

Stand Alone Multiple Trough Solar Desalination with Heat Storage

Abderrahmane Diaf, Kamel Benabdellaziz

Abstract—Remote arid areas of the vast expanses of the African deserts hold huge subterranean reserves of brackish water resources waiting for economic development. This work presents design guidelines as well as initial performance data of new autonomous solar desalination equipment which could help local communities produce their own fresh water using solar energy only and, why not, contribute to transforming desert lands into lush gardens. The output of solar distillation equipments are typically low and in the range of 3 l/m²/day on the average. This new design with an integrated, water based, environmentally-friendly solar heat storage system produced 5 l/m²/day in early spring weather. Equipment output during summer exceeded 9 liters per m² per day.

Keywords—Multiple trough distillation, solar desalination, solar distillation with heat storage, water based heat storage system.

I. INTRODUCTION

THE advent of rapid economic development and the resulting improvements of the standards of living on a global scale exerted considerable stress on natural resources and in some geographic locations caused disruption of the supply and demand state of equilibrium. Without action, more stress on water is expected in that within the next 15 years, the Gross National Product (GDP) of a number of African nations is forecasted to reach and/ be close to one trillion Dollars. The availability of fresh water or its lack there off is one such huge geopolitical challenge facing a great many countries. Running, drinkable water of acceptable health quality, often times taken for granted, is not available on a daily basis let alone the much larger volumes of water for irrigation needed for food production. Atmospheric pollution as well as the accelerated rate of carbon emissions over time contributed to global warming with its disastrous consequences on water in general.

Seawater desalination brought relief to household water supply for coastal metropolitan dwellers worldwide but there still remain painful water challenges for many land locked countries, isolated desert populations and severe shortages and/ a complete lack of irrigation water that affected nations will have to face at one point. Ironically, today's dilemma with seawater desalination plants using reverse osmosis for example, is that they demand colossal amounts of electric energy, most often coming from fossil fuel burning power

plants with all their resulting detrimental impacts on the environment and ensuing particle, pollutant and carbon atmospheric emissions. Nonetheless, water is the essence of life and there is no other way around it. Technically, there are ways to desalinate seawater or brackish water using clean, environmentally friendly energy sources but as of today there is still nervousness around cost barriers and additional process complexity. On a small scale basis, solar thermal desalination can bring relief to potable, distilled or irrigation water needs for communities established in brackish water rich or coastal regions of the African deserts of other similar areas worldwide. Real life applications started in the 19th century with an actual desalination facility in Valparaiso, Chile. The technology based on greenhouse distillation, was simple but quite ingenious for the time. The effective output per m² of the then distillation unit was 3 liters/day. The whole Valparaiso greenhouse desalination site produced at that time 22 m³ per day. Today, there are also exist small scale solar desalination installations running on clean solar thermal energy.

A lot of work and many different ideas in the published literature [1]-[6] were devoted to developing desalination systems with increased output. Solar heat storage using different devices [7]-[12] proved to be one of various effective ways to significantly improve daily output.

This paper presents one new idea that will hopefully stimulate and encourage forward looking astute ideas in the areas of clean solar thermal distillation to reach higher levels of equipment output while keeping the inherent simplicity of the technology and its environmentally friendly character.

II. EXPERIMENTAL

A. The Experimental Model

The schematic diagram of the experimental prototype developed for this work is shown in Fig. 1. The distillation model consists of three components, namely the solar heater, the heat storage tank and the condensation troughs. The evaporator is a 15 liter basin immersed in the heat storage tank for direct heating. The solar heat storage system has a capacity to hold 100 liters of water and is directly connected to the solar heater to maximize the heating efficiency. Vapor condensation at Level 1 takes place at the bottom surface of two separate 3 liter troughs spaced at 2 cm from the walls of the distillation box and from one another to allow vapors to pass through to level 2 and increase the condensation rate. The angle of inclination of the condensation surfaces is 13° for optimum size/efficiency ratio. Level 2 condensers is one single 12 liter trough. Thermal insulation of the heat storage system is ensured by 2cm thick polystyrene foam board

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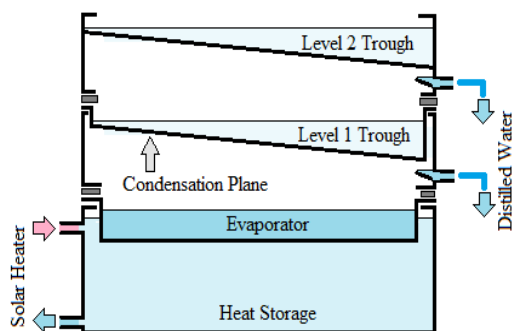


Fig. 1 Schematic diagram of the experimental prototype

B. The Process

Heat from the sun is the only source of energy that drives the process. The evaporator of the distillation unit is heated by the water of the heat storage tank which is turned heated directly by a solar heater. Vapors emanating from the heated stock water condense at the bottom surfaces of the two troughs of Level 1 and on the upper one single trough of Level 2. Heating up of Level 1 troughs from latent heat of condensation causes a temperature rise of the stock water contained in Levels 1 and 2 troughs. Vapors produced from Level 1 troughs condense just above on the bottom surface of Level 2 trough. Evaporation of stock water of Level 2 trough is lost to the surroundings.

C. Data Collection

Distilled water outputs from Levels 1 and 2 are measured separately and recorded every 24 hours. In addition, temperatures of the evaporator, Levels 1 and 2 condensation troughs are measured and recorded automatically at 195 second time intervals.

D. Quality Control

Temperatures of the evaporator, the condensation troughs, the heat storage tank as well as the ambient air are measured with thermocouples and recorded via a data acquisition system. Before use, thermocouples are checked against thermometers for reliability. Electrical conductivity σ_e is used for its simplicity as a quick means to test the quality of the produced distilled water. Reference point for good quality distilled water is for σ_e values $\leq 80 \mu\text{S/cm}$.

III. RESULTS AND DISCUSSION

The solar desalination prototype was evaluated under natural exposure conditions in the Bousmail area situated on the Southern shores of the Mediterranean Sea, more precisely in the central coastal region of the Algerian coastline. Often times with these simple models, small simple design changes can result in significant productivity improvements as will be illustrated later in this study. With that in mind and to gain information on equipment design optimization in order to maximize daily output, the model was tested in several configurations.

A. Two Level Configuration

The experimental set up for this case is identical to the one schematized in Fig. 1. The summer months of June, July and August are the sunniest and hottest month of the year for the geographical location where the equipment was tested. Under summer conditions of sunny and clear skies, equipment output reached its maximum performance at 1420 ml/day which translates into a production capacity of 9281ml/m²/day. It is important to mention at this stage that the Level 2 is mounted with a shade. The temperature of the evaporator reached a maximum of 59°C while that of the Level 2 trough was 38°C.

B. One Level Configuration

In this case the troughs constituting Level 1 are removed and the one single Level 2 trough is mounted right on top of the evaporator. Output measurements were conducted under as similar as possible weather conditions to ensure a meaningful comparison. The apparatus produced 1240 ml of distilled water per day which translates into 8105 ml/m²/day corresponding to a 15% drop in the best case scenario. The temperature of the evaporator reached 61°C with a trough condenser temperature of 41°C.

C. Effects of Heat Storage on Productivity

There are large amounts of data in the published literature that demonstrate the benefits of heat storage in its diverse forms and designs. While there is no doubt that heat storage increases daily output, it is the magnitude of the improvement that will differ from equipment to equipment according to the design features of the storage system.

Furthermore, use of environmentally friendly heat storage media could be preferable especially when trying to develop equipment that use clean renewable energy sources. Ongoing unpublished data showed that concrete as a storage medium is an effective way to boost production. In fact, production of distilled water doubled for a greenhouse effect solar distillation apparatus with an integrated concrete heat storage system compared to a similar standard greenhouse machine.

Water as a solar heat storage medium offers numerous advantages when managed properly. It presents a significant advantage in terms of equipment portability, cleanliness, cost, heat storage capacity to name just a few.

In the case of this present study, Fig. 2 shows experimental measurements of product output during the daytime corresponding to the time period of 7am to 7pm, compared to the production during the night going from 7pm to 7am of the following day. The output results showed that 2/3 of the distilled water product occurred during the daytime. Heat stored in the equipment kept production going at night but at a slower throughput rate and contributed by 1/3 to the total equipment output. The peak equipment production rate occurs in the daytime and centered about the peak of the temperature profile. For the geographical location of the case in study, it corresponds to the time period of 12 am to 6 pm.

As mentioned earlier, one of the many advantages of water-based heat storage systems is that it is possible to flush out the water used for heat storage quickly and easily for any purpose.

Consequently, an experiment was conducted to determine the effects of shutting off the heat storage system on the evaporator temperature profile and the output of the equipment at night. The effects on temperature profile are summarized in Figs. 3 and 4. First, Fig. 3 shows temperature recording over a 24 hour period from 7am to 7am of the following day. “Rect Evap” in the legend refers to unpublished work whereby the heat storage system in a 180kg slab of steel reinforced concrete. The curve is shown here for comparison purposes only. “Heat Stor Top” is the temperature of the water at the top of the heat storage tank. “Evap WHS” is the temperature of the water feedstock in the evaporator. “Cooling Top” is the temperature of the water in Level 2 trough. The graph shows the classical trend that the maximum temperature is reached in the afternoon, typically from 2:30pm to 3:30pm local time. Another important point is that, past the peak temperature, the equipment with the concrete heat storage system cools off faster than the one with the water heat storage as evidenced by the steep slope of the “Rect Evap” temperature trace.

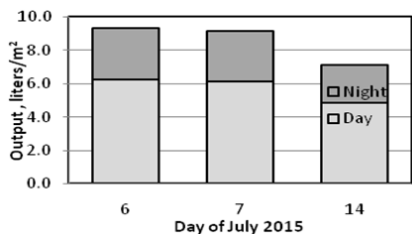


Fig. 2 Day and night output

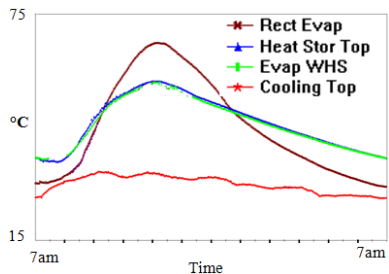


Fig. 3 Temperature profile with heat storage

On the other hand, Fig. 4 shows a similar type temperature recording with the difference that the water of the heat storage tank was flushed off at 7pm. cutting off the heat coming from the heat storage causes an abrupt fall of evaporator temperature which corresponds to the point of change of curvature on the “Evap WHS” curve. Notice also that in this case, the “Evap WHS” evaporator is cooling off faster than the “Rect Evap”. Thus, shutting off the heat storage operation caused a dramatic negative change in the temperature profile of the stock water in the evaporator which impacts directly the evaporation process and ultimately product output.

In order to quantify the output gains from the heat storage, a best case scenario was chosen and that corresponded to draining the water heat storage vessel at 7pm. These

experimental conditions give a measure of the upper limit of product output when the equipment is operated without heat storage. While the daytime output is obviously not affected, conversely, product output fell sharply to 1 liter/m² for the night whereby heat storage was not in use as shown in Fig. 5. To put these results in perspective for this case, the calculated output is 2.4 liters/m², had the heat storage tank been in operation. In the worst case scenario, whereby there is no heat storage capability other than the heat contained in the stock water of the evaporator, the nightly output of distilled water could be zero or negligible compared to the daytime output.

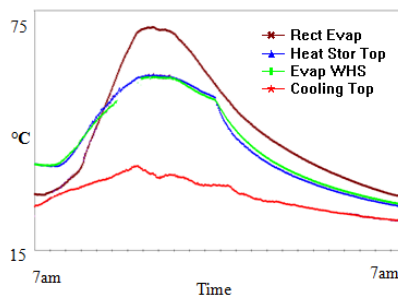


Fig. 4 Temperature profile with heat storage flush off

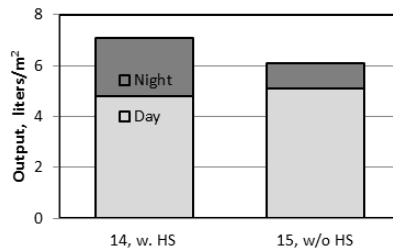


Fig. 5 Output with and without night heat storage

D. Effects of Enhancements: Shading

There are simple equipment enhancements that can produce a significant positive impact on productivity. For example, placing a shade on top of the apparatus contributed a noticeable change in output. Fig. 6 shows experimental data for comparison purposes.

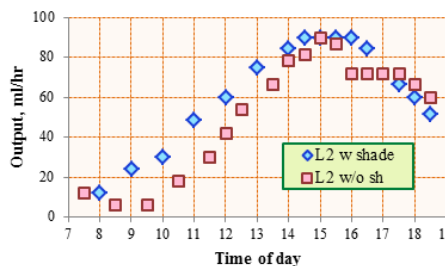


Fig. 6 Effect of shading on output

When the equipment is operated with a shade, see curve referred to as “w shade” in Fig. 7, the top level trough is shielded from the direct heat of the sun thus keeping the condensation surface cooler than the case with no shade,

referred to as “w/o shade”. The equipment produced 1420 ml of distilled water when operated with a shade compared to 1231 when operated without one. It is quite remarkable that a simple thing as a shade could actually produce a 15% output improvement.

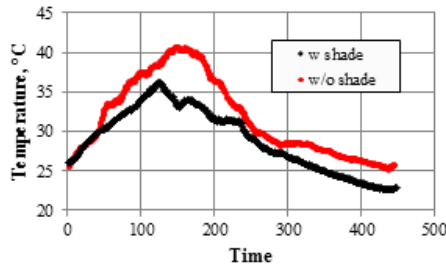


Fig. 7 Effect of shade on Level 2 trough

E. Equipment Mass Balance

First of all, the solar desalination apparatus used for this study is not airtight which implies that some amount of the vapor produced will be lost to the outside. Second, channels to collect the condensate are placed on the inclined surfaces of the condenser troughs only while the condensates on the rest of the equipment walls are lost. Therefore, many mass balance measurements covering 3 to 4 days of operation were conducted to check how much product was lost in the form of vapor and condensate. In the best case set ups, losses were about 1/3 of the equipment output of distilled water whereas in other experimental set ups, losses in potential volume of condensate were equal to collected distilled water. It is thus clear that providing ways to collect condensate from all the inside surfaces of the equipment and good sealing between components will result in a stepwise increase of output.

F. Process Phenomenology

The evaporation and condensation processes of the solar desalination prototype are governed by temperature. Previous work [13] showed that the rates of evaporation and condensation follow the Arrhenius model expressed in the general form: $X = X_0 \cdot \exp(-\Delta E/RT)$ where X is the temperature dependent rate quantity, X_0 is a constant referred to as a frequency factor in some physical phenomena, ΔE is an activation energy term, R is the gas constant and T is the absolute temperature in K. Fig. 8 shows an example of the exponential dependency of output versus temperature.

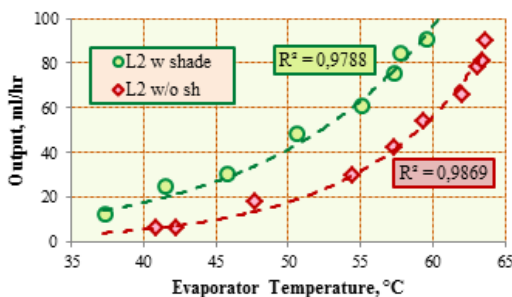


Fig. 8 Effect of temperature on output

The output data shown in Fig. 8 is the same as the data in Fig. 6 with the difference that the former is plotted as a function of time while the latter plot is against temperature. The experimental data follows the Arrhenius model as shown in Fig. 9. Naturally, the constants of the Arrhenius equation X_0 and the activation energy term ΔE can be determined easily from Fig. 9 if need be for design purposes or others. The implications of the Arrhenius process dependency is that at constant condenser temperature the output of the equipment will increase exponentially with increasing evaporator temperature. Conversely, at constant evaporator temperature, output will decrease exponentially with increasing condenser temperature. From an operational standpoint, temperatures of the evaporator and condenser are both increasing at the same time during heat up in the morning till a maximum is reached in the mid-afternoon 2:30 to 3:30pm. Then, both temperatures start going down till they reach the minimum the next morning around 7:00 to 7:30am depending on weather conditions. Thus, in accordance with the Arrhenius dependency, the evaporation and condensation phenomena act in opposite directions with respect to equipment output. From a productivity maximization viewpoint, it is critical to maintain an as low as possible condenser temperature while heating as high as possible the stock water in the evaporator which is the objective of the coming process optimization work in the near future.

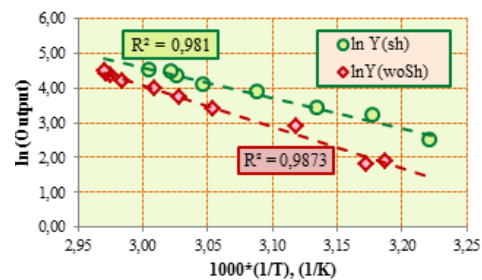


Fig. 9 Arrhenius plot of experimental data

IV. CONCLUSION

Early solar greenhouse effect standard desalination equipment produced a mere 2 to 3 liters per m^2 per day. Today, significant improvements have been achieved with new designs and incorporation of integrated heat storage systems. With this model an output exceeding 9 liters per m^2 per day has been attained via simple, environmentally friendly equipment designs using and relying totally and solely on clean renewable energy, the heat of the sun.

ACKNOWLEDGMENT

This work is financially supported by CDER/UES, Algeria. Special thanks to K. Benabdellaziz workshop team who fabricated the experimental model from scratch.

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