Solar Desalination with Heat Storage

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***Abstract*— Today, very large scale seawater desalination plants are familiar features of the landscape in many freshwater stressed nations. Seawater reverse osmosis desalination advocates claim that reverse osmosis is the most economically viable technique to satisfy ever increasing needs of freshwater in rapidly expanding cities. Planners and water resources management experts in the tropical and sub-tropical regions face situations with no other way around desalination to meet potable water demand to whatever extent possible. Although some progress has been made in improving the energy efficiency and economics of large scale desalination plants, they remain a large consumer of energy and are capital investment intensive. Conversely, on the very small scale side of desalination, renewable energy based solutions may offer flexibility and a competitive edge in terms of design, operation and economics. To that end, we have developed a solar energy driven desalination equipment with heat storage for enhanced productivity. In this study, we present design information as well as preliminary performance evaluation data.**

***Keywords*— Solar desalination, Solar distillation, Greenhouse effect distillation, Desalination with heat storage, Heat storage, Concrete heat storage, Energy storage**

I. INTRODUCTION

The large scale sea water desalination market is dominated by technology based on the principle of reverse osmosis. Essentially it is a membrane filtration technique using high pressures - 60 to 80 bars - to force water molecules trough a semi-permeable membrane thus yielding the production of fresh salt free potable water. All other molecular or atomic/colloidal species larger than the water molecule cannot, theoretically, permeate through the membrane which are thus retained in the inlet feed water. In essence reverse osmosis is a size exclusion high pressure filtration process. The high pressures needed to keep the desalination plant running are provided by large pumps that consume a lot of fossil fuel energy – a non-sustainable resource - driving up the process costs. Although improvements have been achieved in energy savings, reverse osmosis energy requirements remain a heavy cost burden to the process and an issue to the environment.

From the process standpoint of large scale water desalination, other techniques are currently in use but to a substantially lower extent than reverse osmosis. In fact; Multiple Effect Distillation (MED) and Membrane Distillation (MD) are a couple examples, as there are full size commercial sea water desalination plants built around these technologies. These techniques become economically viable when located close to power generation plants where process exhaust heat is available for recovery and re-use. Distillation based processes require a lot of heating energy and up to now, the cost per volume of fresh water produced by distillation is higher than that produced via reverse osmosis. Further technology developments in energy usage and rationalization of desalination by distillation processes may improve financials of MED or MD especially in situations where these plants are driven by recycled process exhaust heat.

The greenhouse distillation machine appeared in the 19th century and was used for the production of fresh water. On a small scale, these types of systems are a simple and flexible way to desalinate water or to produce distilled water. They are easy to build and do not require special skills for operation or maintenance in that operation of the equipment consists of filling up the evaporator and collecting distilled water, while maintenance is limited to replacing gaskets in case of occasional leaks or cleaning the evaporator on a as needed basis. The scope of our research is to develop small scale technology and equipment, based on the greenhouse effect concept, for sea or brackish water desalination to produce fresh or high quality distilled water using clean sustainable energy resources at the lowest cost. In fact the only energy input to our desalination machine is solar radiation collected as heat, stored and transferred as efficiently as possible to where it is needed for use. Desalination by greenhouse effect distillation in its simplest form has been recently studied at by a number of authors [1-3]. Because of the inherent low throughput of these solar distillation devices, other teams [4-8] investigated technologies that could improve equipment output using heat storage devices. Likewise, we are investigating the potentials of energy storage as a way to improve productivity.

The most important part of our distillation model is its heat storage component. For the purposes of cost structure/affordability, equipment robustness and ease of use we decided to investigate the capabilities of a steel reinforced concrete slab attached to the base of the evaporator as a means to store solar heat. We have also added a heat exchanger in the evaporator to speed up the heating process of the stock water with the goal of further improving the overall performance of the distillation unit. It is also the goal of this investigation to evaluate the merit and relative impacts on throughput of these two supplemental energy sources compared to traditional solar greenhouse effect heating.

II. EXPRIMENTAL

A. The apparatus

The greenhouse solar distillation apparatus is represented schematically in Figure 1 below. The footprint size of our model is 1170 mm long by 920 mm in width. The walls of the evaporator are made of 2 mm thick galvanized steel sheet for rust protection. The maximum stock water capacity of the evaporator is 54 liters corresponding to a water depth of 50 mm. The evaporator enclosure is topped with a 5 mm thick heat treated glass pane mounted at a 13° angle with respect to the horizontal.

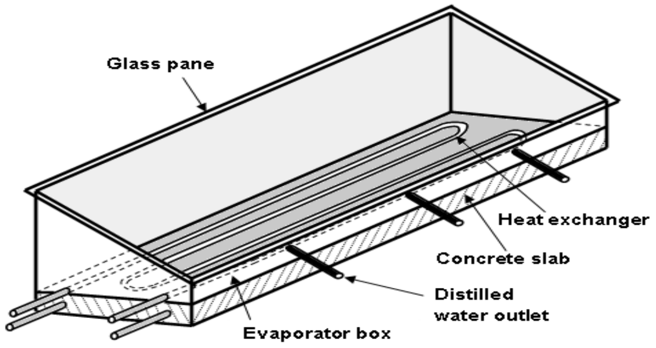

Figure 1. Experimental model.

The sidewalls of the evaporator and those of the concrete base slab are thermally insulated using 20mm thick polystyrene foam board. The exterior side walls of the distillation unit are made of 8mm thick plywood. The evaporator is equipped with a heat exchanger made of 14mm diameter copper tubing which sits at the bottom of the evaporator as shown in Figure 1. The ends of the heat exchanger are connected to a solar water heater. A schematic representation of the solar heat collector is shown in Figure 2. The solar energy storage system consists of a 70mm thick concrete slab molded onto the base of the evaporator box. Solar heat is transferred to the steel reinforced concrete slab via a tubular heat exchanger embedded inside the concrete mass and similar to the one used for the evaporator. The ends of the heat exchanger of the concrete block are connected to a second solar water heater.

Thermocouples are placed in appropriate locations to monitor and record the temperature variation during the day over a 24 hour cycle. Of special interest are temperatures of the stock water in the evaporator, the outside and inside temperatures as well as temperatures of the glass pane and concrete slab.

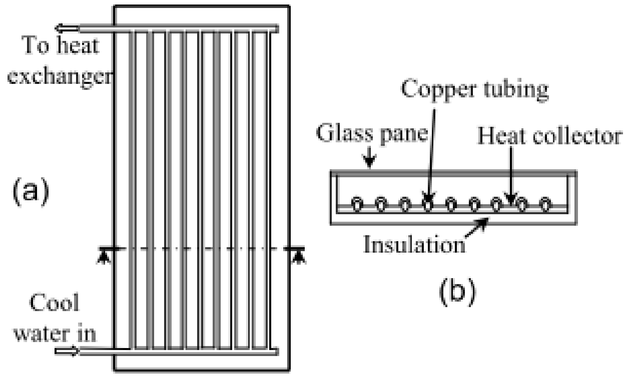

Figure 2. Solar Heat Collector: (a) Front view, (b) Cross section

B. The process

First of all, it is worthwhile to point out that the greenhouse distillation process is one of the earliest and simplest technologies devised in the 19th century to produce fresh water from salt water using the heat of the sun as the only source of energy. In principle, these types of machines use the so-called greenhouse effect to heat up the stock water in an evaporator to produce vapors which condense on a glass plate yielding fresh or distilled water. Because the output of these machines is very small it is imperative to improve their production rate to make them practically useful. Consequently, our model is equipped with a heater in the evaporator to accelerate the stock water heating process in the early morning. In addition, the base of the evaporator is physically attached over its whole surface to a heat storage system consisting of a concrete slab which is also heated using a second heat exchanger. This type of machine is suitable in particular to locations that are sunny and hot during the day then cool at night. During the daytime, our system functions as an improved version of a standard greenhouse effect desalination machine. At night, especially cool nights, the solar heat accumulated in the energy storage system is delivered to the evaporator enabling the desalination process to continue running during the night time. The size of the storage system can obviously be tailored and optimized to meet prescribed cost/performance criteria.

C. Data collection

The data collection procedure for this study consists of collecting and measuring the amount of distilled water produced at specific time intervals for defined experimental conditions or process set up. For the purpose of comparing day and night production, we record the volume of distilled water produced during the daytime that is from 7:00 in the morning to 7:00 in the afternoon. The night time production covers the time period from 7:00 pm to the next day at 7:00 in the morning. Temperature at appropriate locations are measured and recorded automatically at specified time intervals over a 24 hr time period using thermocouples and a dataloger. Of special interest to this study are temperatures inside the concrete energy storage base, the water temperature in the evaporator, the air-vapor mixture temperature inside the distillation apparatus and the outside ambient temperature. In addition we have access to meteorological data such as the sun's radiant energy, relative humidity, wind data etc on a daily basis and continuously over time. Electrical conductivity is used for quality control to ensure the equipment is functioning properly with no cross contamination. For the purpose of this study, we have established borderline electrical conductivity for our distilled water at 80 µS/cm. Thus, measured electrical conductivities lower than 80 µS/cm are indicative of a product with acceptable quality and that the equipment is running well.

III. RESULTS AND DISCUSSION

Startup trials using our solar desalination equipment were carried out at our site in Bouismail where the climate is temperate. Later on, we intend to evaluate the performance of the equipment in real life weather conditions in the Sahara desert. In this current set up, the distillation equipment is connected to 2 solar heat collectors, oriented to the south and tilted at 19° with respect to the horizontal. For this study, the inside walls of the apparatus as well as the bottom of the evaporator and heat exchanger serpentine are bare metal with no solar heat absorbing coating. Heating of the stock water in the evaporator trough is provided by three sources, namely; the greenhouse effect caused by the glass cover, a heat exchanger immersed in the stock water of the evaporator and a heat exchanger embedded in the concrete slab.

First of all and from a yield or productivity standpoint, the highest performance or maximum equipment output of distilled water reported in the literature is about 3.5 kg/m^2 per day for the most favorable weather conditions over the year for distillation units using the greenhouse effect as the only source of energy input. In our case whereby the distillation machine is equipped with a solar heat boost for the evaporator and a solar heat storage system, we have recorded outputs in excess of 4kg/m^2 during some of the sunny but typically cool days in October and November as can be seen in the data reported below. Consequently, it is expected that the output of distilled water would improve significantly in the summer, during the months starting from May to September with sunny days followed by relatively cool temperature at night.

Figure 3 shows an example of temperature profile recorded over a period of 48 hours, two consecutive days that is November 5th and 6th. The top line represents the temperature of the stock water in the evaporator whereas the bottom line corresponds to the ambient temperature. The shape and height of the peak of the water temperature variation curve depends on the sunshine conditions during the day. The solar collector/heat exchanger heating system is fairly sensitive to variations in overcast/sunshine breaks which translate to humps or changes in curvature of the temperature profile. Figure 3 is an illustration of two consecutive days with slightly different overcast/cloud conditions.

During the month of November there were some cloudier and cooler days whereby the temperature profile curve goes through a small, flattened endothermic peak as shown in Figure 4 below whereby the temperature of the stock water barely touches the 25°C line. When the weather is completely cloudy, the temperature profile is essentially flat and the output goes to zero or just several hundred milliliters at best.

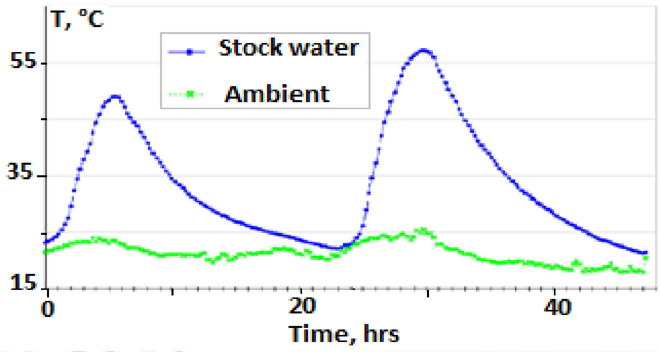

Figure 3. Temperature profiles for two partly sunny days.

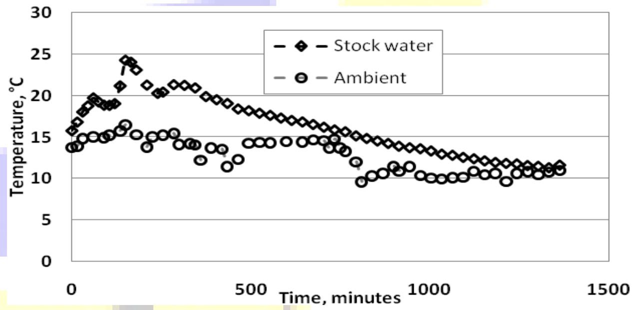

Figure 4. Example of temperature profile for cloudy day

The area under the temperature profile is an evaporation endotherm that is directly related to the amount of heat consumed by the evaporation process inside the desalination equipment. Thus, we have collected equipment output data, expressed by liters of distilled water produced and recorded the corresponding temperature profile of the stock water for a time period of several days with different sunshine/cloud conditions. Figure 5 below shows an example of yield plots as a function of the integrated surface area under the evaporation endotherm.

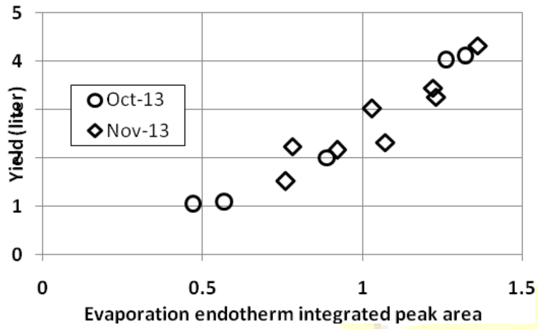

Figure 4. Daily output (ml) of distilled water VS absorbed energy.

As we have shown in our previous studies, the Arrhenius model is a good description of temperature dependent rate processes. More specifically for our case, water evaporation and condensation rates vary exponentially with temperature following the Arrhenius equation $X = X_o * \exp(-\Delta E/RT)$ where in general terms, X is the process rate, X_o is a constant, ΔE is an activation energy for the process, R is the gas constant and T is the absolute temperature. Thus evaporation rates increase exponentially with increasing temperature of the stock water with positive –endothermic- activation energy. On the other hand, condensation rates go down exponentially with increasing temperature of the condensation surface with a negative –exothermic- activation energy ΔE. From an activation energy standpoint, the trend of the data in Figure 5 is the output of two counter-acting process phenomena evaporation/condensation, an endothermic evaporation and an exothermic condensation. As a result, plots like Figure 5 yield a "flattened" exponential which is the sum of the evaporation and condensation exponential curves caused by their counter-acting dependence on temperature. An exponential curve fitting using the least squares technique for the data in Figure 5 results in a correlation factor R^2 of 0.94 which is in agreement with the proposed interpretation.

IV. Conclusions

Although our results so far cover only the fall season with cooler and cloudier weather than summer, we have shown that solar desalination using greenhouse distillation connected to a solar heater and an energy storage system is an effective way to increase output compared to the traditional units that rely solely on the greenhouse effect. There is a substantial advantage in using a solar heat storage system in that it allows the equipment to continue running at night when temperature conditions are very favorable for enhanced condensation resulting in nightly outputs better than those in the daytime. The key variables of the process are the temperatures of the stock water in evaporator as well as the condensation surface, i.e. the glass cover. Significant heat up of the glass pane during the daytime is detrimental to output. A cooler glass surface at night thus translates to significantly improved throughputs. The quality of the distilled water made with this process is good as evidenced by electrical conductivity in the range of 30 µS/cm.

Acknowledgment

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