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Exergy analysis of the SOL-14 plant (Plataforma Solar de Almería, Spain)

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Abstract

In July, 1988, the first start-up of a solar multi-effect distillation system took place at the Plataforma Solar de Almería, a solar research centre located in southeastern Spain, near Almeria. The plant, known as “Sol-14”, is still in operation. The plant was built and connected to the previous existing solar facilities as a result of a Spanish–German project, which consisted of two phases. The main purpose of Phase I was to study the reliability and feasibility of solar desalination. The objective of Phase II was the design and implementation of those improvements that could make solar thermal desalination more competitive. The initial vacuum system was replaced, and a double-effect absorption heat pump was coupled to the MED plant that was already installed. This solar desalination system was thermodynamically analyzed in order to propose possible improvements of the system. This study complements previous sensitivity analyses of the Sol-14 plant. Further thermoeconomic evaluation of these suggestions, which are out of the scope of this paper, will permit optimization of the system.

Keywords: Solar desalination; Multi-effect distillation; Solar parabolic troughs; Exergy analysis; Thermodynamics

1. Introduction

The Spanish research institution, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) and the German Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V. (DLR) decided in 1987 to develop a solar thermal desalination (STD) project at the Plataforma Solar de Almería (PSA). STD project consists of two phases. In the first one a 14-cell multi-effect distillation (MED) plant was designed and constructed [1]. After the

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experimental evaluation of the system, in the second stage of the project [2] several improvements were designed, implemented and tested. In this paper an exergy analysis of the solar desalination system installed at the PSA was performed. This is a complementary study of a sensitivity analysis previously published [2,3].

2. The SOL-14 plant

A 14-cell MED plant was built at the PSA and connected to the previous existing solar facilities. The PSA is located in southeastern Spain, near Almeria. The first start-up took place in July, 1988, and its evaluation was finished in December, 1990. The Sol-14 plant is still in operation.

The objective of Phase II was the design and implementation of improvements that could make solar thermal desalination more competitive. The initial vacuum system was replaced and a double-effect absorption heat pump (DEAHP) was coupled to the MED plant already installed at the PSA. The improvements implemented in the second stage of the project decrease the energy consumption of the plant by about 44% — from 63 kWh/m^3 to 36 kWh/m^3. On the other hand, the electric consumption decreases by 12% — from 3.3 kWhe/m^3 2.9 kWhe/m^3.

The system considered consists of the following subsystems:

- a one-axis tracking parabolic trough solar collectors (PTC) field in which synthetic oil (Santotherm 55) acts simultaneously as a heat transfer fluid and a heat storage medium;
- thermal storage, consisting of a single thermocline vessel;
- a boiler;
- A MED plant, which is a 3 m^3/h unit;
- A DEAHP, which delivers 200 kW of thermal energy at 65°C to the MED plant.

The desalination process only uses 90 of the 200 kW delivered by the DEAHP. Then the remaining 110 kW are recovered by the DEAHP from a temperature of 35°C to 65°C. The DEAHP needs only 90 kW thermal power at 180°C, thereby reducing the energy consumption of the desalination plant from 200 kW to 90 kW.

Since the SOL-14 plant was coupled to the previous existing solar facilities of the PSA, the solar collector field and the thermal storage tank were not designed for this application. Nevertheless, the optimum design of such systems were studied by the authors [4,5].

3. Exergy analysis of the solar desalination plant

The Second Law of Thermodynamic allows the evaluation of the irreversibility and the exergetic performance of a process. Firstly, the global system is divided into different subsystems. The objective of the analysis determines the most suitable division. On the system diagnoses, the exergy analysis evaluates the exergetic performance of the equipment. Comparing the real exergetic performance with the maximum that could technically be reached, the possibility of fuel saving on the real system could be evaluated. Furthermore, the effect on the fuel consumption of a given change of different parameters could be pointed out. The diagnosis of the system identifies the equipment that is the most important consumer of fuel and where the largest irreversibility is in the system. A detailed analysis of this equipment would select the most suitable improvements.

A computer program was developed for the exergy analysis of SOL-14 plant. This software models the stationary state of a MED plant as a function of the main parameters that characterize its preliminary design.

The SOL-14 plant was analyzed considering both phases of the STD project. Fig. 1 shows the diagram of the solar desalination plant initially considered. Besides that, Fig. 2 shows the

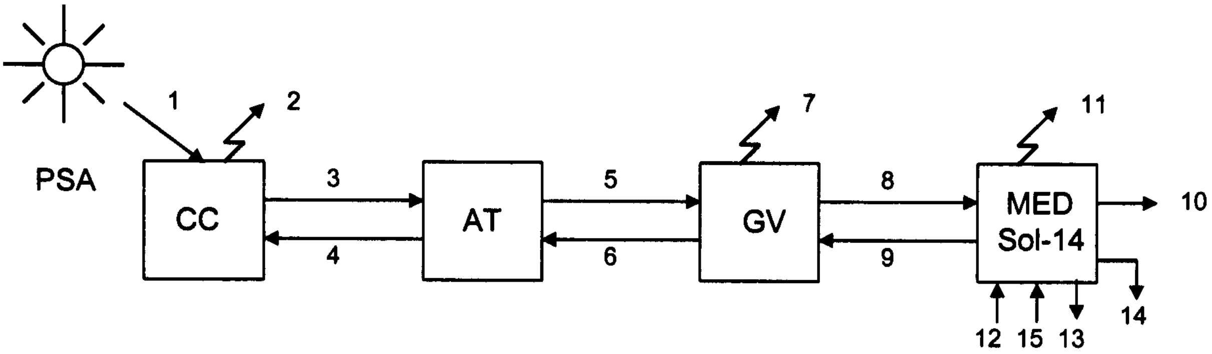

Fig. 1. Solar MED system at Phase I of the STD project. 1 solar input, 2 optic and thermal losses, 3 synthetic oil at T_C, 4 synthetic oil at T_F, 5 synthetic oil at T_C, 6 synthetic oil at T_F, 7 thermal losses, 8 saturated steam, 9 saturated water, 10 fresh water (product), 11 thermal losses, 12 seawater, 13 cooling outlet stream, 14 blowdown, 15 auxiliary power consumption. CC, solar collector field (Solar Kinetics T700A); AT, thermal storage; GV, boiler.

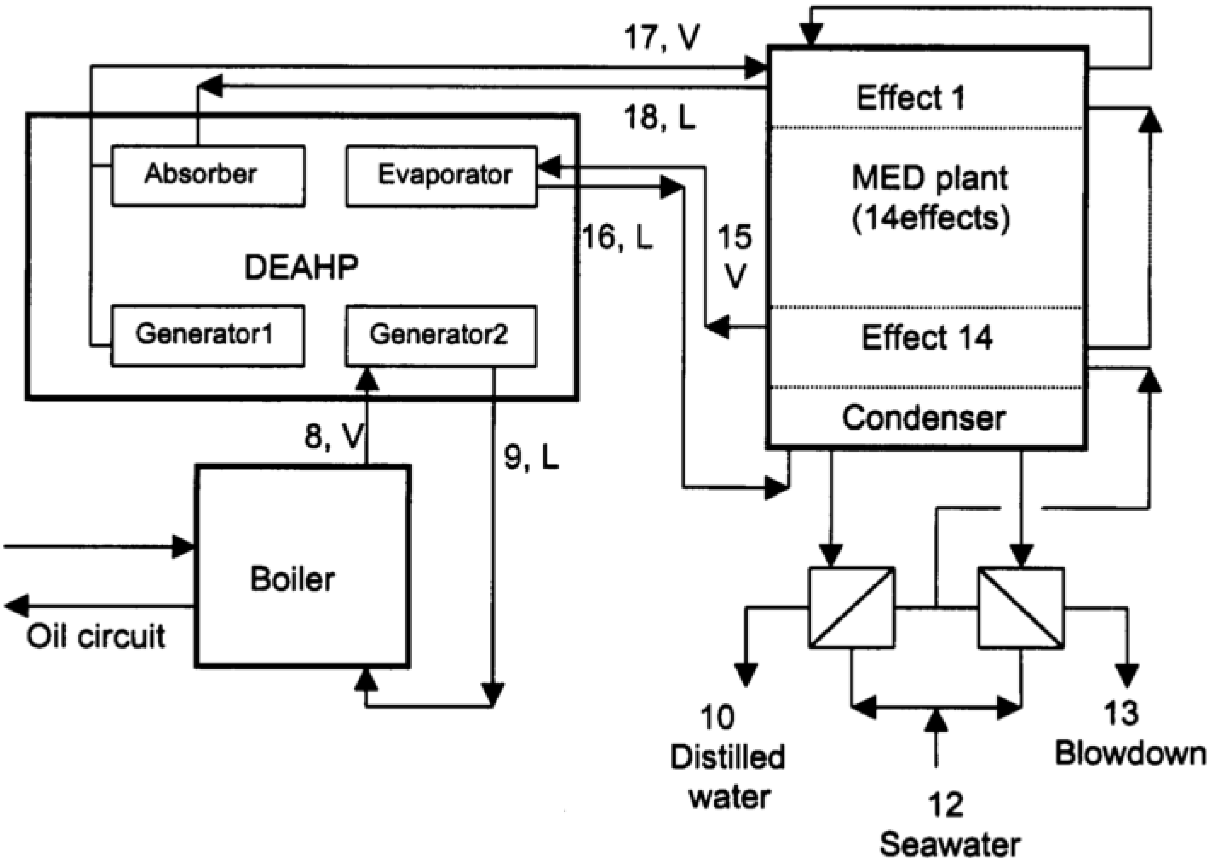

Fig. 2. Design arrangement of the desalination plant at Phase II of the STD project. V, steam; L, liquid.

changes due to the coupling of the DEAHP. Initial assumptions are as follows: negligible thermal losses of the thermal storage; thermal losses at the boiler, 5%; and 10% of performance ratio reduction due to losses in the MED unit.

Since every subsystem plays a particular role in the global system, it can be identified for each one and for the system as a whole: the product streams (P), the streams from which the product is generated or fuel (F), and the streams with no later usefulness. F and P may consist of either an inlet or outlet stream or a mass flow, which crosses the equipment and which might be separated or mixed inside it. The exergy of the product (P), of the fuel (F), and of the useless outlet streams (L) are related by $P=F-L-D$, where D represents the exergy losses in this equipment due to irreversibilities. The exergetic performance of the process, η_{ex}, is the quotient between the exergy of the product (P) and the exergy required in its production process (the exergetic cost of the product): $\eta_{ex} = P/F$. The exergetic performance is lower than 1 since real process are irreversible. Based on the exergy diagram, the exergy required to generate each stream (exergetic cost, Ex^*) is determined from the assignment of these costs to the inlet and useless outlet streams and some rules established

Table 1
Fuel (F), product (P) and useless outlet streams (L) from Fig. 1

Equipment	F	P	L
CC	1	3–4	2
AT	3–4	5–6	—
GV	5–6	8–9	7
MED	8–9,12,15	10	11,13,14
System total	1,12,15	10	2,7,11,13,14

Table 2
Massic and energetic streams of Fig. 1

Stream	m/m_d	b/mol ·kg^{-1}	T,°C	Q/m_d, kJ/kg	Ex/md, kJ/kg
1. Solar input	—	—	—	426.3	404.3
2. Thermal losses CC	—	—	—	199.5	0
3. Synthetic oil	1.25	—	190	—	—
4. Synthetic oil	1.25	—	110	—	—
5. Synthetic oil	1.25	—	190	—	—
6. Synthetic oil	1.25	—	110	—	—
7. Heat losses (GV)	—	—	—	11.94	0
8. Saturated steam	0.098	0.0	73	—	—
9. Saturated water	0.098	0.0	73	—	—
10. Product	1.00	0.0	34.5	—	—
11. Heat losses (MED)	—	—	—	22.68	0
12. Seawater input	6.67	0.568	25.0	—	—
13. Seawater output	4.00	0.568	31.25	—	—
14. Blowdown	1.67	0.929	35.0	—	—
15. Auxiliary energy	—	—	—	—	10.44

by Valero et al. [6]. The suitable assignment of these costs depends on the objective of the analysis performed. If inlet streams are not natural resources but some exergy consumption was necessary for processing them, this exergy could be considered. If the useless outlet streams do not require any exergy consumption for their extraction or dispersal, null exergetic costs are assigned, but null assignations could not be made in other cases.

Table 1 classifies F, P and L streams of the flux diagram given in Fig. 1. In addition, Table 2 shows the thermodynamic quantities that characterize the mass and energy fluxes of Fig. 1. In Table 2, *m*, *b* and *T* represent mass, molality and temperature, respectively; m_d is the mass of product; and *Q* and *Ex* are, respectively, thermal energy and exergy. In addition, Tables 3–5 complete the exergy analysis of the solar MED plant initially considered. Tables 6–10 are related to the solar MED plant of the second phase of the STD project in which the DEAHP was coupled.

These tables are analogous to the previous ones. Tables 4 and 10 give the unitary exergetic costs, *Ex*/Ex*, that were calculated as follows. The algebraic sum of exergetic costs of the fluxes connected to a given unit is zero. This rule establishes 4 equations. In addition, the Ex* of the external inputs are equivalent to their exergy, and the Ex* assigned to the useless outgoing streams are zero. Moreover, the unitary exergetic

Table 3
Exergetic performance of the equipment at Phase I of the STD project

Equipment	F, kW	P, kW	F–P, kW	η_{ex}=P/F, %
CC	336.9	58.63	278.3	17.4
AT	58.63	≅58.63	≅0	≅100
GV	58.63	26.21	32.42	44.7
MED	34.91	4.992	29.92	14.3
Global system	345.6	4.992	340.6	1.4

Table 4
Solar MED system (phase I of the STD project) where *H* represents enthalpy and *Ex*/Ex* is the unitary exergetic cost

Fluxes	m/m_d	$\Delta H/m_d$ /kJ·kg^{-1}	Ex/m_d /kJ·kg^{-1}	Ex^*/Ex
1. Solar input	—	426.3	404.3	1
2. Thermal losses CC	—	199.5	0	0
3–4. Synthetic oil	1.25	238.7	70.36	5.747
5–6. Synthetic oil	1.25	≅238.7	≅70.36	5.747
7. Thermal losses (GV)	—	11.94	0	0
8–9. Saturated steam/liquid	0.098	226.8	31.45	12.86
10. Product	1.00	39.69	5.991	69.23
11. Thermal losses, MED	—	22.68	0	0
12. Seawater input	6.67	1.92	0	1
13. Seawater outlet	4.00	106.0	1.084	0
14. Blowdown	1.67	70.76	−0.974	0
15. Auxiliary energy	—	10.44	10.44	1

Table 5
Useless fuel consumption of the equipment at Phase I with reference to the global system (subscript T)

	CC	AT	GV	Sol-14
$(F_k–P_k) / (F_T–P_T)$	0.817	≅0	0.095	0.088
F_k / F_T	0.975	0.17	0.17	0.10

Table 6
Massic and energy streams of Fig. 2

Stream	m/m_d	b/mol ·kg^{-1}	T, °C	Q/m_d, kJ/kg	Ex/m_d, kJ/kg
1. Solar input	—	—	—	213.7	202.7
2. Losses, CC	—	—	—	94.03	0
3. Synthetic oil	0.556	—	270	—	—
4. Synthetic oil	0.556	—	190	—	—
5. Synthetic oil	0.556	—	270	—	—
6. Synthetic oil	0.556	—	190	—	—
7. Thermal losses (GV)	—	—	—	5.98	0
8. Saturated steam	0.055	0.0	180	—	—
9. Saturated water	0.055	0.0	180	—	—
10. Product	1.00	0.0	33.5	—	—
11. Thermal losses (MED)	—	—	—	24.0	0
12. Seawater input	2.67	0.568	25.0	—	—
13. Blowdown	1.67	0.929	35.0	—	—
14. Auxiliary energy	—	—	—	—	10.44
15. Saturated steam	0.055	0.0	34.6	—	—
16. Saturated water	0.055	0.0	34.6	—	—
17. Saturated steam	0.102	0.0	65	—	—
18. Saturated water	0.102	0.0	65	—	—
19. Thermal losses (DEAHP)	—	—	—	5.68	0

Table 7
Fuel (F), product (P) and useless outlet streams (L) (see Fig. 2)

Equipment	F	P	L
CC	1	3–4	2
AT	3–4	5–6	—
GV	5–6	8–9	7
DEAHP	8–9, 15–16	17–18	19
Sol-14	12, 14, 17–18	10, 15–16	11, 13
Global system	1, 12, 14	10	2, 7, 11, 13, 19

Table 8
Exergetic performances of the equipment in phase II of the STD project

Equipment	F, kW	P, kW	$F–P$, kW	$\eta_{ex} = P/F$, %
CC	168.9	40.59	128.3	24.0
AT	40.59	≅40.59	≅0	≅100
GV	40.59	23.66	16.94	58.3
DEAHP	27.09	23.66	3.43	87.3
MED	32.36	8.317	24.04	25.7
Global system	177.6	8.317	169.3	4.7

Table 9
Useless fuel consumption of the equipment referred to the global system (subscript *T*) in Phase II of the STD project

	CC	AT	GV	DEAHP	Sol14
$(F_k–P_k)/(F_T–P_T)$	0.743	≅0	0.098	0.153	0.182
F_k/F_T	0.951	0.229	0.229	0.020	0.142

Table 10
Solar MED–DEAHP plant

Flux		m/m_d	$\Delta H/m_d$, kJ·kg^{-1}	Ex/m_d, /kJ·kg^{-1}	Ex^*/Ex
1.	Solar radiation	—	213.7	202.7	1
2.	Losses (CC)	—	94.03	0	0
3–4.	Synthetic oil	0.556	119.7	48.71	4.16
5–6.	Synthetic oil	0.556	≅119.7	≅48.71	4.16
7.	Heat losses (GV)	—	5.983	0	0
8–9.	Saturated vapour–liquid	0.055	113.7	38.89	7.14
10.	Product	1.00	35.31	5.863	36.347
11.	Heat losses (MED)	—	24.0	0	0
12.	Seawater input	2.67	0.768	0	1
13.	Blowdown	1.67	59.88	−1.303	0
14.	Auxiliary energy	—	10.44	10.44	1
15–16.	Saturated vapour–liquid	0.055	132.0	4.118	36.35
17–18.	Saturated vapour–liquid	0.102	240	28.39	12.41
19.	Heat losses (DEAHP)	—	5.684	0	0

cost of fluxes that belongs to the same fuel, as 3–4 in Table 1, are equivalent. Finally, if the product of equipment consists of more than one component, as 10 and 15–16 in Table 7, their unitary exergetic costs are equivalent.

To sum up, with regard to the improvements of Phase II of the STD project, results show that:

- the η_{ex} of the global system goes up from 1.4% to 4.7%.
- The η_{ex} of the MED plant changes from 14.3% to 25.7% due to the energy recovery. Note that the thermal energy output of the cooling seawater output is replaced in Phase II by the recovery of this energy in the DEAHP.
- The increasing of the operation temperature of the CC results in an increasing of its η_{ex}.
- The unitary exergetic cost of the product decreases from 69.2 to 36.3.

On the other hand, additional improving of the system would be possible improving the solar generation of the steam consumed by the MED–DEAHP system. It can be possible using direct steam generation parabolic troughs.

4. Conclusions

The exergy analysis performed quantifies the improvement implemented in Phase II of the STD project from a thermodynamic point of view. Further thermoeconomic evaluation of these improvements, which are out of the scope of this paper, will permit optimization of the system.

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References

[1] E. Zarza Moya, Solar thermal desalination project: first phase and results and second phase description, Secretaría General Técnica del CIEMAT, Madrid, 1991.

[2] E. Zarza Moya, Solar thermal desalination project, Phase II results and final project report, Secretaría General Técnica del CIEMAT, Madrid, 1995.

[3] L. García-Rodríguez and C. Gómez-Camacho, Desalination ,122 (1999) 195.

[4] L. García Rodríguez and C. Gómez Camacho, Desalination, 122 (1999) 205.

[5] L. García Rodríguez and C. Gómez Camacho, Desalination, 122 (1999) 215.

[6] L. García-Rodríguez and C. Gómez-Camacho, Thermoeconomic optimization of SOL-14 plant (Plataforma Solar de Almería, Spain). EUROMED 2000, Desalination Strategies in South Mediterranean Countries, Jerba, Tunisia, 2000.

[7] A. Valero, M.A. Lozano and M. Muñoz, ASME, 2–3 (1986) 1.