IMPROVING THE EFFICIENCY OF HIGH CAPACITY SOLAR THERMAL SEAWATER DESALINATION SYSTEMS: THE AQUASOL PROJECT

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ABSTRACT

Despite the energy efficiency advances reached during the last decade, seawater desalination continues to be an intensive fossil energy consumer. In the current global framework, with growing oil price instability and the environmental requirements derived from compliance with the Kyoto Protocol, the sustainability of this technological solution inevitably passes through continued improvement of energy efficiency of the physical processes involved, as well as the use of renewable energy resources, such as for example, solar energy. In 2002, a new combined (research & demonstration) project called Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology (AQUASOL) was initiated at the facilities of the Plataforma Solar de Almería. The main objective of this project is the development of a seawater desalination technology based on multi-effect distillation that is energy efficient, low-cost and has a zero discharge. In August 2004, the AQUASOL Project research phase was successfully concluded and all the subsystems have been designed and implemented for their evaluation during the demonstration phase. This paper describes the final design of the overall system, and all erection works performed.

INTRODUCTION

Seawater desalination is one of the possible solutions to the severe water shortage problem our planet is experiencing during the first half of this century [1], a problem that is not exclusive to developing countries, as the appearance of seasonal episodes of persistent drought in certain regions of the so-called developed countries is becoming more and more frequent.

The latest world inventory of desalination facilities established a historical accumulated production capacity (installed or contracted) of 37.75 million cubic meters per day, of which around 26.50 million cubic meters per day are currently in operation [2]. Insofar as desalination processes are concerned, basically only two technologies are implemented on a commercial scale, membrane processes (reverse osmosis, electrodialysis) and thermal distillation processes (multi-stage flash distillation, multi-effect distillation, mechanical vapor compression). In reality, only two processes, reverse osmosis (RO) and multi-stage flash distillation (MSF) take up 80% of the market, one or the other leading this classification depending on the salt concentration of the product water. If only seawater desalination is considered, then the MSF process takes up 47.2% of the global production capacity compared to 36.5% for RO. However, if both desalination of brackish water and seawater are considered, then osmosis processes constitute 47.2% of the worldwide production capacity compared to 36.5% for multi-stage flash distillation. Retrospectively, a decade ago these proportions were 32.7% and 51.3%, respectively, which clearly indicates the current market tendencies of the two technologies.

If the progress of the energy efficiency of the two technologies in the last three decades is considered, thermal distillation systems, which in the last thirty years have hardly undergone any appreciable reduction in the desalination process energy requirement, are found to have stagnated. In fact, today, thermal distillation of seawater can only compete economically in large seawater-electricity cogeneration plant layouts, with the additional requirement of relatively low-cost fossil fuel, such as in the Persian Gulf. However, in the case of seawater desalination with reverse osmosis, consumption has gone from 30.84 kWh/m^3 (1970) to a consumption of 3.5 kWh/m^3 (2000), that is, the energy efficiency has multiplied by nine. Moreover, there are realistic perspectives of these values diminishing even further, as illustrated by the ADC project, now underway in the United States, which intends to demonstrate that that a consumption of 1.7 kWh/m^3 can be achieved in reverse osmosis seawater desalination [3].

Nevertheless, in spite of all these improvements, the seawater desalination process continues to be an intensive fossil energy consumer. In the current global framework, with growing oil price instability and the environmental requirements derived from compliance with the Kyoto Protocol, the sustainability of this technological solution inevitably passes through continued improvement of energy efficiency of the physical processes involved, as well as the use of renewable energy resources, such as for example, solar energy.

In 1988, the Solar Thermal Desalination (STD) Project was initiated at the facilities of the Plataforma Solar de Almería (PSA) in the south of Spain [4]. This research project lasted until 1994 and had two main objectives: i) to study the technical and financial feasibility of seawater desalination with solar thermal energy, ii) to optimize the solar thermal desalination system implemented by introducing and evaluating improvements minimizing electrical and thermal energy consumption. The solar technology initially proposed was based on the use of parabolic-trough solar concentrators with single-axis tracking working with thermal oil as the heat transfer and thermal storage fluid, for the purpose of supplying the energy required for a multi-effect (MED) distillation plant installed at the PSA. With this configuration, a performance ratio (kg of distillate per 2,326 kJ heat input) of 10 was obtained. With the goal of improving that value, two procedures for recovering heat in the MED unit were studied, thermal compression (which is usually used in conventional MED plants) and absorption heat pump technology, which upgrades low temperature heat with much higher second law efficiency than ejector compressors [5]. A first-world prototype of double-effect absorption (LiBr-H_2O) heat pump (DEAHP) for desalination applications was built and installed in the PSA MED plant in order to recover the latent heat of the steam produced in the last effect. This configuration increased the performance ratio to 20.

Although the technical feasibility of the system was demonstrated, its economics remained far from those of conventional desalination technologies. Since 1994, this desalination system has been providing the distilled water required by all the experimental facilities located at the PSA, accumulating a large number of operating hours and demonstrating the robustness of the technology proposed, as no major failure has occurred during this period.

Research activities in solar desalination at the PSA were recently boosted by the startup in 2002 of a new combined (research & demonstration) project called Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology (AQUASOL, FP5-

EVK1-CT2001-00102) partially supported by the European Commission under the Energy, Environment and Sustainable Development Programme. The main objective of this project is the development of a seawater desalination technology based on multi-effect distillation that is energy efficient, low-cost and has a zero discharge. In August 2004, the AQUASOL Project research phase was successfully concluded and all the subsystems have been designed and implemented for their evaluation during the demonstration phase. This paper describes the final design of the overall system, and all erection work performed.

DESCRIPTION OF THE AQUASOL SYSTEM

The seawater system designed under the AQUASOL Project is made up of:

- A multi-effect distillation plant with 14 cells in a vertical arrangement.
- A stationary CPC (Compound Parabolic Concentrator) solar collector field.
- A thermal storage system based on water.
- A double effect (LiBr-H_2O) absorption heat pump.
- A smoke-tube gas boiler.
- An advanced solar dryer for final treatment of the brine.

These subsystems are interconnected as shown in Fig. 1. The system operates with water as the heat transfer fluid, which is heated as it circulates through the solar collectors. The solar energy is thus converted into thermal energy in the form of the sensible heat of the water, and is then stored in the tanks. Hot water from the storage system provides the MED plant with the required thermal energy. In absence of solar radiation, the gas boiler feeds the absorption heat pump, which is also fed with low temperature steam from the last MED plant effect , in order to heat the water coming from first effect from 63.3ºC up to 66.5ºC.

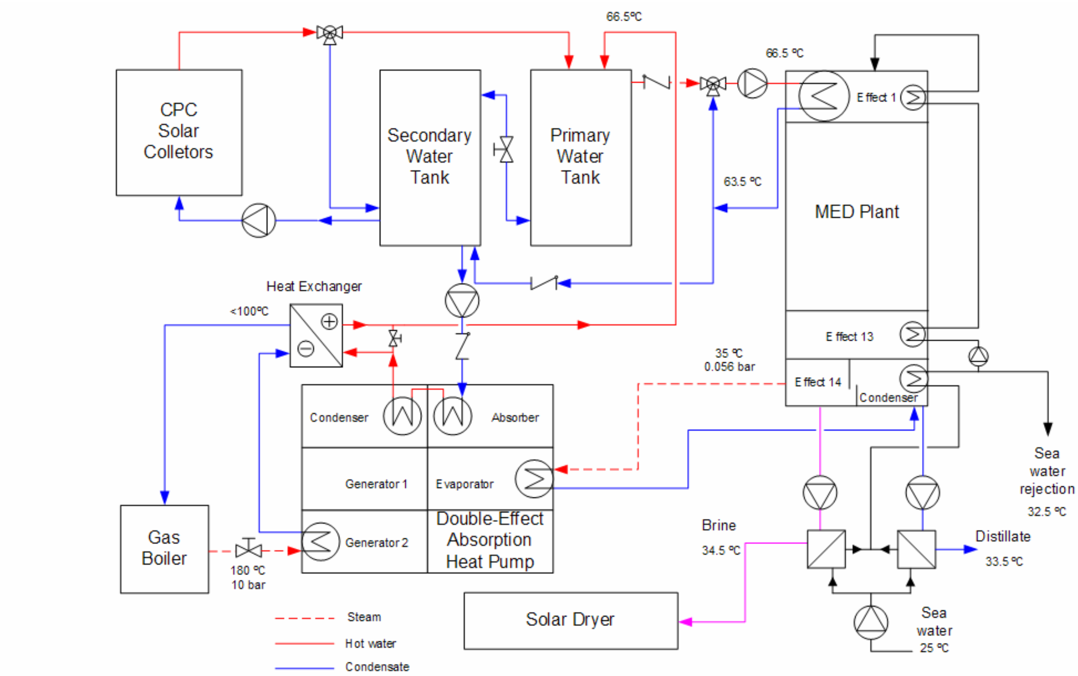

Fig. 1: Final configuration proposed for AQUASOL seawater desalination system

The distillation unit

The PSA SOL-14 desalination plant (See Fig. 2, left) is a forward-feed multi-effect distillation unit manufactured and delivered by Weir ENTROPIE in 1987 (See Table 1 for specifications). It has 14 cells, or effects, in a vertical arrangement, in which seawater is preheated on its way towards the first cell of the plant, which is at the top of the desalination tower.

Table 1: Technical specifications of the PSA MED distillation plant

Feedwater flow	8 m^3/h
Brine reject	5 m^3/h
Distillate production	3 m^3/h
Seawater flow at condenser: **at 10ºC:** **at 25ºC:**	 8 m^3/h 20 m^3/h
Output salinity	5 ppm TDS
Number of cells	14
Heat source energy consumption	190 kW
Performance Ratio	>9
Vacuum system	Hydroejectors (seawater at 3 bar)
Top brine temperature	70ºC
Condenser temperature	35ºC

The original first cell that worked with low-pressure saturated steam (70ºC, 0.31 bar), has been replaced in the AQUASOL Project by a new one (See Fig. 2, right), working with the hot water coming directly from the thermal storage tank (See Table 2 for expected performance). A new horizontal tube bundle, front and rear water boxes and a new spraying tray with technical characteristics constrained to the dimensions of the first cell, have also been installed in the SOL-14 plant.

Table 2: Estimated performance of the new PSA MED plant first effect

	Desalination driven by solar collectors	**Desalination driven by absorption heat pump**
Power	200 kW	150 kW
Inlet /Outlet hot water temperature	75.0 / 71.0 ºC	66.5 / 63.5 ºC
Brine temperature (on first cell)	68ºC	62.0 ºC
Hot water flow rate	12.0 kg/s	12.0 kg/s
Pressure drop	0.4 bar g	0.4 bar g

Fig. 2: The PSA MED plant (left) and the new horizontal tube bundle installed at the first effect (right)

The solar field

The solar field is made up of 252 stationary solar collectors (CPC Ao Sol 1.12x) with a total surface area of approximately 500 m^2 arranged in four rows of 63 collectors (See Fig. 3). Due to the specially designed hydraulic layout (reverse feeding mode), total flow rate (14.97 m^3/h) is equally distributed into the four rows (3.74 m^3/h) without further regulation (See Fig. 4).

Fig. 3.: 500 m^2 stationary CPC solar collector field

The collectors are organized in groups of nine, all connected in parallel in each row, which in turn are connected in parallel to each other, feeding into the thermal storage system. Each group of nine collectors is organized in the following way: i) the collectors are oriented east-west to maximize energy collection; ii) each group is subdivided into three subgroups of three collectors; iii) in each subgroup, the collectors are connected in parallel; iv) each subgroup is connected to the next in series (See Fig. 4).

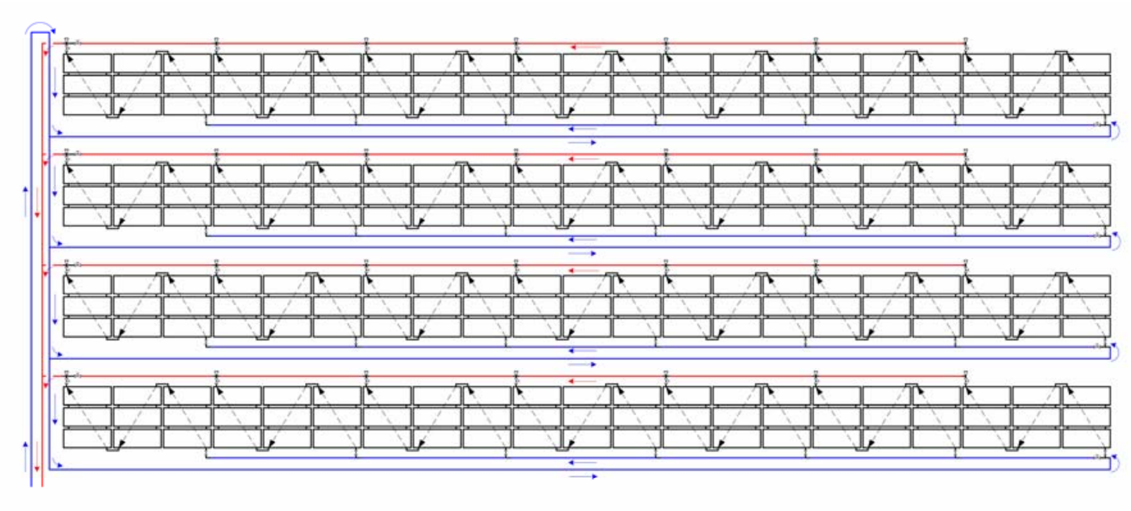

Fig. 4: Water flow scheme in AQUASOL solar field

A transparent honeycomb-type insulation material inside the solar collector was considered during the research phase. However, at the operating temperatures that are expected in the system (below 80ºC) there is no net advantage in this. Furthermore, stagnation temperatures reached without the honeycomb are much safer in case of pump failure. The use of a new higher concentrating CPC collector prototype (1.5x) was considered, but was finally rejected because it would have meant a reduction in the number of hours operating with solar energy, and there was no need for higher temperatures than could be reached with the 1.12x CPC collector.

Table 3: Technical characteristics of Ao Sol CPC 1.12x collector

Dimensions	2012 x 1108 x 107 mm
Aperture area	1.98 m^2
Absorber (selective coating) Emissivity Absorptivity	 0.10 – 0.15 0.94 – 0.95
Weight (empty)	38 kg
Operating pressure	6 bar
Testing pressure	12 bar
Optical efficiency	0.70 – 0.71
Thermal loss factor	3.4 W/m^2K

Thermal storage system

The thermal storage system is made up of two interconnected 12-m^3-capacity water tanks (See Fig. 5). The total volume finally chosen is based on the response time required by the gas boiler and the absorption heat pump to reach nominal operating conditions. The use of two tanks enables the solar contribution to be increased over the year as well as obtain certain temperature stratification necessary to avoid the heat pump water inlet temperature exceeding the permissible range (60ºC – 70ºC).

Fig. 5: Front view of the PSA desalination building with the two thermal storage tanks

The tanks are A106 grade B carbon steel that had to be treated to prevent corrosion on the surfaces in contact with hot water. After studying several options, paint treatment resistant to water up to 150ºC was finally chosen (See Table 4). .

Table 4: Tank inner surface paint treatment

Preparation	Sandblasting SA-2	
Metal primer	Zinc silicate	75 μm
Intermediate layer	Two-epoxy components paint	100 μm
External layer	Aluminum silicone	45 μm

The outer surface of both tanks is thermally insulated, and for this reason only a minimum primer after sandblasting was required.

<u>Gas boiler</u>

A propane gas-fired backup system is necessary to guarantee the necessary operating conditions (the DEAHP requires steam at 180ºC) and permit 24-hour MED-plant operation (to reduce the impact of capital costs) in absence of solar radiation. During the design phase of the AQUASOL Project, it was decided to install a C-class smoke tube boiler so that the DEAHP can work at variable loads (from 30% to 100%). The gas to be burnt is stored in a 2,450-liter tank installed next to the distillation plant building. This tank volume provides an estimated autonomy of 143 hours at full load. Return condensate flow must be cooled in order to avoid flashing, and a heat exchanger is to be installed for this reason, transferring the energy to the stream that connects the absorption heat pump with the thermal storage tank.

Fig. 6: Gas boiler system installed into the PSA desalination building

Double-effect absorption heat pump

The double effect absorption heat pump increases the energy efficiency of the distillation process by making use of the 35ºC saturated steam produced in the last MED plant effect, which would otherwise involve the loss of the energy (100 kW) in the evacuation of the cooling fluid used for its condensation, as the cold sink (See Fig. 7).

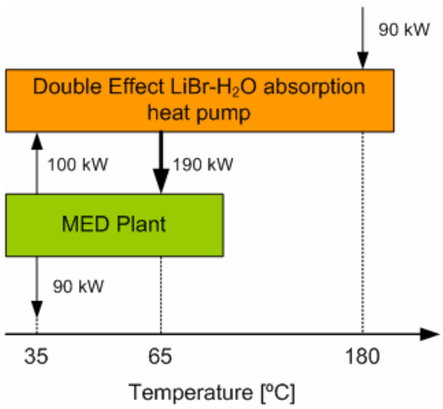

Fig. 7: The new double-effect absorption heat pump installed at the PSA and the energy balance of its coupling to the PSA MED plant

Three different system operating modes of the AQUASOL plant are possible depending on where the desalination unit energy supply comes from:

- Solar-only mode: energy to the first distillation effect comes exclusively from thermal energy from the solar collector field.
- Fossil-only mode: the double-effect heat pump supplies all of the heat required by the distillation plant
- Hybrid mode: the energy comes from both the heat pump and the solar field. It is planned to test two different operating philosophies. In the first, the heat pump works continuously 24 hours a day with a 30% minimum contribution, while second, pump starts up or shuts down, depending on the availability of the solar resource.

Table 5 shows the thermal design of the DEAHP working at different load values. As can be seen, the coefficient of performance (COP), defined as the ratio between the power recovered at low temperature and the power delivered to the heat pump, drops as the steam load decreases.

Table 5: Thermal design of the new DEAHP to be installed in AQUASOL Project

		DEAHP load (%)			
		100	**75**	**50**	**30**
Low pressure steam	**Power (kW)**	100	75	50	30
	Pressure inlet (bar)	0.051	0.051	0.051	0.051
	Temp. inlet (ºC)	35	35	35	35
	Flow rate (kg/s)	0.041	0.031	0.021	0.012
Cooling water	**Power (kW)**	182	139	95	56
	Temp. inlet (bar)	64	64	64	64
	Temp. outlet (ºC)	67.7	66.7	65.8	65.2
	Flow rate (kg/s)	12	12	12	12
High pressure steam	**Power (kW)**	82	62.5	42	26
	Pressure inlet (bar)	10	10	10	10
	Temp. inlet (ºC)	180	180	180	180
	Flow rate (kg/s)	0.039	0.031	0.021	0.014
COP		1.22	1.20	1.18	1.15

An advanced control system regulates the three-way regulating valve in the recirculation loop of the MED plant first cell. Temperatures inside the thermal storage tanks must be carefully monitored to determine the appropriate recirculation flow and avoid temperatures above 70ºC inside the MED first effect and also the DEAHP operating load (when available solar radiation becomes insufficient to feed the MED plant by itself).

Advanced solar dryer

The purpose of the advanced solar dryer is to increase the concentration in the brine until it has reached the saturation point of calcium carbonate (16ºBe, Baumé scale). After the experimental evaluation of a series of small prototypes, a final solar dryer design has been proposed for evaluation during the AQUASOL Project demonstration phase. This dryer consists of three parallel 4-m-x-17-m interconnected evaporation channels with brine stream circulating inside them. The evaporation channels have a plastic cover, a preheating section at the inlet, and a solar chimney located at the outlet to promote air stream inside the channels (See Fig. 8).

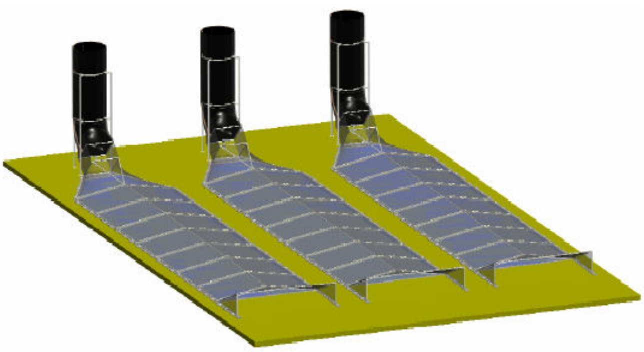

Fig. 8: Simulated view of the three advanced solar dryer modules proposed in the AQUASOL Project (courtesy of INETI)

A fourth open-air channel will be erected at the same time for realistic comparison of the new prototype's performance. A north-south orientation was finally chosen due to the predominant winds at the installation site. Simulation models foresee a 2.5 increase in efficiency compared to traditional open-air salt evaporation ponds.

CONCLUSIONS

Research activities in solar thermal seawater desalination are currently carried out at the facilities of the Plataforma Solar de Almería in the framework of the AQUASOL Project. After the conclusion of the research phase, the final design of the proposed desalination system is being erected for testing during the project's demonstration phase. Use of a renewable energy source, such as solar thermal energy, in the desalination process, improved MED process efficiency through incorporation of the absorption heat pump technology, and reduction of the environmental impact of the desalination process effluent are the main goals of AQUASOL Project.

ACKNOWLEDGMENTS

The authors wish to thank the European Commission (DG XII Research) for its financial assistance within the Energy, Environment and Sustainable Development Programme ("AQUASOL" Project; Contract Nr. EVK1-CT2001-00102).

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