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Connection of absorption heat pumps to multi-effect distillation systems: pilot test facility at the Plataforma Solar de Almería (Spain)

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ABSTRACT

Theoretical analysis demonstrates that coupling a double effect absorption heat pump (DEAHP) cycle to a multi-effect distillation (MED) process shows higher overall performance than other conventional heat pumps like steam ejectors. However, only two demonstration facilities have been implemented worldwide to date, both of them at the Plataforma Solar de Almería (Spain). The first experience (1992) allowed the expected performance results to be achieved, but some operational problems showed that the technology was not mature enough for its commercial implementation. This paper reports on the assessment of a second heat pump prototype (2005) more successful than the first one. Advances in both the DEAHP unit and design layout of the desalination system as a whole have led to proven reliability of the DEAHP/MED concept, which has an overall performance ratio of 20 with stable and fully automatic operation. It requires a 180ºC saturated steam supply which can be provided by solar linear-focusing concentrators. This is a 100% increase over the performance ratio of the MED unit, thus becoming the most efficient solar distillation technology.

Keywords: Seawater desalination; Absorption heat pumps; Multi-effect distillation; Solar desalination

1. Introduction

An absorption heat pump coupled to a multieffect distillation unit is able to recover part of the thermal energy rejected in the distillation process, thus increasing its performance ratio. The authors reviewed the status of this technology in a previous paper [1]. Theoretical analysis showed that the coupling of an absorption heat pump cycle to multi-effect distillation (MED) exhibits higher performance than other heat pumps, as thermal vapour compression with steam ejectors [2]. However, only two pilot facilities have been implemented worldwide to date. Both of them have been developed and tested under the framework of two different research and demonstration projects carried out at the Plataforma Solar de Almería (CIEMAT, Spain). In both projects, two different prototypes of Double-Effect Absorption ($LiBr-H_2O$) Heat Pump (DEAHP) were coupled to an existing 14-effect MED unit. The two prototypes have a modified design with respect to conventional DEAHP´s used for chilling purposes in order to fit the operation temperature range of the distillation unit.

At the beginning of the nineties, in the first pilot plant installed at the Plataforma Solar de Almería, a consumption of 108 kJ/kg of distilled water at 180ºC was measured. It results in a performance ratio of 21.3 while that of the distillation unit (SOL14 plant) was about 10.

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Then, previous experimental test campaign performed at the Plataforma Solar de Almería (PSA) proved that multi-effect distillation process has already considerable potential of development by means of coupling a double effect absorption heat pump (DEAHP). Nevertheless, the reliability of the technology was not proved since some operation problems were not solved:

- Irregular performance of the DEAHP. Changes in efficiency from one day to another were usual, even when temperature and pressure profiles were the same.
- Randomly unstable operation and difficulty in achieving steady state conditions.

In 2001, a combined research and demonstration project called "Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology" (DGXII-FPV AQUASOL Project, 2002–2006) was approved by the European Commission under the Energy, Environment and Sustainable Development Programme. The main objective of this project was the development of a seawater desalination technology based on the multi-effect distillation technology that is energy efficient, low-cost and has zero discharge. One of the main technological objectives of the project was the assessment of the second prototype of DEAHP that was coupled to the existing MED plant at the PSA. The state of the art and design differences between first and second prototypes of DEAHP have been previously reported by the authors [3].

A set of experimental test campaigns have been conducted since the second prototype was installed, which were focused on the following objectives:

1. Assessment of the performance of the system DEAHP and MED as a whole.
2. Selection of the most suitable way to connect the DEAHP to the MED unit either, directly or by means of two auxiliary water tanks.
3. Comparative assessment of the first and second prototypes of DEAHP.

Test campaigns related to the first two objectives were previously reported by the authors [4,5]. Besides that, the successful assessment of the design of the second DEAHP prototype is reported in this paper.

2. Objectives of the experimental test campaign

Technical feasibility of powering a DEAHP with high pressure steam coming from a parabolic trough solar field was already demonstrated within STD Project at the PSA [6]. Therefore, the new DEAHP prototype tested in AQUASOL Project is powered by a propane gas boiler, in order to focus the study only into the performance of the absorption cycle and prototype behavior. It was decided to install a C-class smoke tube boiler in order to permit the DEAHP to operate at variable loads (from 30% to 100%).

The second DEAHP prototype design was substantially changed regarding the first prototype [6] in order to improve the operational behaviour of the DEAHP-MED system as a whole. One of the most important changes in the DEAHP design of the second prototype is that it provides the thermal power to the MED unit by means of liquid water, which is heated as it circulates through the absorber and condenser of the absorption unit. The first cell of the SOL14 plant was then replaced by a new one, which is able to operate with hot water as heat transfer substance. On the other hand, both prototypes of DEAHP receive low pressure steam from the last MED plant effect.

The main goal of the experimental test reported in this paper is the assessment of the second prototype of DEAHP, in particular to the following points:

- *Replacement of the first cell of the MED unit.* The previous first cell of the MED unit was replaced to receive the thermal input by means of liquid water instead of steam. Therefore, the MED unit has to be previously assessed to identify any change in the performance ratio of the unit.
- *Trouble free operation*. The trouble free operation has to be verified at nominal conditions as well as in the starting and shut down operations. To obtain a trouble-free operation with the second prototype would be the best achievement compared to the first prototype.
- *Performance at nominal operation conditions.* Once the trouble free operation is ensured, the design performance has to be verified in order to compare it to previous results with the first prototype. Although performance values obtained for the first prototype were satisfactory, to obtain regular performance would be an important advancement compared to it.
- *Discontinuous operation of the DEAHP.* The ability of a solar desalination system of being operated with no conventional energy backup is important. Then, the capability of discontinuous operation of the DEAHP was assessed. The first prototype test campaign concluded that discontinuous operation was not advisable.

3. Experimental system

3.1. Main subsystems

The SOL-14 desalination plant is a forward-feed multi-effect distillation unit manufactured and delivered

Table 1
Technical specifications of the SOL-14 MED plant.

Feedwater flow	8 m^3/h
Brine reject	5 m3/h
Distillate production	3 m3/h
Seawater flow at condenser:	
at 10ºC	8 m3/h
at 25ºC	20 m3/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

by ENTROPIE in 1987 under the framework of a previous research project [6]. It has 14 effects, in a vertical arrangement. The original first cell worked with low-pressure saturated steam (70ºC, 0.31 bar) coming from the first prototype of DEAHP. Table 1 shows technical specifications of SOL-14 unit.

The first DEAHP prototype presented some small modifications in its design from a classical configuration of a DEAHP. The low temperature condenser was placed out of the absorption circuit, being its role played by the MED first effect, where the steam produced in the low temperature generator and the absorber was condensed. With this configuration no temperature difference was needed in order to perform the heat transfer to a heat transfer medium, thereby, increasing the "temperature lift" of the DEAHP.

The second prototype of the DEAHP (see Figure 1) was also manufactured by ENTROPIE and uses a

Fig. 1. Double-effect LiBr-H_2O absorption heat pump in AQUASOL plant.

water/lithium bromide solution as working fluid. It was installed in 2005 next to SOL-14 distillation unit. It has the two solution circuits connected in series. Series flow configuration offers lower thermodynamic and heat transfer performance over parallel flow configuration but requires less control complexity, mainly in transient operation [7].

In absorption heat pumps, liquid pumps are used for circulating liquid streams through heat exchangers and to convey liquid from the low pressure side to the high pressure side. The second prototype of DEAHP has three internal pumps, two of them with frequency variators in order to be able to operate with the absorption unit at different power input loads (30%–100%).

The second prototype of the DEAHP was installed as a subsystem of the AQUASOL project test facility, which includes other subsystems required to fulfill other objectives of the project. This test facility is described in the next sub-section.

3.2. AQUASOL project test facility

The experimental test reported in this paper makes use of part of AQUASOL project test facility (see Fig. 2), which mainly consists of the following systems:

- A Double-Effect (LiBr-H2O) Absorption Heat Pump (DEAHP).
- A Multi-Effect Distillation (MED) unit with 14 cells (SOL-14 plant).
- A smoke-tube gas boiler.
- A thermal storage system based on water (primary and secondary tanks), just used as auxiliary tanks for connecting both DEAHP and MED units when the gas boiler operates.

An automatic regulation valve is placed between the primary water tank (see V2 in Figure 2) and the first cell of the MED plant in order to recirculate some water coming from the first cell when the set-point temperature of the controller is below the outlet temperature of the primary water tank. A centrifugal pump with frequency variator is employed to keep constant the circulation of water inside the tube bundle of the MED first effect.

A compound parabolic concentrator (CPC) solar field 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 into 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 pressure steam from the last MED plant effect.

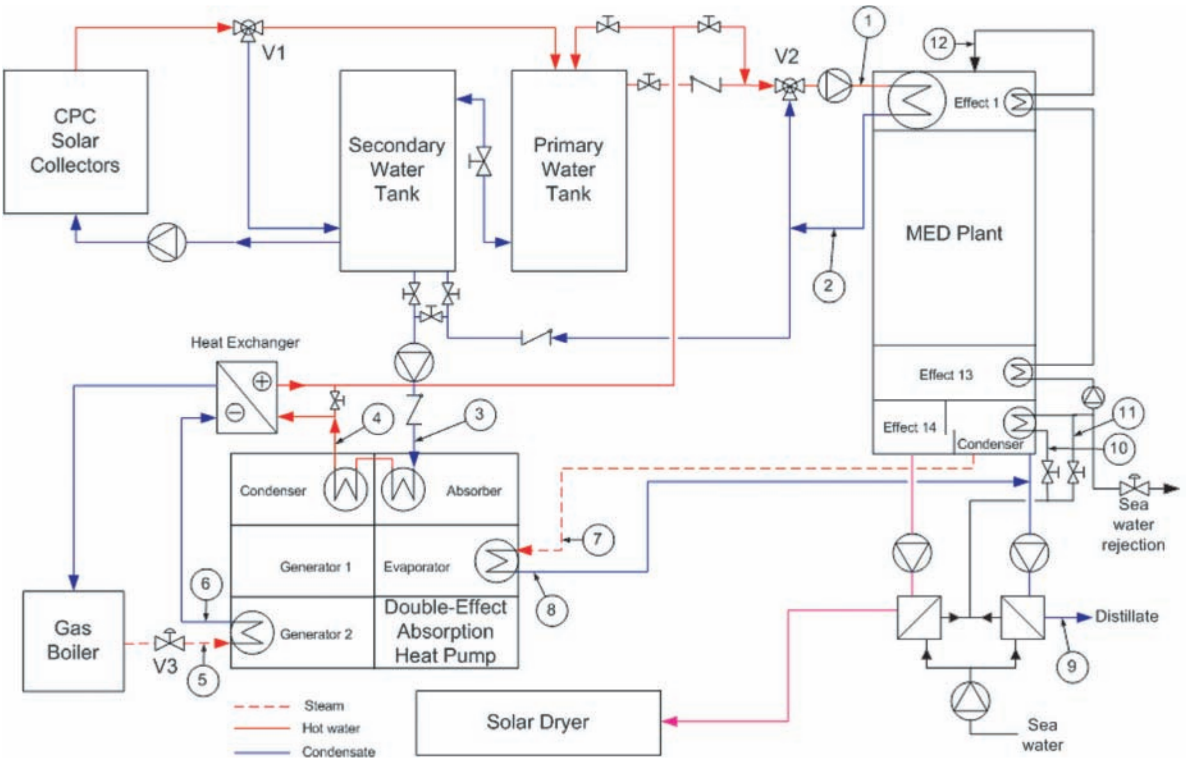

Fig. 2. Final configuration of AQUASOL seawater desalination system.

As a result, the heat pump heats the water coming from first effect of the MED unit from 63.5ºC up to 66.5ºC. In the DEAHP, condensate return flow (point 6 of Fig.2) must be cooled in order to avoid flashing, and a heat exchanger was installed for this reason, transferring the energy to the stream leaving DEAHP condenser. Main design features of the MED unit with the new first cell designed for AQUASOL project are given in Table 2.

Table 2
Modified MED unit (AQUASOL project).

	Desalination driven by solar collectors	Desalination driven by absorption heat pump
Power	200 kW	150 kW
Inlet /outlet hot water temperature	75.0 / 71.0ºC	66.5 / 63.5ºC
Brine temperature (on first cell)	68ºC	62.0ºC
Hot water flow rate	12.0 kg/s	12.0 kg/s
Pressure drop	0.4 bar	0.4 bar
Nominal plant production	3.1 m³/h	2.7 m³/h

4. Experimental results

Figure 3 presents a 35-hour continuous test within the framework of AQUASOL Project test campaign. It shows main thermal power interchanged in the system as time functions:

- Q_MED: thermal power consumption of the MED unit.
- Q_DEAHP: thermal power supplied by the DEAHP unit.
- Q_fossil: DEAHP power consumption at high pressure (180ºC, 10 bar)
- Q_solar: thermal power delivered by the solar field (CPC collectors), and the Performance Ratio (PR).

This figure shows many up and downs as a results of the unsuitable type of valve (on/off valve) installed between the low temperature generator and the condenser shell of the absorption heat pump. The test was carried out by coupling the DEAHP and the MED unit through the two auxiliary tanks (see Fig. 2), starting in June 2006.

From the initial time, it can be seen that the starting of the DEAHP took 2 hours until nominal conditions were reached and a PR around 20 was measured. Later,

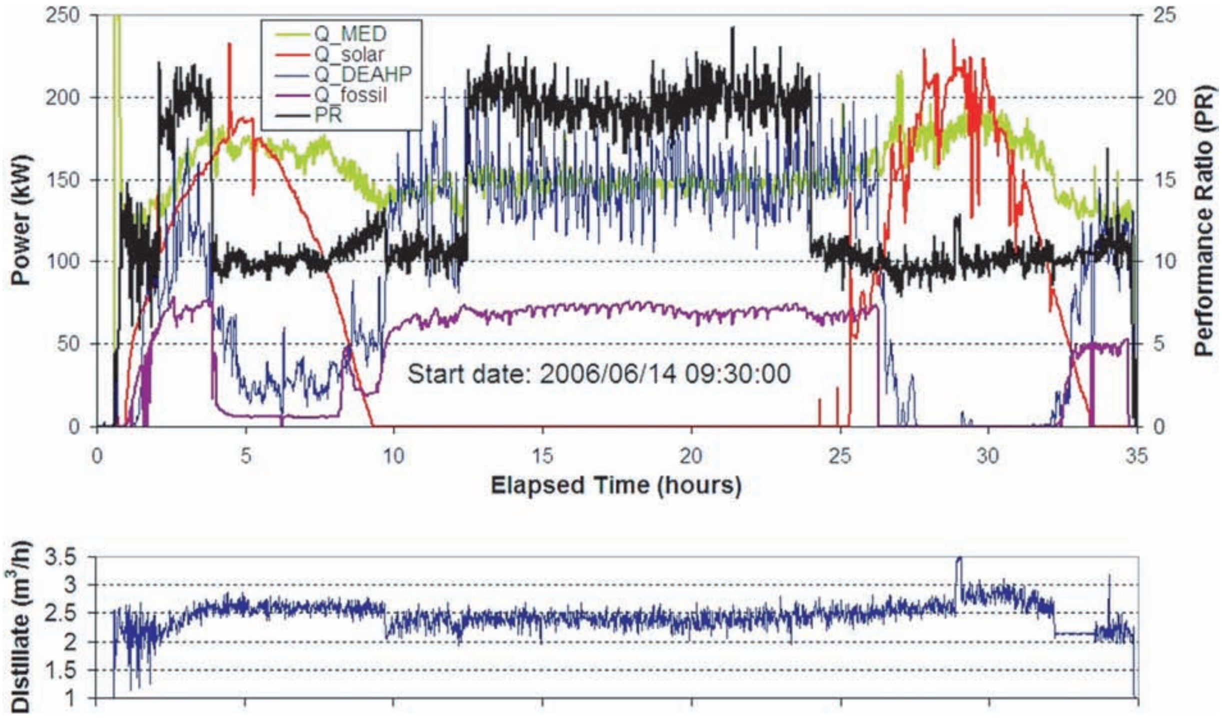

Fig. 3. A representative experimental test within the framework of AQUASOL Project.

when the solar field was able to drive the MED unit by itself, the DEAHP was operated at minimum load. Then, the MED unit was operated with higher top temperature (Stream 1 in Fig. 1) and higher thermal consumption (200 kW) was set in order to avoid damage in the DEAHP due to the high temperature within the tanks. These working conditions remained unchanged until sunset. When the solar field was not able to provide 200 kW to the MED unit, the DEAHP was gradually returned to nominal conditions, resulting and overall PR of 20. The DEAHP was operated after the sunrise, until the solar field was able again to drive the MED unit by itself. Then, the DEAHP was shut down. The next evening, DEAHP was started again and the testing period finished at hour 35. Figure 3 is analysed next.

a) Replacement of the first cell of the MED unit

The assessment of the modified MED unit was analysed from a period of time in which the DEAHP was not operated (Q_DEAHP = 0). Figure 4 shows that the modified SOL-14 plant has the same performance ratio of 10, working with hot water instead of saturated steam.

b) Trouble free operation of the DEAHP connected to the MED unit

When the DEAHP and the MED units are operated coupled by the auxiliary tanks (Figure 3, hours 20–27), both of them exhibited stationary operation and the ability of coming back to the nominal conditions after slight changes in working conditions. This operation was fully automatic and proved that the control system was suitable for such a coupling. On the other hand, the supplier did not include in the automatic control the starting and shut down procedures.

Further the start up should be completed in 30 minutes, it took more than two hours (see in Figure 3 the first two hours of the test and the period between hours 33 and 35). In both cases, even after these two hours of operation, the nominal power production of the DEAHP was not completely reached. On the other hand, the prototype exhibited good behaviour when returning to nominal load after being operated at partial load (see hours between 9 and 11 in Figure 3).

A longer time is required when the heat pump is started from scratch but good behaviour after changes in operation load is due to the increase of LiBr solution temperature required within the high temperature generator of the DEAHP. Hence, the long time required for heating the LiBr to around 150ºC (nominal conditions) results in the recommendation of avoiding daily starts.

The vacuum in the prototype was preserved even after long periods without operation (almost four months). In this aspect, the prototype has shown superior behaviour than expected.

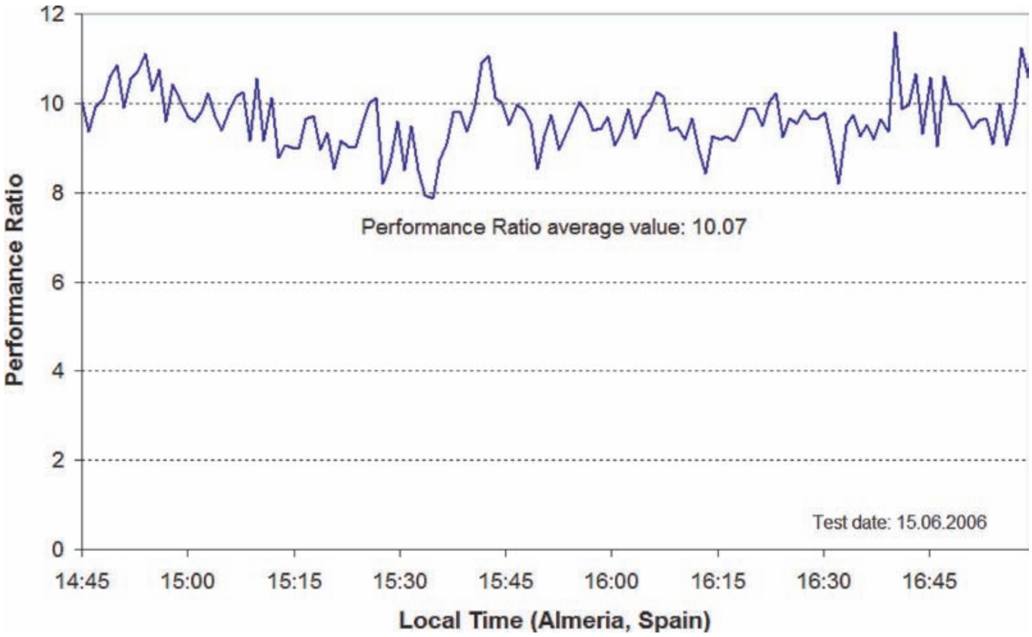

Fig. 4. Assessment of the modified MED unit (Performance Ratio).

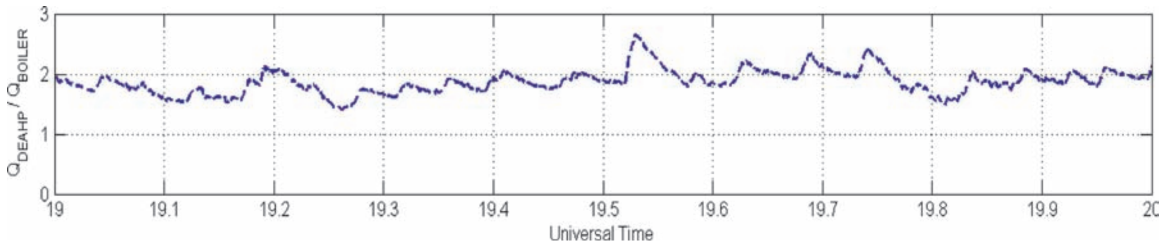

Fig. 5. Coefficient of performance (COP) of the DEAHP second prototype (date 15/11/07).

c) Performance of the second prototype of DEAHP at nominal operation conditions

In Figure 3, between hours 10 and 27 approximately, the DEAHP operates at nominal load and it can be observed that:

- Many up and downs are due to aforementioned valve installed between the outlet of the low temperature generator and the condenser shell of the DEAHP.
- The DEAHP reached its nominal production 150 kW and nominal COP (ratio between power delivered by DEAHP and power delivered by gas boiler) around 2 according to the rest of experiments carried out during the whole test campaign. Figure 5 shows an example of this performance.
- The fresh water production of the MED unit was that expected of the modified unit.

d) Discontinuous operation of the DEAHP

As it was pointed out, DEAHP showed a high thermal inertia during start up due to the heating of the working substance up to 150ºC. Then a daily start up of the absorption machine is not recommended.

5. Conclusions

The successful assessment of the second prototype of the DEAHP reported in this paper pointed out the interesting prospects of solar desalination based on multi-effect distillation coupled to absorption heat pumps.

The second prototype of DEAHP operated trouble free with nominal production (150 kW) and Coefficient of Performance (COP = 2). However, some minor changes as the valve installed between the low temperature generator and the condenser shell have been identified in order to improve the performance of the system.

When the DEAHP and the MED unit were operated connected by auxiliary tanks, both of them exhibited stable and fully automatic operation. The performance ratio of the system DEAHP–MED as a whole is 20.

It is highly recommended to use DEAHP in solar desalination systems with conventional energy backup in order to avoid discontinuous operation of the absorption unit.

To sum up, the reliability of the technology of connecting a DEAHP to a MED unit has been proved by means of AQUASOL test facilities installed at the Plataforma Solar de Almería (PSA, Spain). This technology exhibits an overall performance ratio of 20 with stable and fully automatic operation and requires a saturated steam supply at 180ºC. It could be provided by solar linear concentrators as it was demonstrated with the first pilot facility of the PSA. The solar collector area used for driving the DEAHP-MED plant would be one half of that required for driving the single MED unit. Then, the cost of precommercial DEAHP units for desalination purposes should be compensated by this significant reduction of the solar field.

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