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Evaluation of a pilot saline water treatment unit using a solar-thermal concentrator with zero energy cost for arid regions

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Abstract

This work compares the performance of a solar still during winter and summer months for purification of salty water, suiting arid conditions to produce distilled water. To ensure zero energy cost, the apparatus is completely run on ambient *solar energy pipes* for water circulation and heating, without any pumping requirement. The performance of the unit is evaluated over daylight hours under standard operating conditions during summer where sunshine is almost at its peak. However, the design of the solar still is modified to enhance the heating rate inside the solar basin during winter months with low ambient temperature through the attachment of a solar pipe warm water circulation into the water basin, which was fed by *solar panel system* water heating units. The water circulation from the basin to the solar collectors is solely due to the temperature difference and no pumping is required to increase the flow of water. The modified arrangement was found to achieve a temperature inside the water basin of over 50°C on a typical winter day when the ambient temperature was as low as 9°C. This resulted in the maximum amount of produced condensate yield reaching up to 2 l/hr, which was found to exceed the typical yield of 1.5 l/hr under summer conditions.

Keywords: Solar Energy; Water Treatment; Wastewater; Clean Energy; Water Reuse; Arid Region.

INTRODUCTION

The World Economic Forum on the Middle East and North Africa, held in 2019 at the Dead Sea in Jordan, identified some peculiar features of climate change witnessed across Jordan, including lowering of the average winter temperatures, erratic rainfall patterns, and higher average summer temperatures, leading to increased evaporation of surface water. Jordan is the fourth water-poorest country and is predicted to become one of the worst water-stressed countries by 2040, characterized by its pronounced scarcity of renewable fresh-water resources and high vulnerability to climate change impacts (source: World Resources Institute Report, 2015 "Aqueduct Projected Water Stress Country Rankings").

In arid areas of the Middle East and North Africa potable water is often extracted through desalination plants, requiring very large energy consumption. The development of cost-effective and energy-efficient solar-desalination systems has been considered as the key to a future "terraforming" of otherwise desert and near-desert regions of the world (Reif & Alhalabi 2015). At the same time, these locations are gifted with high solar irradiance, which has led to small-scale solar stills (i.e. evaporation apparatus powered by solar energy) widely used in arid areas for desalination of brackish

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water (Singh et al. 2019; Hanson et al. 2004; Patel et al. 2019; Sampathkumar et al. 2010; Ali et al. 2011). Several advanced mechanical systems have been applied for potable water generation from wastewater (Dehghan et al. 2015; Patel et al. 2019; Radhwan 2005; Sampathkumar et al. 2010) but they take additional power to operate the system properly and always not suitable in remote areas. Different types of specially designed single basin solar stills have been reviewed to find out the performance based on its efficiency, productivity, and economy (Singh et al. 2019). The regions in most needs of additional freshwater are also the regions with the most intense solar radiation. For this reason, thermal solar energy in desalination processes should be the most promising application of renewable energies to seawater desalination (Garzia-Rodriguez L, et al. 2002). The situation today is, however, somewhat different, since only 0.02% of the global desalination capacity is represented by renewable energy systems (Lourdes García-Rodríguez, 2002) while water reiuse is another option here in the region (Boogaard, and Eslamian, 2015)

The main problems with the use of solar thermal energy in large-scale desalination plants are the relatively low productivity rate, the low thermal efficiency, and the considerable land area required. Since solar desalination plants are characterized by free energy and insignificant operation cost, this technology is, on the other hand, suitable for small-scale production, especially in remote arid areas and islands, where the supply of conventional energy is scarce (Naim and Abd El Kawi Part 1, 2002, Naim and Abd El Kawi Part 2, 2002). The use of solar energy for driving the desalination plant is also motivated in these areas by the fact that they imply a way for energy independence and water insurance (Klass 1998). The low environmental impact as well as the easy operation and maintenance are also incitements for this technology (Garzia-Rodriguez L, et al. 2002, Fath, 1998). There are different types of solar stills built in different countries on the world, which in common have a saline water basin with a black bottom, a transparent cover, and collecting pipes, which give the condensed water as the end product. Sunlight heats the water in the basin. This heated water evaporates and condenses on the underside of the sloping transparent cover and runs down into collecting through along the inside lower edges of the transparent cover. Usually, the transparent cover is made of glass or plastic such as polyvinyl chloride or polyvinyl fluoride. The basin is covered with a thin black plastic film, like butyl caoutchouc, and insulated against the heat losses into the ground (Kalogirou, 1997).

Solar stills could be widely applied in any process requiring separation of liquid and solid phases owing to relatively high temperatures achieved in the still and reduced energy consumption, however, under ambient conditions it is quite a time taking (Vishwanath Kumar et al. 2015; Haralambopoulos et al. 2002). An evaluation of solar still application in domestic and industrial wastewater treatment (Zarasvand Asadi et al. 2013) showed chemical oxygen demand (COD) removal efficiency of greater than 86.83 ± 3.45%, with the condensate quality in terms of total dissolved solids (TDSs), total suspended solids (TSSs), COD and turbidity matching the quality of high-grade water, suitable for discharging into surface water.

The main purpose of this study is to evaluate the performance of a small-scale solar still for saline water under the ambient condition with zero energy cost (i.e. no net fossil energy input). It incorporates design modification to accelerate the evaporation rate during the winter months. The proposed unit could also be used for wastewater treatment such as olive mill wastewater which is going one now on the same principle as a continuation of this research.

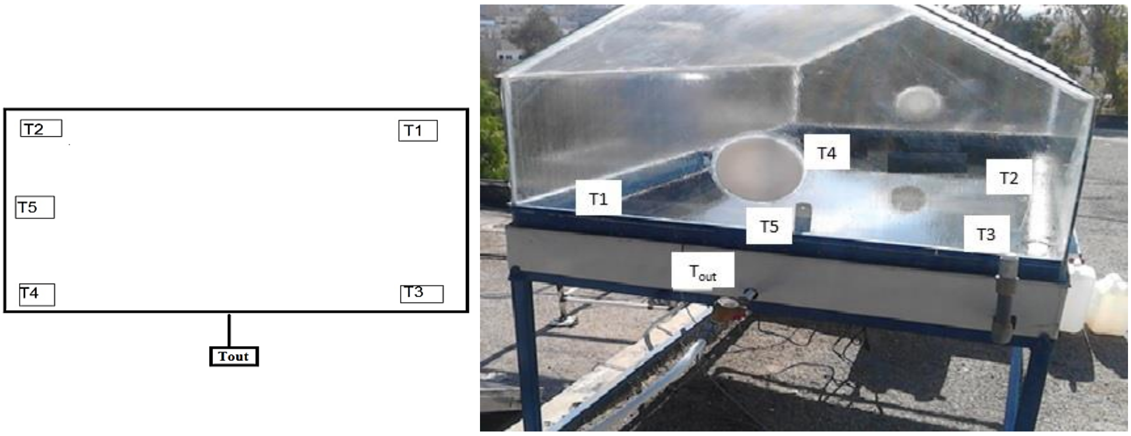
METHODOLOGY

2.1 Case study description and data collection

This system consisted of the following components (**figure 1**). A basin liner, to absorb the incident solar radiation transmitted through the glass cover. The basin liner was made of inert material to avoid corrosion from wastewater and meant to have high absorbance to solar radiation and resistance to accidental puncturing. To increase the absorption of solar rays, the water basin was painted in black. A glass cover, with a glass of 5.5 mm thickness was used with an average transmissivity of 88%, fixed at an angle of 32.5 degrees to the horizontal (*Issa et al., 2010)*. Glass cover was sealed with silicone rubber for efficient operation, avoiding any leakage preventing vapor to be maintained inside the greenhouse. Insulating material was used to reduce the heat losses from the bottom and the sidewalls of the solar still in this work. The insulating material was polyester, with rock wool of 5 cm thickness and 0.048 W/m^2 ^0C thermal conductivity. Also, the solar still was modified with a solar-thermal panel to heat the water, which was used to warm the basin to *improve and enhance* the evaporation over winter.

Five thermocouples (model- Ewelly/ EW-988H) were used to measure the temperature of the water inside the basin and in the feed. The thermocouples were distributed inside the basin at 5 locations; 4 of them are based on the basin interior surface (T1, T2, T3, and T4) and the fifth (T5) based on the feed of water (**figure 2**).

Fig. 1. Design of the solar still with – (a) Single solar panel; (b) Modified solar panel in series for accelerated evaporation during winter**.**



specification	dimensions
Basin water	(1.0×2.0×0.11)m
Glass cover	(1.0×2.0×0.40)m

Fig. 2. Spatial distribution of thermocouples within the water basin for temperature zoning and dimensions.

Set up calibration

The operating principle of a solar still is the entry of water from the reservoirs to the basin, which is maintained at a certain level. During the summer month (June-November) the water is heated in the basin by the sunlight (solar Fallen), whereas during the winter months (December-May), to accelerate the evaporation under lower ambient temperature, the set up was combined with a warm water jacket to the water basin, which was tested using two designs of solar-thermal panels – one, with a single panel; two, introducing an additional panel in series with the old one (Figure 1a and 1b respectively). This enabled raising the temperature of the water in the basin to over 56°C when the ambient temperature was around 9°C, thereby accelerating the evaporation process during the winter month. The water used in the warming jacket was recirculated through the solar-thermal unit without any pumping need due to gravity. Several conditions were investigated to make the water flow through the system, including installing the solar panel near the greenhouse basin; introducing a steam trap; checking the head difference between the basin, solar panel, and feed tank, etc.

Sampling protocol

Samples were collected during the period of the experimental run usually from 08:00 till 16:00. The samples analyzed for its conductivity (Siemens per meter (S/m)), its pH value. The conductivity measure can also give an indication of the total dissolved solids (TDS) of collected water after distillation. The distillate was found to have 90-80% lower in conductivity compared to its initial value at the solar basin.

DISCUSSION

Comparison between the winter season and the summer season

The temperature distribution within the solar still between 08:00 and 16:00 hrs for a typical summer and winter day are shown respectively in Figures 3a and 3b. While the summer temperatures showed a consistent increase as the day progressed, the winter temperature showed a peculiar pattern of raising up to noon and then subsiding. However, the temperature inside the basin reached over 50°C during peak daylight hours while the ambient temperature still ranged between 10-15°C.

The solar still was found to yield more distilled water as the day progressed beyond 10 am, both over summer and winter, albeit the condensate flow rate over summer continuously increased with daylight hours whereas overwinter it peaked around 13:00 hrs and then started slowing down (figure 4). This corresponded to the continuous rise in temperature inside the water basin with daylight hours recorded over summer months (figure 3a). However, the modified solar still with added solar-thermal warming unit allowed for higher condensate yield reaching up to 2 l/hr, which was found to exceed the typical yield of 1.5 l/hr under summer conditions.

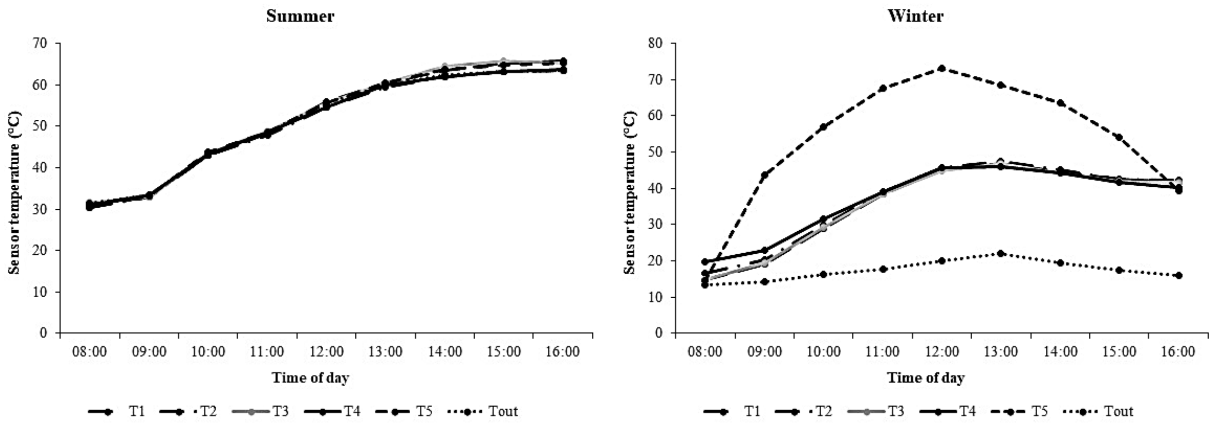


Fig. 3. Temporal pattern of temperature readings in the solar still – (a) Typical summer, (b) Typical winter (refer to the spatial location of the sensors in Figure 2).

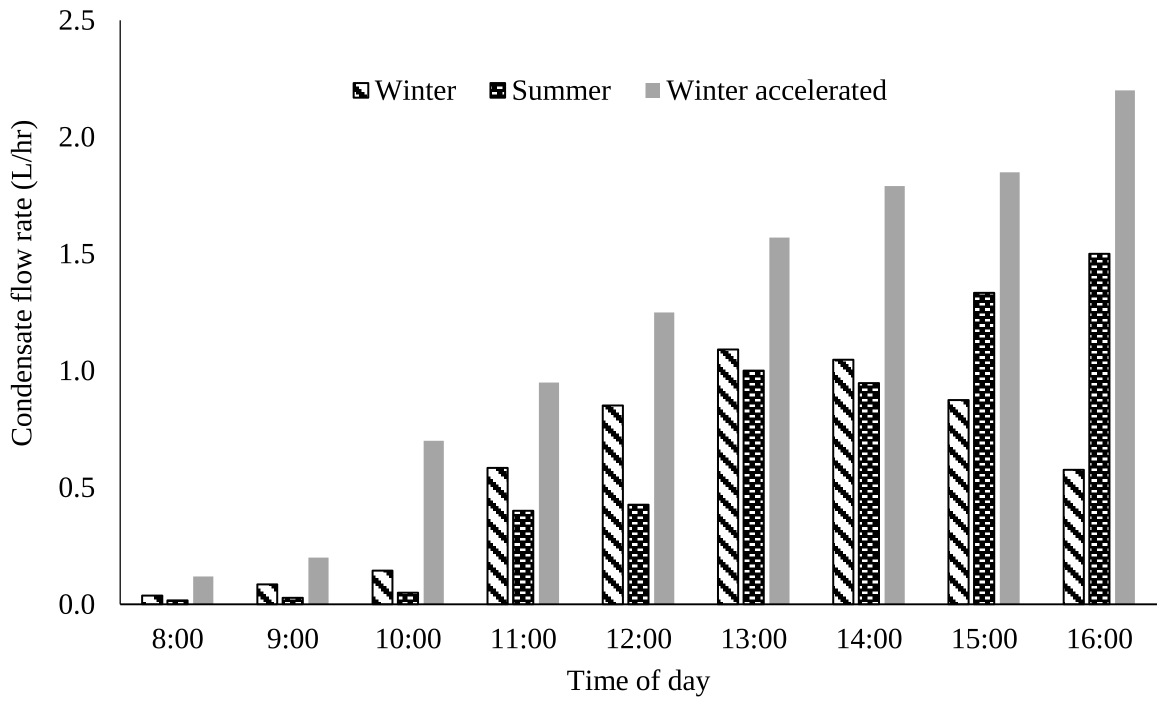


Fig. 4. Hourly patterns of condensate flow over the daylight hours for a typical summer and winter day.

RESULTS

The ambient temperature during the experimental work was noticed to be ranged from 37C° to 41C° with the highest temperatures always observed around 11:00-16:00hrs. Solar radiation increases gradually as time goes by, and reaches its maximum value in the afternoon. The heat absorbed by basin water depends on solar radiation, transmissivity, absorptivity, and heat losses from basin water. As the temperature increase inside the solar still basin; increase the condensed water flow rate. The greenhouse angle face sun concerning horizon is fixed 32.5°. This degree is agreed upon in the solar collection system in Jordan. To allow for the largest amount of radiation entering the basin of water and soak the largest amount. The height of the water level inside the water basin working to reduce the amount of distilled water that flows from the basin water. For this the less the height of the water in the basin increases the amount of evaporation. The amount of distilled water collected, in 12 hours was 10 litters. The measured conductivity is ranging from (27 to 45) µS. Comparing this result with what has been mentioned in literature "A general rule of thumb for solar stills is that a solar collection area of about one square meter is needed to produce 4 liters of water per day (10 square feet/gallon)", (Buros, 2000). Thus, for a 4000 m^3/d facility, a minimum land area of 100 hectares would be needed (250 acres/mgd). This operation would take up a tremendous area and could thus create difficulties if located near a city where land is scarce and expensive (Buros, 2000). According to Awaad et al. (2020), for a greenhouse technique under tropical and temperate conditions, humidification–dehumidification, water desalination system can produce 11.6 and 20.4 m3/year-ha freshwater, with a power consumption of 1.6 and 1.9 kWh/m3, respectively. There are many types of greenhouses, including lean-to, even-span, uneven-span, Quonset/hoop-house, Gothic arch, elliptical, spherical dome, conventional and smart, which will make the economical comparison is difficult. In this current study it is clear that 10 litters on average can be collected in 12 hours, for a unit has 100 litters in its basin, can produce 10% distilled water per day with almost no energy used for producing such distilled water can be a good proposal to produce water for saline one and might be feasible in the desert area in comparison with Awaad et al. (2020).

CONCLUSIONS

The designed apparatus was capable to produce distilled water from seawater or salty water. The amount of collected distilled water is 10 litter per 24 hours. This is a good achievement. For highly efficient solar still, a large temperature difference between evaporated water and condensing surface should be maintained. The performance evaluation carried out on the fabricated Solar Still has shown that it can be used for the desalination of salty water. The results have shown that a high enough temperature was attained which produced evaporation and the distillate produced was confirmed fit for drinking by the salinity test conductivity. The daily temperature and type of absorber materials are factors that can influence the distillate yield. The flow rate of distilled water depends on the level of the water in the basin, the lower the water level in the basin the greater the flow of distilled water. As well as high glass cover affects the amount of heat inside the basin of water, the greater the elevation increased heat inside the water basin. The conductivity of distilled water is good and can be used in many things, for example, is used in the laboratory. The largest quantity of distilled water one can acquire is usually in the afternoon time, between time (13 – 16) pm. The sunbeams are Intense at this period. Operational data and experience from this study can be utilized to further enhance the performance of a solar still in olive mill wastewater treatment, especially enhancing the distillation rate over winter months due to the seasonal nature of olive mills wastewater production nearing wintertime. Further research in developing affordable modification is warranted to make this technology more widely used in remote arid regions. These may include, suitable application of heat exchangers, improving the effective evaporation and condensation through the addition of thermoelectric heating module at the liner of still basin. Heat storage phase change materials (PCM) can be especially applicable in extending the operability of the still beyond daylight hours through the use of thermal energy during off light or dull light which can be utilized for additional evaporation of basin water, thereby increasing the clean water yield.

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