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Experience gained through the implementation and operation of a solar humidification–dehumidification desalination plant

E. Mathioulakis*, G. Panaras, V. Belessiotis

Solar & Other Energy Systems Laboratory, NCSR ''DEMOKRITOS'', 15310, Agia Paraskevi Attikis, Greece
Tel. +302106503810; Fax +302106544592; e-mail address: math@ipta.demokritos.gr

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ABSTRACT

The proposed work aims at evaluating the experience gained by the design, implementation and operation of a pilot solar thermal desalination plant installed in the Geroskipou municipality, Cyprus, based on the humidification-dehumidification technology. The design of the plant enables the direct use of the heat produced by the solar thermal system in periods of low water demand. The working principle and the technological solutions adopted for the specific application are presented. The various technical problems encountered during the installation and operation of the unit are discussed. Finally, the critical parameters which affect the performance of the desalination unit and the techno-economical sustainability of the installation as a whole are analysed.

Keywords: Solar thermal desalination; Humidification-dehumidification; Autonomous systems

1. Introduction

For many areas desalination using renewable energy sources is becoming a realistic alternative solution. Not only is solar energy abundant in places having problems with the availability of fresh water, but also fresh water demand and solar radiation follow a similar time pattern. In isolated areas with unreliable or no connection to the water and energy networks and often characterized by aridity, negative hydrological balance and abundance of saline or brackish water, small scale solar desalination installations can be a promising option.

Solar thermal desalination technologies, can often use rather simple technological solutions, where installation and maintenance can be done locally and there is, in most cases, a strong solar thermal industry. However, experience with such installations is extremely limited. One of the reasons for the absence of experience is the fact that there are no available standardized commercial desalination units, with specifically defined characteristics and adequate technical support. The opposite can be stated for the solar part of these installations, as there are available commercial products, sufficient documentation and significant experience on their installation and operation. In order for small autonomous desalination systems to present a realistic and sustainable solution for the discussed areas, adequate solutions for the problems of high installation cost, as well as the lack of reliability and maintenance are necessary. It is also important to mention the absence of standardized and explicit information as regards the characteristics and the performance of the desalination unit. The relevant information, although necessary for the proper design of such an installation, is usually inadequate or inexplicit. As a

*Corresponding author

consequence, specific uncertainties do exist as regards the determination of the techno-economic prospects as well as the sustainability of such an installation in due time (quality and resistance of materials). These problems are the main cause for the lack of confidence of potential users towards these technologies [1,2].

Low capacity solar desalination installations, solar stills, have been based on the use of simple distillation systems of the greenhouse type. The demand for the improvement of performance of these systems has led to more elaborate technological solutions, as the multistage solar stills, the humidification-dehumidification (HD) and membrane distillation [2].

The humidification-dehumidification desalination concept has been developed in order to solve the basic problem of the single solar still, namely the high latent heat losses to the environment due to the condensation of evaporated water at the transparent cover. The HD principle of operation is based on the evaporation of saline water in one part of the desalination unit, that is the evaporator, and the condensation of produced vapor in another part, that is the condenser. Despite the various alternative configurations the discussed concept might present, in the most common version the process takes place within a unified space, where continuous natural circulation of the humid air under atmospheric pressure takes place (Fig. 1) [3].

The hot saline water entering the evaporator, comes in contact with the air of the enclosure, thus providing the air with heat and humidity. The air of the enclosure comes into contact with the condenser where it releases part of its humidity in the form of desalted distillate, while at the same time it preheats the saline water which flows in the interior of the condenser. The preheated saline water is further heated by solar energy,

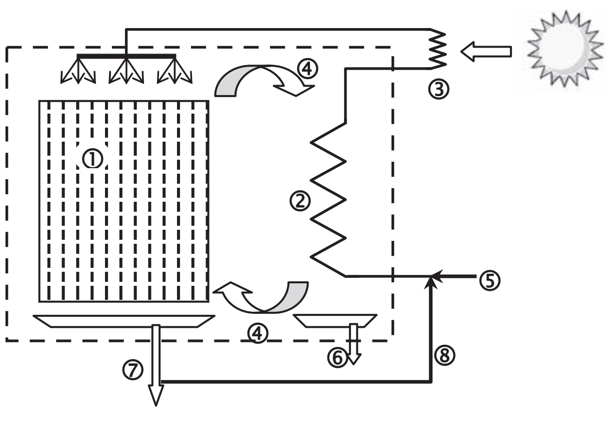

Fig. 1. Diagram of a HD unit: ① evaporation area, ② condensation area, ③ heat source (from the solar system) ④ natural circulation of air ⑤ supply in fresh water, ⑥ distillate, ⑦ brine, ⑧ brine recirculation.

through the use of a heat exchanger, in order to increase the temperature of saline water and, consequently, the evaporation rate. Amongst the parameters affecting the HD process, the maximization of the evaporation surface through the use of appropriate filling material on the evaporator, enabling the wetting of the surface, the maximization of the heat exchanger-condenser external surface, as well as the recirculation of part of the outcoming brine in order to decrease the saline water consumption, can be considered to be of high importance [3,4].

Since the 60s, when the first prototype pilot plants appeared, there have been several attempts aiming at improving the performance of the whole process. Measurements in prototype systems have demonstrated that the expected water production can reach production rates as high as 12 $lm^{-2}d^{-1}$, which is about twice the production of the classical solar still [5].

Nevertheless, and despite the significant number of research works and demonstration actions concerning HD systems, the implementation on an actual scale of this technology has not been feasible until recently, due to the lack of standardized, appropriately tested and ready for installation commercial products. The systematic investigation of the performance and the optimization of the design of a compact unit can be considered as a critical step for the wider penetration of this technology.

For this reason, it has been decided to include the assessment of the HD technology within the scope of the Euro-Mediterranean Co-operation Program ADIRA [6] which is aimed at the implementation and evaluation of the operation of small scale desalination systems in real operation.

The scope of this work is to summarise the experience gained by the implementation and operation of a solar HD desalination unit. It should be noted that this is the first attempt to implement an independent, third party evaluation of such a product in actual working conditions. The results of an independent evaluation can be considered significant for the potential users of this technology, as experience has shown that there are often remarkable deviations between the theoretical expectations and the actual behaviour of the real scale desalination installations, especially for low capacity systems.

2. The desalination system

A small solar desalination unit, with a nominal production of 1,000 l/d, was built in the Municipality of Geroskipou, Cyprus. Obviously, given the low production capacity of the system, the scope of the installation was not to contribute significantly to the hydrological balance of the municipality, but to evaluate in practice all the issues relevant to the implementation of a small autonomous desalination unit with the use of solar thermal energy. The existence of permanent stresses to the hydrological balance of Cyprus, the high solar potential of the selected site, and its proximity to the sea, favor a realistic assessment of the technology.

Choice of location depends on the availability of the required surface for the solar field installation. The system was thus installed at the Olympic Swimming Centre of the Municipality. The availability of space is considered to be an important issue, especially in coastal areas characterized by intense touristic activity. The selection of the specific place is also related to the capability of the system to operate on a hybrid mode where the solar energy can be used in winter for heating of the swimming pool and in summer when water demand is high for desalination. As the major cost of such an installation is that of the solar system, the operation on a hybrid mode favors the economics of the related investment, the critical aspect for small scale desalination systems powered by renewable energy [7].

Given the lack of information concerning the actual performance of HD technology and the limited availability of standardized data for the energy requirements of the specific system by the manufacturers, the design of the solar part of respective desalination systems is an approximation. The most characteristic example refers to the figure of the nominal efficiency of the desalination unit provided by the manufacturer, as the conditions for this figure to be valid, mainly the ambient temperature and saline water supply temperature, are not defined.

Regarding the specific system, the design has resulted as a compromise between the intention to achieve a high degree of autonomy for the system, the availability of the surface for the installation of the collectors, the nominal consumption of the desalination unit, as well as the budget limitations of the ADIRA Project. It must be noted that the selection of the solar collectors is not strictly dependent on their efficiency, as a potential lower efficiency can be compensated by a larger surface for the solar field.

Another important parameter is the selection of local suppliers (according to the rules of the ADIRA Project), and it contributes to the achievement of a higher degree of sustainability for the installation. Nevertheless the selection of a local partner has not been feasible for the desalination unit, as only one potential supplier of a commercial available product has been found.

Thus, the basic characteristics of the system which has been finally installed, according to the respective suppliers, are the following:

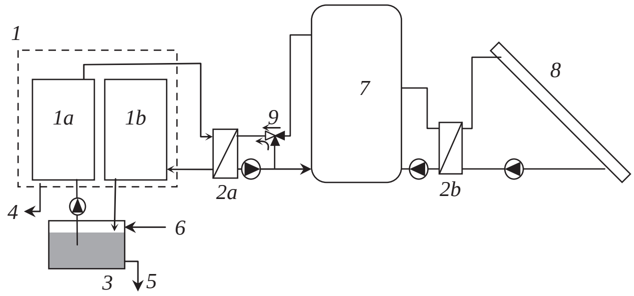

Fig. 2. Solar HD desalination system diagram, 1: HD unit, 1a: condenser, 1b: evaporator, 2: heat exchangers, 3: brine collection tank, 4: produced distillate, 5: brine disposal, 6: supply of saline water, 7: solar tank, 8: solar field, 9: mixing valve.

2.1. Desalination Unit HD [8]

- Supplier: TiNox – MAGE Water Management (Germany).
- Main unit dimensions: 1.08 m × 2.37 m × 2.70 m.
- Total weight 480 kg (during operation 650 kg).
- Minimum saline water supply flow rate 0.5 m^3/h.
- Saline or brackish supply water of maximum salinity TDS 100,000 ppm (maximum conductivity 120,000 μS/cm).
- Required nominal thermal power: 4.5 kW on a temperature of 85°C.
- Required nominal electrical power: 200 W (230 V AC, 50/60 Hz).
- Nominal production of fresh water: 1,000 l/d.

2.2. Solar thermal system

- Supplier: KAFSON LTD (Geroskipou, Cyprus).
- Solar collector field: 48 collectors of total surface 96 m^2.
- Collector's type: flat plate, selective coated.
- Solar tank of 5 m^3 volume.
- Plate heat exchanger of nominal power 70 kW.

A schematic diagram of the system is presented in Fig. 2.

During the operation of the desalination unit, the brine recirculates continuously through the condenser, the heat exchanger and the evaporator. More specifically, as it comes out from the brine collection tank it enters the condenser, where it is preheated by recovered condensation heat. It is further heated at the heat exchanger and finally it is forced to the evaporator where part of the water is evaporated. The vapor produced occupies the interior space of the desalination unit, comes in contact with the colder condenser surface where it is condensed. The remaining part of the brine comes out of the evaporator, it is mixed in the brine collection tank with additional quantity of saline water.

The addition of saline water is discontinuous and is accompanied by the partial disposal of the brine from the collection tank. This operation aims not only at compensating for the quantity of the evaporated water, but also at ensuring that the salinity and the temperature in the brine collection tank remain at acceptable levels. Especially for the brine entering the condenser, an uncontrollable increase of its temperature would have a negative impact on the condensation rate and consequently to the distillate production. The discontinuous operation of the saline water addition and of the brine disposal are controlled by a programmable controller. The controller settings are selected by the user, aiming at a reasonable compromise between the achievement of high production rates and the excessive consumption of saline water.

The same controller is the one which regulates the temperature of the solar heat supply, ensuring that it does not exceed 85°C, as well as it remains higher than the appropriate value for the operation of the unit. The control of the maximum level of the supply heat temperature aims at protecting the materials of the system from overheating and at avoiding the deposition of salts on the secondary circuit of the heat exchanger.

The operation of the desalination system requires the implementation of some other auxiliary processes, as that of the saline water supply and of the post treatment of the distillate. Even though the cost of these processes for large industrial type desalination systems is rather low if compared to the total investment, and these processes can be characterized as trivial, this is not the case for small systems. In fact, for small scale systems the arrangements have to be the simplest possible, and techno-economically compatible with the total investment. Given that the respective bibliography is rather poor on this issue, and there is lack of sufficient experience and of ready-to-implement solutions, for the present installation emphasis has been paid to the elaboration of simple and efficient solutions, especially as regards the simple technical work which has been implemented for the sea water supply.

More specifically, for the post-treatment of the produced distillate, the solution of mixing distillate water with saline water is adopted. The mixing is performed with the use of a dosimetric pump, on an analogy 150:1, and the product is subsequently sterilized through the use of a UV lamp. This solution can be considered as acceptable for most cases, noting that for the case studied in this work the produced water would be mixed with water from the irrigation network.

For the supply of saline water, the solution of sea water pumping has been selected. The investigation

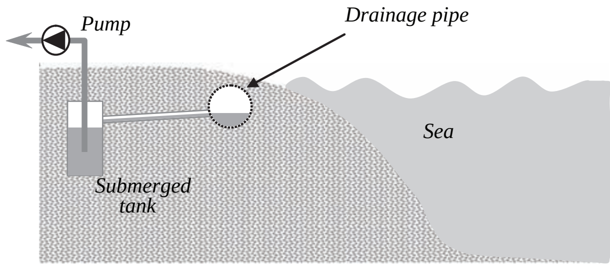

Fig. 3. Sea water collection system.

of this solution, although it presents some technical difficulties, it has been preferred as this can be the only option in cases where other saline water sources, e.g. brackish water, are not available. More specifically, a drainage pipe has been submerged (Fig. 3) on the same level, on a parallel direction and at a short distance from the seashore. The pipe is perforated, it presents sealed tailpieces and is embraced by geotextile. The aim is to collect sea water which is relatively clear, due to the filtering taking place through the sand layer surrounding the geotextile. The collected water by the pipe flows gravitationally into a collection tank, placed on a lower level with regard to the drainage pipe. The water is pumped from the tank to the desalination unit through the operation of a pump compatible with the sea water environment.

For the monitoring and recording of the most important parameters describing the system operation, a data logging system has been installed. The collected data can be remotely monitored through the use of a GSM modem. The recorded quantities concern the solar radiation, ambient temperature, solar tank temperature, temperature and thermal power of hot water supplied to the unit, and last, but most important, the produced distillate water quantity. The direct measurement of the produced distillate presents some difficulties as the negligible flow pressure at the outlet of the desalination unit does not allow the use of flow meters with moving parts. In addition, neither the use of electromagnetic flowmeters is effective, due to the absence of minerals in the distillate. For this reason, the solution of collecting the distillate in a small tank of 100 lt has been preferred. The periodical discharge of the tank each time the tank is full, is recorded by the monitoring system.

3. Experience gained from the implementation and operation of the system

3.1. Reliability aspects

It is commonly accepted that reliability problems are often the main cause of sustainability problems of small autonomous desalination systems, especially for promising technologies in the beginning of their implementation. For this reason special attention has to be paid to the assessment of the operation of such systems in terms of reliability and durability as well as to the elaboration of appropriate solutions. Within this framework, the evaluation of the overall performance of the systems installed, including the reliability aspects, was set as one of the main targets of the ADIRA project.

Regarding the specific installation discussed in this work, it should be pointed out that this has been one of the first attempts to implement the HD technology by using a commercially available desalination unit. Moreover, the specific product is considered new in the market.

The operation of the system can be considered satisfactory, especially after fixing of some minor problems which have been detected during the first period of the system operation. More specifically, by the beginning of the operation of the system, some problems, relevant to the fluid flow (leakages, pipe blocking) have appeared. A major reason for the presence of these problems can be the extensive use of pipes and connection components from polyethylene. The use of this material in desalination applications presents some evident advantages, such as its resistance in temperature and corrosion, as well as the simple assembly and its compatibility with potable water. On the other hand, the welding of various parts is a rather demanding process, especially when the target is to ensure tightness of the connections and unobstructed flow.

Even if this kind of problems can at first glance be considered of minor importance, it should be noted that their existence can significantly affect the performance as well as the quality of the produced water. For this reason, the implementation of systematic tests before the delivery is of high importance, noting that these tests have to consider the extreme conditions which would occur during the actual operation of the unit.

Another category of problems is related to the presence of high temperatures in the operation of the unit. Even if such problems have not appeared during the operation of the specific system, they could potentially affect the unit performance on a long term. The requirement to operate the heat exchanger, which is used to supply the desalination unit with heat, with temperatures of the order of 85°C, leads to the requirement of even higher temperatures in the solar system. Thus, special care has to be taken during the selection of the materials for the solar part (collectors, piping, insulation and tank), ensuring that the long-term exposure in the above mentioned temperatures, would not affect the sustainability of the installation.

3.2. System performance

The evaluation of the desalination unit performance with regard to the predicted values by the manufacturer, has to overcome the objective difficulty related to the absence of a commonly accepted standardized methodology for the evaluation of the performance of desalination systems. Especially in the case of the HD technology, such a methodology would have to consider not only the temperature and flow rate of the supplying heat, but other parameters as well, like the ambient temperature, the saline water temperature and the adopted control strategy for the brine disposal. These parameters are not included in the standardized characteristics provided by the manufacturer of the specific unit.

Moreover, the performance of the desalination unit is highly dependent on the materials used in some critical locations inside the unit, so the standardization of the unit has to include precise specifications for these materials. From this point of view, the material used in the evaporator has been proven critical for the performance of the system.

The desalination system has operated for two consequent years, until today. As it has been mentioned, the decrease of the demand for fresh water during the winter period coincides with the increase of the demand for heat, according to the needs of the sporting center. It was, thus, decided to operate the system in the desalination mode only during the summer period. For the remaining period of the year, and more specifically for the period between October and April, the desalination unit was not in operation and the solar heat was used for the covering of the hot water needs of the swimming center. Focusing on the operation of the system in the desalination mode, it is noted that even though the system was permanently switched on, it produced fresh water only when the solar field enabled the existence of the required temperature level in the solar tank. During the days the solar radiation was rather low, the operation of the desalination unit was intermittent, while during the sunny days the operation could be continuous, even for many consequent days.

In Fig. 4, the values of the basic quantities which characterize the operation of the system during a typical summer operation day are presented. The discontinuity in the fresh water production, Md, can be attributed to the fact that the distilled water is directed through natural flow to a collection tank, which is evacuated by the time it is full. Thus, every peak in the curve of Md represents an evacuation of the tank, in other words a specific quantity of produced fresh water.

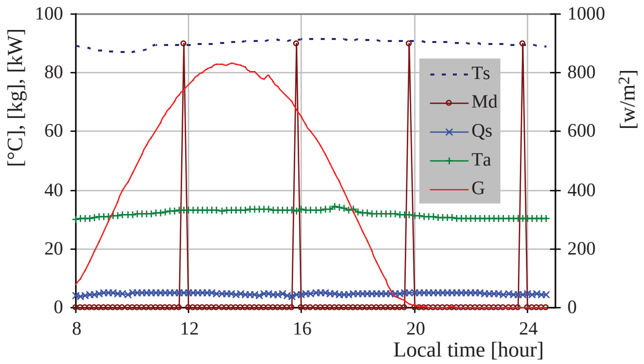

Fig. 4. Typical day of system operation (T_a: ambient temperature [°C], T_s: hot water supply temperature [°C], *Md*: fresh water production [kg], *Qs*: heat power [kW], *G*: solar radiation [W m^{-2}]).

It should be noted that the temperature *Ts* is measured at the upper part of the solar tank, and that the control system ensures, through the use of the mixing valve (position 9 in Fig. 2), that the temperature of hot water at the inlet of the desalination unit heat exchanger heat supply remains below a specific value. If the quantity of heat stored in the tank is adequate, the desalination unit continues to produce fresh water during the night period as well.

The experience gained by the operation of the desalination unit up to now, leads to the following general conclusions:

The control system of the HD unit, and consequently the user of the installation, presents the capability to regulate the temperature for which heat is supplied to the desalination unit, as well as to regulate the criteria for the control of the brine disposal. In practice, given that the regulation of temperatures in the supply heat exchanger concerns the avoidance of temperatures higher than 85°C, the only intervention to the operation of the unit concerns the brine disposal (position 5 in Figure 2). Even though it has been decided initially to operate the disposal in prescribed frequency, this solution has been abandoned as it leads to a potential waste of saline water, especially in periods of low sunshine. A more realistic approach, which has finally been adopted, concerns the brine tank evacuation (and its subsequent filling by saline water), when the temperature exceeds a prescribed limit, e.g. 40°C. A higher value for this limit, leads to a higher temperature in the condenser, and therefore lower productivity of the system. On the contrary, a lower evacuation temperature limit, would lead to higher productivity but higher saline water consumption as well.

A crucial parameter for the improvement of the efficiency of the desalination unit is that of the return temperature of brine to the condenser. The decrease of this temperature accelerates the condensation rate, increases the productivity of the desalination unit and decreases the sea water consumption, even if it presents the disadvantage of higher energy consumption. The decrease can be achieved through the installation of an appropriate device (e.g. cooling tower) between the brine tank and the condenser (positions 1a and 3 in Fig. 2). In any case, the final choice has to be the result of a compromise between the increase of the productivity and the reduction of the energy consumption.

As results from the data which have been collected during the operation of the system in the desalination mode, noting that a representative sample of these data is presented in Fig. 4, a value on the order of 600 lt/d can be attributed to the fresh water production rate. As pointed out above, it is not easy to compare the measured efficiency of the system with that expected due to the absence of standardized evaluation procedures of the performance of relevant systems. A basic element of such a procedure has to be the determination of the evaluation conditions, including the ambient temperature and the temperature of the saline water before entering the desalination unit.

As regards the solar system, the use of efficient collectors is required, taking into account the demand for rather high temperature at the inlet of the heat exchanger (positions 2a in Fig. 2). A decrease in the efficiency of the selected collector has to be compensated by an increase of the surface of the installed solar field. In any case, the system design has to consider the heat demand of the system, the temperature level at which the heat has to be provided to the desalination unit, the surface available for the installation of the solar field and, of course, the cost of one or the other choice.

4. Cost data

The total cost of the solar desalination system, excluding the equipment for the supply of sea water, as well as the measuring equipment, is about 38,000€ (year 2008 prices). It is evident that even if the maximum daily production of 1,000 l/d proposed by the manufacturer is achieved, the cost of the produced water is rather high, also depending on the actual climatic conditions of the installation location.

The investigation performed through the use of the AUDESSY software [6], has provided a cost of the order of 16 €/m^3 for the specific installation. The specific software has been developed within the framework of the ADIRA Project and it is suitable for the cost evaluation of desalination systems.

This cost, is comparable to the cost of other low capacity desalination systems driven by RES. Moreover, it can be significantly reduced if the operation of the system is examined within the hybrid mode framework. As already mentioned, in this mode the heat which is produced by the specific solar system can be used for the heating of the swimming pool. Thus, the cost of the solar system, which comprises the most expensive part of the installation, can be depreciated by the saved conventional fuel. This configuration would strongly affect the actual cost of the produced water, the final value being a function of the time distribution between the referred operation modes.

5. Conclusions

This solar HD system is the first commercial system installed and set in operation under actual conditions, and assessed by a third party. It has demonstrated the potential as well as the weaknesses of the technology. Positive characteristics are the technological simplicity of the process, the exploitation of local resources – especially for the solar part of the plant – and the improvement of the profitability of the investment through the exploitation of the produced heat for other uses in periods of low water demand. Weaknesses are the absence of choices for ready to install products, the lack of an adequate standardization level of the system performance, and the rather poor experience related to the operation of these systems under actual conditions.

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