy (thermal and electric) and distilled water flow rate. In particular, for MED plants with hot water as energy source, PR is the most representative performance index. PR along with fresh water or distilled rate production $\dot{m}_{dis}$ and $\bar{E}$ have been used as criteria in the present work integrating the criteria vector (C_1) in the optimization problem. In multi-criteria optimization cases, the criteria have been scaled using the maximum value of PR as demand values (d_1 components), the maximum $\dot{m}_{dis}$ and the minimum $\bar{E}$ found previously. So that, in the optimization process there are no preferences, all the criteria have the same weight. There are no restrictions in the criteria space (d_2, d_3), only it has been considered each tuner parameter range as constrains. The objective scalar function f is selected to minimize the sum of the square of the objectives.

The PSA MED plant needs a thermal energy contribution in its first effect in the form of inlet hot water flow, defined by its flow rate ($\dot{v}_{H0}$) and its temperature (t_{H0}). Also a sea water flow, in the condenser, satisfies the condenser demands ($\dot{v}_{C0}$, t_{C0}), part of this water flow is used as feed water ($\dot{v}_{C2}$) while the remaining part is returned to the seawater pool. Note that the water temperature in C_2 depends on the condenser outlet temperature so this temperature cannot be considered as a variable. Therefore, these variables ($\dot{v}_{H0}$, $\dot{v}_{C0}$, $\dot{v}_{C2}$, t_{H0}, t_{C0}) form the tuner parameter vector (p) in the optimization problem. Furthermore, the operational range of the tuner parameters form the decision space (B). Table 3 shows the nominal, minimum and maximum values of the MED plant for each criteria and tuner parameter.

Table 2
Symbols and abbreviations

	Description	Equation
t, °C	Temperature	
$\dot{m}$, kg/s	Mass flow rate	
$\dot{v}$, m^3/h	Volumetric flow rate	
$\dot{q}$, kJ/s	Heat flow rate	
$\dot{e}$, kJ/s	Electric flow rate	
Δ, %	Variation from nominal	
$\bar{E}$, kJ/kg	Specific energy consumption	$(\dot{e}+\dot{q})/\dot{m}_{dis}$
PR	Performance ratio	$(\dot{m}_{dis}\cdot 2326)/\dot{q}$
GOR	Gain output ratio	$\dot{m}_{dis}/\dot{m}_{steam}$
SFWC	Specific feed water consumption	$\dot{m}_{dis}/\dot{m}_{feedwater}$
H_0	Heater inlet	
H_1	Heater outlet	
C_0	Condenser inlet	
C_1	Condenser outlet	
C_2	Feed inlet	
br	Brine outlet	
dis	Distilled water outlet	

4. Results

The decision space generated, considering minimum, maximum and some intermediate values of the tuner parameters, has been built and simulated with the model and the tool previously cited. The criteria space generated is showed in Fig. 2.

Grey points represent all the criteria results obtained simulating each tuner parameter combination of the decision space. Arrows represent the changes in the criteria space due to the variations of each tuner parameter and the end of the arrow shows the maximum value of the tuner parameter. Table 4 shows the values of the criteria for each maximum value of the tuner parameter.

As the simulated data in Table 4 shows, for nominal conditions and just considering one modification in a tuner parameter, distilled mass flow rate ($\dot{m}_{dis}$) can be risen (16.4%) by increasing t_{H0} to the maximum, without significant

Table 3
Criteria and tuner parameters, limits and nominal values [21]

		Nominal	Min	Max
Tuner	t_{H0} (°C)	66.5	57	75
	$\dot{v}_{H0}$ (m^3/h)	43.2	28	72
	t_{C0} (°C)	20	0	35
	$\dot{v}_{C0}$ (m^3/h)	24	8	28
	$\dot{v}_{C2}$ (m^3/h)	8	4	12.5
Criteria	$\dot{m}_{dis}\left(\frac{kg}{s}\right)$	0.7		
	PR	>9.5		
	$\bar{E}\left(\frac{kJ}{kg}\right)$	>210		

variations in $\bar{E}$. Furthermore, when increasing $\dot{v}_{C2}$ to its maximum value, $\dot{m}_{dis}$ can reach an increment of 22.8% while reducing 1.2% $\bar{E}$ from nominal conditions. Finally, reducing t_{C0} to its minimum value allows for an improvement of 19.7% in $\dot{m}_{dis}$ and a reduction of 1.5% in $\bar{E}$.

Considering the optimization algorithm introduced in previous sections and according to the criteria, the results provided by the genetic algorithm in the optimization process are depicted in Fig. 3 and summarized in Table 5.

As the simulated and optimized data in Table 5 show, $Max\ \dot{m}_{dis}$ point leads to an increase of the distillate mass flow rate in 79.1%, decrease in PR of 0.11 points and decrease in $\bar{E}$ of 1.1% from nominal conditions. $Min\,\bar{E}$ decreases $\bar{E}$ a 3%, improves $\dot{m}_{dis}$ 36.4% and improves PR 1.5%. The main difference between $Max\ \dot{m}_{dis}$ and $Min\,\bar{E}$ points is that while $Max\ \dot{m}_{dis}$ needs to increase $\dot{v}_{H0}$ and v_{C0} to values close to its minimums, $Min\,\bar{E}$ needs to reduce those turners or decisions variables to values lower than the nominal ones. Max PR improves $\dot{m}_{dis}$ a 5.3%, PR 0.23 points and decreases $\bar{E}$ 2.8%.

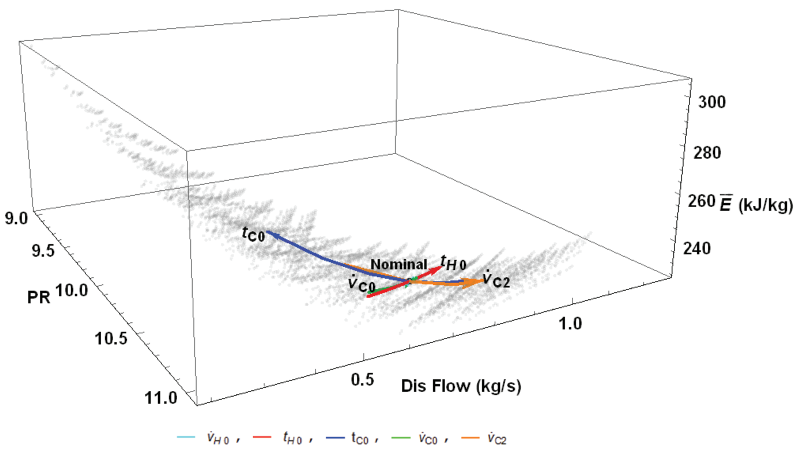

Fig 2. Criteria space and variation relation of just one tuner parameters when considering nominal operating conditions.

Table 4
Tuner parameter effects from nominal operating conditions

	t_{H0}	$\dot{v}_{H0}$	t_{C0}	$\dot{v}_{C0}$	$\dot{v}_{C2}$	$\dot{m}_{dis}$	$\Delta\dot{m}_{dis}$	PR	ΔPR	$\dot{q}$	$\dot{e}$	$\bar{E}$	$\Delta\bar{E}$
	°C	$\frac{m^3}{h}$	°C	$\frac{m^3}{h}$	$\frac{m^3}{h}$	$\frac{kg}{s}$	%		%	$\frac{kJ}{s}$	$\frac{kJ}{s}$	$\frac{kJ}{kg}$	%
Nominal	66.5	43.2	20	20	8	0.714	0	10.75	0	154.5	11.4	232.3	0
$Max\ t_{H0}$	75	43.2	20	20	8	0.831	16.4	10.67	–0.7	181.2	11.5	231.7	–0.3
$Min\ t_{C0}$	66.5	43.2	10	20	8	0.855	19.7	10.80	0.5	184.1	11.5	228.8	–1.5
$Max\ \dot{v}_{C0}$	66.5	43.2	20	28	8	0.735	2.9	10.75	0	159.1	12.2	233.0	0.3
$Max\ \dot{v}_{C2}$	66.5	43.2	20	20	12	0.877	22.8	10.84	1	188.2	13.1	229.5	–1.2

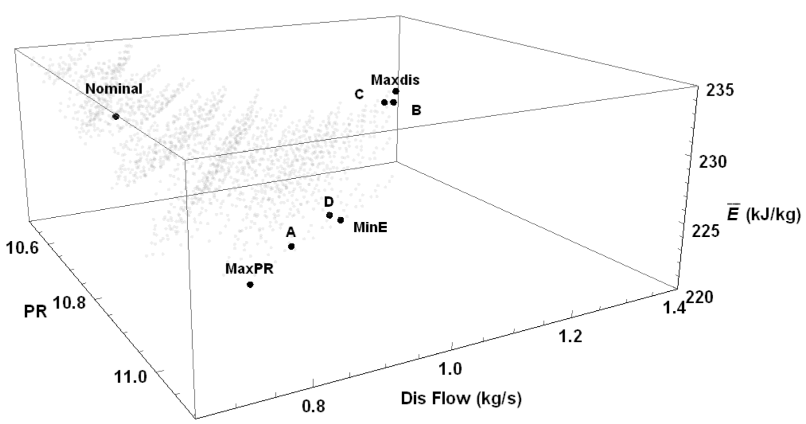

Fig 3. Criteria space and optimized points.

Table 5
Optimization

	t_{H0}	$\dot{v}_{H0}$	t_{C0}	$\dot{v}_{C0}$	$\dot{v}_{C2}$	$\dot{m}_{dis}$	$\dot{m}_{dis}$	PR	ΔPR	$\dot{q}$	$\dot{e}$	$\overline{E}$	$\Delta\,\overline{E}$
	°C	$\frac{m^3}{h}$	°C	$\frac{m^3}{h}$	$\frac{m^3}{h}$	$\frac{kg}{s}$	%		%	$\frac{kJ}{s}$	$\frac{kJ}{s}$	$\frac{kJ}{kg}$	%
Nominal	66.5	43.2	20.0	20.0	8.0	0.714	0	10.75	0	154.5	11.4	232.3	0
Max $\dot{m}_{dis}$	75.0	66.1	10.2	27.1	12.5	1.279	79.1	10.64	–1.0	279.6	14.3	229.7	–1.1
Min $\overline{E}$	72.7	28.4	10.4	10.9	11.2	0.974	36.4	10.91	1.5	207.1	11.5	225.3	–3.0
Max PR	57.1	28.0	10.0	10.8	12.4	0.752	5.3	11.05	2.8	158.4	11.4	225.8	–2.8
$Min\ \overline{E}$, $Max\ PR(A)$	66.6	28.0	10.0	14.42	11.7	0.862	20.7	10.96	2.1	183.1	11.3	225.3	–2.9
$Min\ \overline{E}$, $Max\ \dot{m}_{dis}(B)$	74.6	63.0	10.0	23.94	12.4	1.255	75.7	10.67	–0.7	273.7	14.0	229.2	–1.3
Max PR, $Max\ \dot{m}_{dis}(C)$	74.4	70.3	11.9	25.84	12.3	1.228	72.0	10.68	–0.7	267.5	14.2	229.5	1.2
Max PR, $Max\,\dot{m}_{dis}$ $Min\ \overline{E}(D)$	74.0	28.8	10.6	10.6	12.5	0.968	26.2	10.89	1.3	206.8	11.4	225.3	–3.0

5. Conclusions

Focusing on the PSA MED heater and operational parameters, simulation results show that $\dot{v}_{H0}$ variations have a very small influence in the criteria result space. On the other hand, increments in t_{H0} mainly increase the fresh water production. Furthermore, increments in feed water flux $\dot{v}_{C2}$, lead to a decrease in $\overline{E}$ and to an increase in the distillation production so that to an increase in PR. Very similar results are obtained when the temperature t_{C0} is reduced.

The fact that $\dot{v}_{H0}$ variations have a very small influence in the criteria result space while increments in feed water flow $\dot{v}_{C2}$ decreases $\overline{E}$ and increases distillation production, in nominal conditions, suggests that the heater could be oversized or the feed flow could have been underestimated.

Seven operational parameter combinations due to different criteria and its performance has been studied and shown that, regarding the optimal criteria points, *Max* $\dot{m}_{dis}$ is reached increasing t_{H0} and $\dot{v}_{C2}$ to their maximum values, increasing $\dot{v}_{C0}$ and $\dot{v}_{H0}$ while decreasing t_{C0} to the minimum value. $Min\,\overline{E}$ can be achieved decreasing to the minimum t_{C0} and decreasing $\dot{v}_{C0}$ and v_{H0}, the values of the remaining tuning parameters should be increased. Even in the $Min\,\overline{E}$ point, the energy consumption continues being high. *Max* PR point is obtained decreasing all the tuning parameters to the minimum except $\dot{v}_{C2}$, which is increased. Therefore, in order to increase the operation performance of the plant according to the three selected criteria, it is necessary to decrease t_{C0} or/and increase $\dot{v}_{C2}$.

Although $\overline{E}$ and $\dot{m}_{dis}$ have shown to be good optimization criteria to improve the process operation from the point of view mentioned previously, $\overline{E}$ and $\dot{m}_{dis}$ do not refer to the quality of the energy used or the quality of the process, only provide information in quantitative terms independently of the nature, temperature or the state in which the energy has been supplied or discharged into the environment, just some of the main thermal distillation advantages.

Although PR provides qualitative information when comparing distillation, it has been shown not to be a good optimization criterion by itself in order to improve the process operation. The effects of some operational parameters are higher on distillate production and $\overline{E}$ than in PR and it is not constant throughout the decision space, as already indicated in previous experimental studies [21]. Furthermore, PR only considers thermal energy without taking into account that the electric consumption in thermal distillation may be a 10% of the total energy consumption.

Optimization results show that the PSA MED plant can reach improved results according to the selected criteria, especially in *Max* $\dot{m}_{dis}$ where the distillate production is increased while energy consumption is reduced.

Ongoing work includes the definition of appropriate optimization criteria which takes into account the energy quantity, as well as, the energy quality in order to increase the distillate production while preserving and reducing energy consumption. Another goal is to perform an experimental campaign in the PSA MED plant in order to validate the simulation results obtained from these optimizations.

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References

[1] UNESCO, The United Nations World Water Development Report 4: Managing Water Under Uncertainty and Risk, in World Water Assessment Programme, Vol. 1, 2012, p. 407.
[2] United Nations Department of Economic and Social Affairs, Back to Our Common Future: Sustainable Development in the 21st Century (SD21) project, UNDESA, p. 39, 2012.
[3] WWAP (United Nations World Water Assessment Programme), The United Nations World Water Development Report 2015: Water for a Sustainable World., United Nations Educational, Scientific and Cultural Organization, Paris, 2015.
[4] F. Van Weert, J. Van der Gun, Saline and Brackish Groundwater at Shallow and Intermediate Depths: Genesis and World-Wide Occurrence, 2012 Congr. Can. Branch Int. Assoc. Hydrogeol., 2012, pp. 1–9.

[5] C. Li, Y. Goswami, E. Stefanakos, Solar assisted sea water desalination: a review, Renew. Sustain. Energy Rev., 19 (2013) 136–163.
[6] P. Palenzuela, G. Zaragoza, D. C. Alarcón-Padilla, J. Blanco, Evaluation of cooling technologies of concentrated solar power plants and their combination with desalination in the mediterranean area, Appl. Thermal Eng., 50 (2013) 1514–1521.
[7] A. Gregorzewski, K. Genthner, E. Zarza, J. Leon, J. de Gunzbourg, G. Alfeld, J. Scharfe, Solar thermal desalination research project at the Plataforma Solar de Almeria, Desalination, 82 (1991) 145–152.
[8] A. Al-Karaghouli, L.L. Kazmerski, Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes, Renew. Sustain. Energy Rev., 24 (2013) 343–356.
[9] A. Ghobeity, A. Mitsos, Optimal design and operation of desalination systems: new challenges and recent advances, Curr. Opin. Chem. Eng., 6 (2014) 61–68.
[10] R. K. Kamali, A. Abbassi, S.A. Sadough Vanini, A simulation model and parametric study of MED-TVC process, Desalination, 235 (2009) 340–351.
[11] I. Janghorban Esfahani, A. Ataei, K.V. Shetty, T. Oh, J.H. Park, C. Yoo, Modeling and genetic algorithm-based multi-objective optimization of the MED-TVC desalination system, Desalination, 292 (2012) 87–104.
[12] E. Ali, Understanding the operation of industrial MSF plants. Part I: stability and steady-state analysis, Desalination, 143 (2002) 53–72.
[13] F. Nematollahi, A. Rahimi, T.T. Gheinani, Experimental and theoretical energy and exergy analysis for a solar desalination system, Desalination, 317 (2013) 23–31.
[14] H.S. Choi, T.J. Lee, Y.G. Kim, S.L. Song, Performance improvement of multiple-effect distiller with thermal vapor compression system by exergy analysis, Desalination, 182 (2005) 239–249.
[15] C. Frantz, B. Seifert, Thermal analysis of a multi effect distillation plant powered by a solar tower plant, Energy Procedia, 69 (2015) 1928–1937.
[16] T.H. Dahdah, A. Mitsos, Structural optimization of seawater desalination: II novel MED-MSF-TVC configurations, Desalination, 344 (2014) 219–227.
[17] A.O.B. Amer, Development and optimization of ME-TVC desalination system, Desalination, 249 (2009) 1315–1331.
[18] P. Palenzuela, A.S. Hassan, G. Zaragoza, D.C. Alarcon-Padilla, Steady state model for multi-effect distillation case study: Plataforma Solar de Almeria MED pilot plant, Desalination, 337 (2014) 31–42.
[19] A. de la Calle, J. Bonilla, L. Roca, P. Palenzuela, Dynamic modeling and simulation of a solar-assisted multi-effect distillation plant, Desalination, 357 (2015) 65–76.
[20] D.C. Alarcón-Padilla, J. Blanco-Gálvez, L. García-Rodríguez, W. Gernjak, S. Malato-Rodríguez, First experimental results of a new hybrid solar/gas multi-effect distillation system: the AQUASOL project, Desalination, 220 (2008) 619–625.
[21] P. Fernández-Izquierdo, L. García-Rodríguez, D.C. Alarcón-Padilla, P. Palenzuela, I. Martín-Mateos, Experimental analysis of a multi-effect distillation unit operated out of nominal conditions, Desalination, 284 (2012) 233–237.
[22] D.C. Alarcón-Padilla, L. García-Rodríguez, J. Blanco-Gálvez, Assessment of an absorption heat pump coupled to a multi-effect distillation unit within AQUASOL project, Desalination, 212 (2007) 303–310.
[23] M. Ibarra, D.C. Alarcón-Padilla, J. Blanco-Gálvez, G. Zaragoza, P. Palenzuela, Performance of Small Parabolic Through Collector as Thermal Energy Supply to Steam Generation, Proc. SolarPACES Conference, 2012, p. 24997.
[24] J. Blanco, D. Alarcón, E. Guillén, W. Gernjak, The AQUASOL system: solar collector field efficiency and solar-only mode performance, J. Sol. Energy Eng., 133 (2011) 11009.
[25] M. Association, Modelica ® – a unified object-oriented language for physical systems modeling language specification, Interface, 5 (2010) 250.
[26] M. Otter, H. Elmqvist, F.E. Cellier, Modeling of multibody systems with the object-oriented modeling language Dymola, Nonlinear Dyn., 9 (1996) 91–112.
[27] L.R. Petzold, A Description of Dassl: A Differential/Algebraic System Solver, Sand828637, January 1982, pp. 3–7.
[28] A. Pfeiffer, Optimization Library for Interactive Multi-Criteria Optimization Tasks, Proc. 9th International Modelica Conference, 2012, pp. 669–680.