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Solar Still with Heat Sink

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Abstract— **Desalination of ocean water via solar greenhouse effect distillation was used at the turn of the 19th century to produce fresh water on a small industrial scale. The plant was built to relieve the needs for fresh water for the residents in the vicinity of the town of Valparaiso in Chile. The average daily output of the plant was reported to be around 20 cubic meters. Literature reports indicated that the daily output per distillation unit at that time, was around 3 liters per day per square meter of evaporator surface area. Since then, solar distillation has come a long way with the advent of new materials, new technologies and innovation. From that perspective, this study presents design features of a new, stand alone solar desalination equipement with enhanced output. Further, experimental data showing the outdoor performance evaluation results are reported and discussed. The daily output of this prototype peaked at 13 liters per day per square meter in the summertime. Finally, a kinetics analysis of the process is presented.**

***Keywords*— Distillation, Solar Desalination, Heat Storage, Desalination, Solar Distillation**

I. Introduction

The Algerian Sahara desert conceals enormous volumes of brackish water resources beneath the vast expanses of its scorching arid lands, an invaluable treasure, for now on standby to be hopefully harnessed to its fullest and diverse potentials by future generations. Beneath the searing heat of the desert surface, there are also regions that are characterized by holding reserves of underground fresh water such as the Adrar region as epitomized by the "foggara", a local ingenious water distribution network throughout the town, known to the indigenous tribes for ages. These networks of subterranean channels were also known and constructed in other areas of the greater Sahara desert spanning across many nations and cultures over lifetimes covering hundreds of years. The water flowed in constructed underground conduits to storage/hold ponds then distributed to individual farms or gardens in a systematic rational irrigation program conceived and managed by locals for a fair resource utilization for all with no waste. Communities, tribes and cultures thrived and flourished around fresh water spots in the desert. With the availability of fresh water in sufficient quantities, desert agriculture soon transformed a barren arid area into a fertile oasis with beautiful gardens and mansions. As time passed and up to the present time, population growth and higher standards of living demanded more and more of the most precious resource in the desert, which is fresh water. As a consequence, excessive stress was exerted on the "foggaras" which led to their unfortunate demise, in some areas. With the advent of new advanced desalination technologies using clean renewable energies, it is thus natural to envision the use of the radiant energy of the sun to produce fresh/distilled water from the brackish water aquifers. This sort of endeavor has been accomplished successfully at the end of the 19th century with the start up of the first seawater solar desalination plant in the world with a daily capacity of about 22 m3 to provide the city of Valparaiso, Chile with fresh water. The low output of solar desalination equipments that use the distillation process is a major drawback for commercial scale up. The solar distillation concept, for the most part, consists in actuality of an evaporation/condensation operation whereby seawater or brackish water is heated to an as high temperature as possible using the radiation of the sun to produce water vapor which is then made to condense on a relatively cooler surface. Many different approaches were investigated and reported in the literature [1]-[12] with the primary goal of finding ways to increase the daily output of solar desalination devices. To that end, this work is an experimental study of a new type of autonomous, stand alone, 100% solar, distillation equipment that achieved a maximum output of 13 liters per day per square meter of evaporator surface area.

II. Experimental

The design details of the experimental prototype are presented in Fig. 1. The footprint surface of the evaporator is 0.5 m2. Number 1 in Fig. 1 represents the heat storage tank. The volumetric holding capacity of the hot water storage vessel is 150 liters. Because of its physico-chemical properties, water was selected as the heat storage medium and thus the prototype was designed to operate with water as the calorific fluid for heating simultaneouisly the evaporator and the water in the heat storage enclosure. For enhanced heating power, the heat storage tank is heated directly by two solar heat collectors. The arrow referred to as 4 in figure 1 shows the inlet to the heat storage tank of hot water from the solar heat collector, whereas arrow number 5 shows the flow of relatively cooler water from the bottom of the heat storage tank going into the solar heat collector. Circulation of the heating water occurs in a closed loop configuration and driven naturally by the naturel phenomenon of the thermo siphon without the need for any pumping of flow mechanisation. The evaporation pan, shown in Fig. 1 with label '2', sits right on top of the heat storage tank.

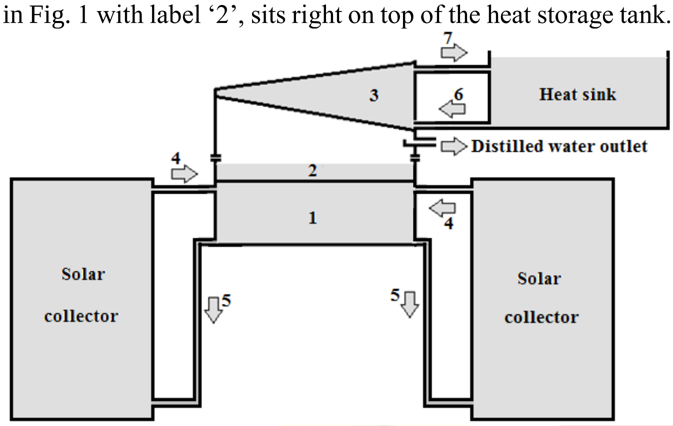

Fig. 1 A simplified schematic drawing of the experimental prototype

The maximum volumetric capacity of the evaporation pan is 35 liters. The condenser, shown in the figure as number 3 is shaped as a prism and holds 65 liters of cooling water. The condensation surface is inclined at an angle of 13° which was found in previous works [13] to be optimum. The condensation unit, number 3, is connected to a heat sink which is a 150 liter open top water tank. The cooling loop is designed to function autonomously as it is also driven by the thermo siphon phenomenon. The latent heat released by the condensation of water vapor is transferred to the heat sink as a result of cool water movement into the condenser, arrow 6, and warm water flowing out of the condenser, arrow 7 into the heat sink. The goal is to keep the condensation surface at the lowest possible temperature to boost production. The condensed water flows down the inclined condensation surface into a collection channel and out of the distillation unit through exit labelled 'Distilled water outlet'. Type K thermocouples and a data logger were used to measure and record temperature at relevant points in the distillation unit. The time interval between temperature scans was set at three or five minutes depending on data requirement needs. Temperature recordings were collected daily over a 24 hour period of operation. The volume of distilled water output was measured and recorded on a daily basis, along with the corresponding temperature profiles of the evaporator and condenser, except for week-ends. Electrical conductivity measurements were used as a simple and quick means for checking the quality of the distilled water. Electrical conductivity checks were performed on a daily basis as a quality control test.

III. Results and Discussion

A. *Temperature Profile*

An example of a temperature profile raw data plot is presented in Fig. 2.

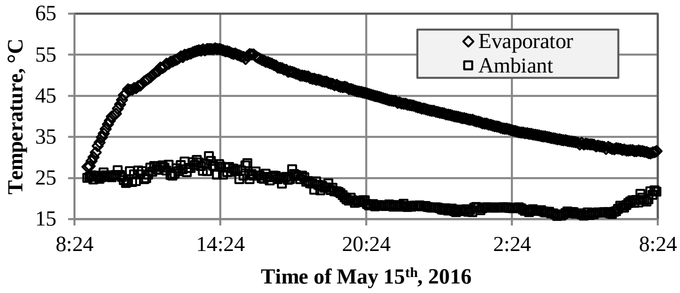

Fig. 2 Example of temperature profile

The diagram shows that the heating system enters into operation in the morning soon after sunlight hits the solar collectors. The temperature of the evaporator reached a maximum in the afternoon at 2:30 then gradually decreased for the rest of the day as the sun moved down to sunset, through the night and until the next day when the sun was up again, thus closing a heat/cool cycle. The heating system is quite sensitive to sunshine conditions, such as for example an overcast, as can be seen in figure 2 as a little 'plateau' when the evaporator temperature was about 45°C during the morning heat up. Another hump can be seen when the temperature was 55°C in the afternoon when the sun was coming out of the overcast haze and thus causing an upward temperature peak. The effectiveness of the heat storage system can be assessed by the temperature differential ΔT between the evaporator and the ambient air which is quite impressive in this case.

B. *Daily Production Data*

Normalized daily output results of the current solar desalination prototype are presented in Fig. 3. Data referred to as "Reference still" corresponds to an improved version of the greenhouse effect distillation model in that it is equipped with ancillary solar heaters for the evaporator and its heat storage component that consists of a concrete slab. Fig. 3 shows that the normalized output of the current model is substantially higher than that of the reference prototype.

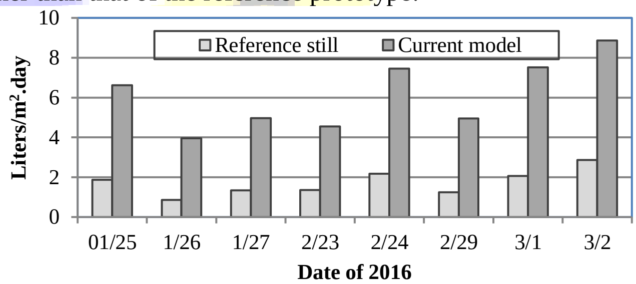

Fig. 3 Comparison of normalized daily outputs

C. *Throughput Assessment*

For desalination equipments with well characterized performance behaviors like the ones being studied, there are many ways to estimate daily throughput. Two of them will be presented below as illustrations. The first approach is through a correlation between equipment daily production and the corresponding daily average temperature of the evaporator. Fig. 4 shows an example of such a plot derived from experimental data collected over several months of equipment daily production versus the corresponding daily average temperature of the evaporator calculated from the temperature recordings for the whole day. Because of the fact that there is an exponential dependency of equipment output versus temperature, the graph is presented as a plot of the natural log of the daily throughput (expressed in ml) as a function of the reciprocal of the absolute daily average temperature of the evaporator that is $1/T_{avg}$ in reciprocal Kelvin, K-1. The linear dependency observed in the graph, Fig. 4, is a confirmation of the exponential relationship between equipment output and temperature in general. The graph shows the raw data collected during the months of October through December. In general and for these types of desalination equipments, evaporator temperature is the critical variable that drives the process. That is to say that for the highest possible output, the evaporator needs to be heated as high as possible, in the ideal situation the closest to the boiling temperature of water the better.

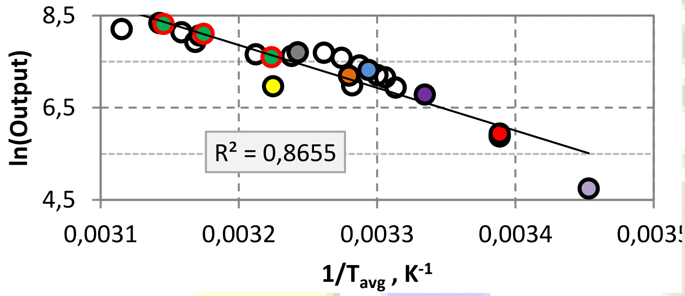

Fig. 4 Output versus reciprocal evaporator average temperature

The temperature of the condenser is another critical variable. It prescribes the condensation process which is a reverse exponential variation with respect to the condenser temperature. That means that the throughput of the equipment increases with decreasing temperatures of the condensation surface. Notice that the condenser of the model being studied is not equipped with a temperature control system. Therefore as the day progresses, the temperatures of the evaporator and the condenser go up. The data scattering observed in Fig. 4, as evidenced by the R^2 value, is caused by day to day temperature changes of the condenser. To illustrate this point, Fig. 5 shows data points taken from Fig. 4 whereby the daily average condenser temperatures were between 20 and 20.9°C. The graph in Fig. 5 is evidence that in general, at constant condenser temperature, the daily equipment output varies exponentially with the daily average temperature of the evaporator as evidenced by the correlation factor R^2.

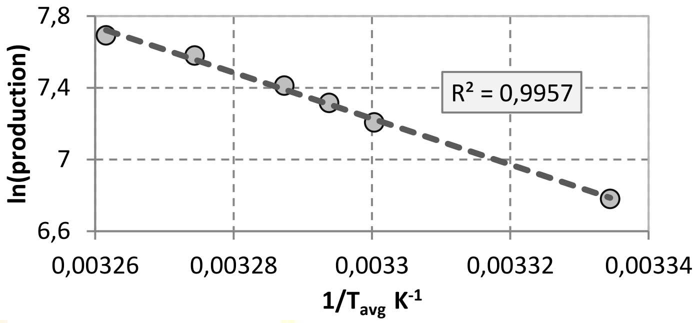

Fig. 5 Output versus T_{avg} at constant condenser temperature

The significance of these results is that, under similar operating conditions, it is possible to predict daily equipment output from the daily temperature profile of the evaporator. The other point is that increases in condenser temperatures result in a deviation of the output from linear dependency, in a log (output) versus (1/T) plot, to a curvature pointing down to lower output levels, detrimental to equipment performance.

Another way to estimate equipement daily throughput is through correlation with the maximum daily evaporator temperature T_{max}. As an example, Fig. 6 shows the same daily output data plotted as a function of T_{max}.

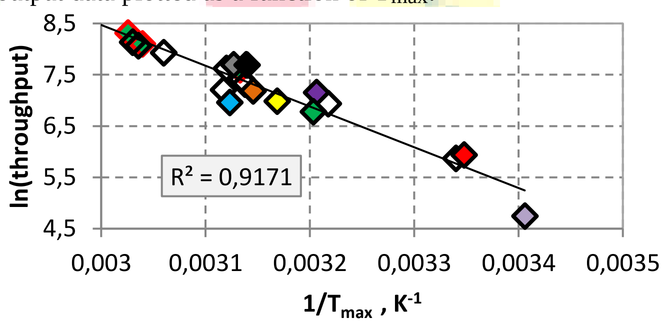

Fig. 6 Output versus reciprocal maximum evaporator temperature

The previous discussions about the scatter of the data hold true in that for the range of evaporator daily average temperature being studied i.e. from 15 to 50°C there is a linear relationship between the two variables T_{max} versus T_{avg} as shown by the experimental data in Fig 7. Nevertheless, the use of the evaporator temperature as the critical variable is the preferred method for process analysis.

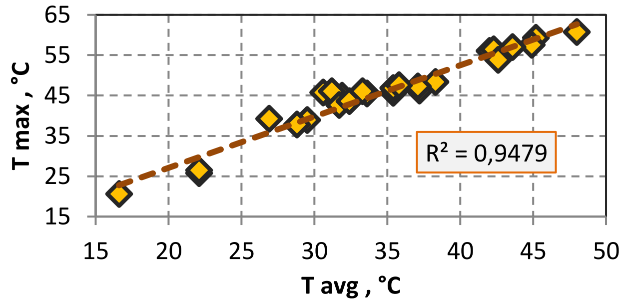

Fig. 7 Relationship between T_{max} and T_{avg}

D. Process Kinetics

The kinetics of the solar desalination prototype is represented schematically in Fig 8.

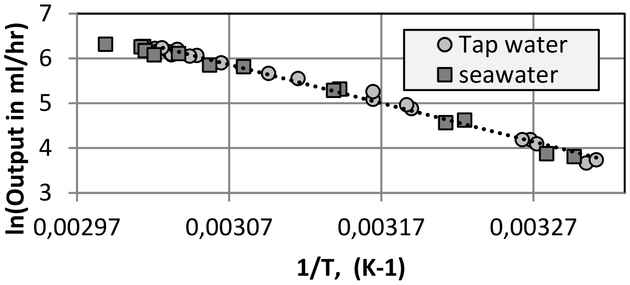

Fig. 8 Experimental prototype Arrhenius plot

The experimental data showed that the evaporation/ condensation phenomena that prescribe the operation of the equipment are consistent with the exponential Arrhenius model. The plot in Fig. 8 yielded the correlation between equipment output and evaporator temperature:

$$LnQ = 31.74 - 8443/T$$

with a correlation factor $R^2 = 0.987$

The experimental data in the kinetics plot indicate that salt content has no effect on the kinetics of the process.

IV. Conclusions

Desalination of brackish water using solar energy is an environmentally friendly process to produce good quality fresh water independently of the water salt content of the water feedstock. Performance evaluation of this model showed that the normalized daily output reached a maximum of 13 liters per m2 during the summer in June when days are hot and long. This performance level is significantly better than that of greenhouse effect based solar distillation models. The kinetics analysis showed that the process follows the classical exponential Arrhenius model.

Acknowledgment

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