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Experimental and theoretical study of a single-basin solar still in Jordan☆

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Abstract

This paper presents experimental results of a single-basin solar still using various absorbing materials. The still has equal angle double-sloped covers with an effective basin area of 3 m^2. The experiments were conducted in Amman, Jordan during the months of April and May. The materials used to enhance the absorptivity of water for solar radiation include dissolved salts, violet dye, and charcoal. The salts were potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$). Significant increase in still efficiency and productivity was obtained. For example, the addition of potassium permanganate resulted in 26% improvement in efficiency. Also, a comparison between theoretical and measured water productivity is presented. It was found that there is a good agreement between theory and experiment.

Keywords: Solar still; Absorping materials; Jordan

1. Introduction

Jordan is classified as a low rainfall country in that most of its land is considered as either arid or semiarid. The average annual rainfall ranges from 600 mm in the northern highlands to less than 50 mm in the deserts and southern Ghor (Jordan Valley) which form about 91% of the country's surface area [1]. Also, Jordan is considered as a dry country due to the severe scarcity of its water resources. Water scarcity is aggravated by high population growth which exceeds 3%. By the year 2010, the population is

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expected to increase beyond 7 million. The water demand for different uses could reach 1350 million cubic meters (MCM) annually [2] while the total estimated available water from surface and ground resources is about 1135 MCM [1]. Clearly by then, the country will face serious water shortages. There are many actions that are being taken to solve this problem. This includes exploiting resources shared with neighboring countries such as the Disi Basin and the Yarmouk River. Work is already underway in constructing the Wehda Dam on the Yarmouk River which could supply more than 100 MCM. Another scheme being considered is the Red–Dead Seas canal. It is a potential hydro-power development used for desalination of seawater by linking the Red and Dead Seas. The Dead Sea is located at an elevation of more than 400 m below sea level. In recent studies [2,3], it was estimated that 530 MCM of fresh drinking desalted water using reverse osmosis (RO) technology can be produced from such a grand project. The total costs of this project ranges from 3 to 5 Billion US$ which is beyond Jordan's financial capability and it needs outside funding.

There are good prospects for non-conventional water resources such as recycling and reusing municipal wastewater, rain-water harvesting projects for different Wadi basins, cloud seeding, and importing water from neighboring countries. Desalination of brackish water also offers a viable option for water supply enhancement [4] with a potential of 130 MCM in the Jordan Valley alone [1]. Many aquifers in different parts of the country have either already been deserted due to salinization or reported to have shown high salinity due to over-exploitation. Communities in these regions rely on such resources for drinking and other uses. In many cases, fresh water has to be either transported for long distances or connected with an expensive distribution network at extremely high cost for, usually a small population [5]. Therefore, the use of solar water distillation becomes, partially, an attractive alternative solution for such a problem. According to Howe [6], at an average water consumption of about 400 l/person-per-day, a small community with a total population of 200 can benefit more from solar desalination than transporting water at distances of 16 km or longer with lower costs. For example, a community that is located at about 100 km from a fresh water source can save about 33% in total cost if solar distillation was adopted instead of transporting fresh water.

Also, Jordan is a non-oil-producing country that is almost totally dependent on imported oil. This is causing a big financial burden on the national economy with an estimated energy cost of 9% of the GNP in 2001 [7]. On the other hand, Jordan has a high potential of solar energy resources with a daily average radiation on a horizontal plane of 5.5 kWh/m^2, and average sunshine duration of 9.1 h [8]. The abundance of solar energy coupled with limited conventional water and energy resources, makes solar distillation that much more attractive. A recent study was performed to compare different types of solar systems for various applications in Jordan, according to their benefits and costs [9]. Results showed that solar distillation was found to be the best option, and should be given the highest priority in terms of research and development.

The performance of solar stills can be improved by using non-conventional designs and techniques. Naim et al. [10] constructed a solar still in which charcoal particles bed was used as an absorber medium and a wick. The productivity was improved by 15% over wick-type stills. Nafey et al. [11] studied the effect of using a floating perforated aluminum black plate on the productivity at different brine depths. It was found that the still output increased by 15% and 40% at brine depths of 3 cm and 6 cm, respectively. In another work [12], a continuous single-stage solar still that makes use of a phase energy storage mixture was constructed and tested. The mixture was an emulsion of paraffin wax, paraffin oil and water in a specific ratio to which aluminum turnings were added to assist in heat transfer by conduction. The design makes use of the latent heat of fusion of the mixture for obtaining continued desalination even after sunset. Results indicated that the use of an energy storage material led to a larger productivity. The increase depends on the concentration, flow rate, and temperature of the inlet saline water.

Other researchers investigated different designs and techniques to achieve better still efficiency. Hinai et al. [13] investigated the performance of single- and double-effect solar stills in Oman. It was found that the average annual yield was significantly higher for the double-effect still and with a potential unit cost saving for distilled water of 15.7%. Akash et al. [14] studied the effect of using black ink and dye on the productivity of a single-basin solar still. They reported an enhancement of 45% and 60%, respectively. Numerous other works were concerned with the enhancement of distillate output. For example, an improvement by about 13–15% can be achieved by using reflector, cotton cloth, or regenerative effect in the back wall [15,16]. The objective of this study is to determine the effect of adding different types of absorbing materials in order to enhance the performance of a single-basin solar still. Some of these absorbents are novel and have never been tested in the field of water distillation.

2. Experimental

A schematic diagram of the solar still used in this study is shown in Fig. 1. It is a single-basin still with an effective area of 3 m^2 (i.e., 3 m length by 1 m width). It is constructed of 316 stainless steel. The bottom and sides of the basin are insulated by a 10-cm-thick Styrofoam to reduce heat losses. The still cover has equal angles double-sloped at 35°. It consists of galvanized iron frame holding 4 panes of 4

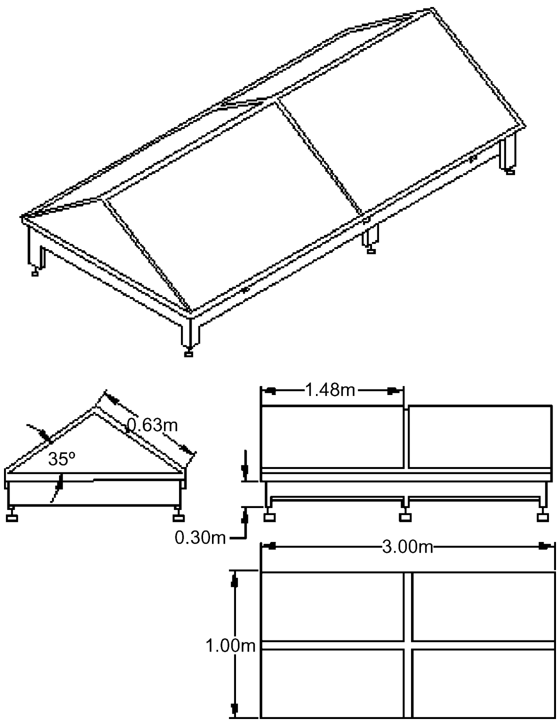

Fig. 1. Schematic diagram of the experimental setup.

mm toughened glass. The whole system is made air tight with the help of 8 latches and a rubber gasket seal placed between the frame cover and the basin. The water vapor inside the still condenses on the cooler inner surface of the glass, forms droplets and runs down the glass. The distilled water drips into tilted troughs attached to the lower edges of the glass cover. The distillate is collected in two bottles on both sides (i.e., north and south). A graduated cylinder is used to measure the volume of the distillate output produced. The still was positioned on an east–west axis with the cover facing north-south orientation. This gives the highest possible yield per day. Sets of thermocouples connected to a PC via data logger were used to measure and record temperatures of different parts of the still. This included basin water, enclosure vapor, and the inner and outer sides of the glass cover. The ambient temperature and wind speed were also monitored. The global solar radiation on each tilted cover and on a horizontal surface were measured using three Kipp and Zonen pyranometers.

Experiments have been carried out in Amman (Latitude 32°), Jordan during the months of April and May. The effect of using different absorbing materials on the still yield and performance was studied and compared. Floating charcoal pieces were spread over the water mass in different proportions (25%, 50%, and 100% of surface area). It has two desirable properties: large black surface area for absorption of solar radiation and a large surface area for evaporation.

Dissolving certain salts in water enhances its absorptivity of solar radiation by extending the absorption to the visible region of the spectrum [17]. This could result in increased rise in water temperature by more than 10 °C, which is of prime importance in improving the still efficiency. In this work, some of the proposed salts were tested to study their possible effect in water desalination application. This included potassium permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$). These substances are potentially hazardous and care should be taken in handling them. For example, potassium permanganate is a strong oxidizer and has been suggested to be used as a substitute for chlorine in water treatment plants, and is widely used in the water industry [18]. Salt crystals were added to form colored weak concentration solutions (70 mg/l $K_2Cr_2O_7$ and 50 mg/l $KMnO_4$). The distillate output was measured hourly over the duration of the experiments. The effect of using a violet dye (35 mg/l) and a reflector (2.8 m by 1.4 m) on the performance of the still was also tested. Comparison between different materials was based upon still daily efficiency given by [19]:

$$\eta = \frac{2\dot{m}_{\mathrm{e}} \cdot h_{\mathrm{fg}}}{A(I_{\mathrm{S}} + I_{\mathrm{N}})} \tag{1}$$

where $\dot{m}_{\mathrm{e}}$ is the measured daily output of distilled water from both sides, h_{fg} the latent heat of vaporization, A the glass cover area, I_{S} and I_{N} the measured daily solar radiation on south and north covers, respectively.

3. Comparison of theoretical and experimental productivity

Theoretically, the production of distilled water output of the solar still depends on the theoretical mass transfer rate and vapor pressures of the basin and cover temperatures. It is estimated form the following relationship as given in Ref. [19]:

$$\dot{m}_{\mathrm{th.}} = 9.15 * 10^{-7} * h'_{\mathrm{c}} * \left(P_{\mathrm{wb}} - P_{\mathrm{wg}}\right) \tag{2}$$

where $\dot{m}_{th}$. is the theoretical mass transfer rate in kg/m^2 s, P_{wb} and P_{wg} are the vapor pressures of water in mm Hg at basin temperature (T_b) and glass cover temperature (T_b) both in degrees Kelvin, and h_c' is the still convection coefficient. It is given by:

$$h_c' = 0.844\left[\left(T_b - T_g\right) + \left(\frac{P_{wb} - P_{wg}}{2016 - P_{wb}}\right)T_b\right]^{\frac{1}{3}} \tag{3}$$

The theoretical hourly productivity is calculated from the above equations using measured values of T_b and T_g, and compared with the experimental values.

4. Results and discussion

The solar still daily efficiency using the different absorbing materials was determined and presented in Fig. 2. It was decided to compare the results in terms of the daily efficiency to take into account any variation in climatic conditions during the testing period such as cloud cover and solar radiation. Fig. 2 shows that the maximum efficiency was obtained for the violet dye, 19.1%, as compared with 14.8% for water. The increase is significant and amounts to about 29%. Significant improvements were also obtained using other materials with 17% for $K_2Cr_2O_7$ and 26% for ($KMnO_4$). This enhancement in performance can also be seen from the observed cumulative water productivity in ml presented in Fig. 3 with increases of more than 20% for all cases. Fig. 4 compares the theoretical and measured hourly productivity of distillate water. It can be seen that the agreement between experiment and theory is satisfactory. The difference could be due to the

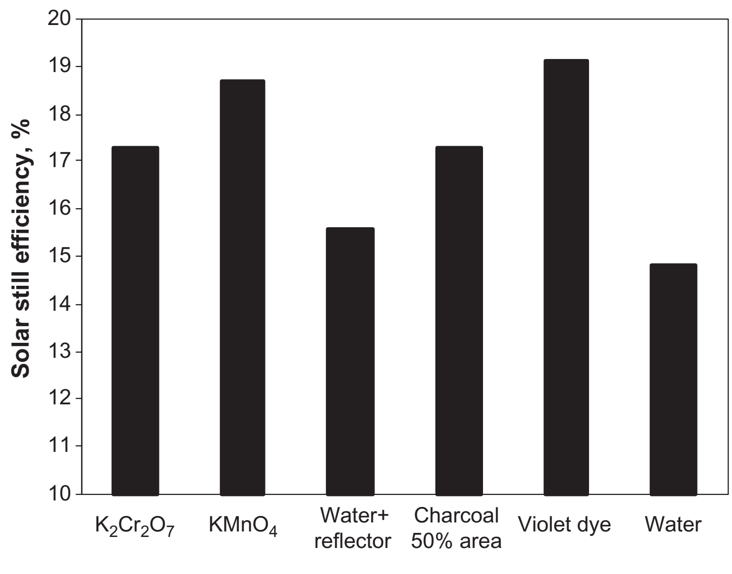

Fig. 2. Comparison of solar still daily efficiency using different absorbing materials.

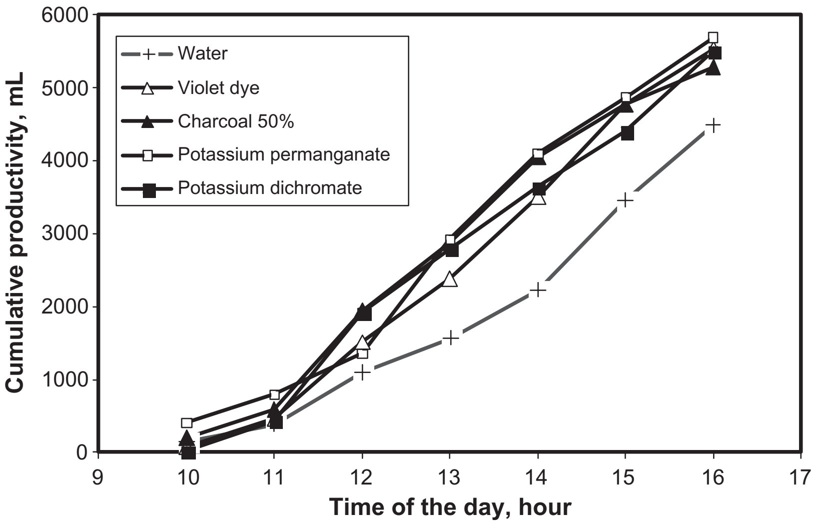

Fig. 3. Measured cumulative productivity of the still.

leakage of humid air from openings in the cover, condensed water dripping from the cover back into the still, and by evaporation or leakage from the collecting troughs.

Fig. 5 shows typical measured temperature–time history curves of still containing violet dye–water and water. It can be seen that the presence of violet dye results in higher basin temperatures due to higher absorption of solar radiation with an average temperature difference of more than 7 °C. This leads to a marked improvement in productivity and efficiency of the still. The effect of proportion of still surface area covered by charcoal is presented in Fig. 6. It can be seen that the optimum percentage is around

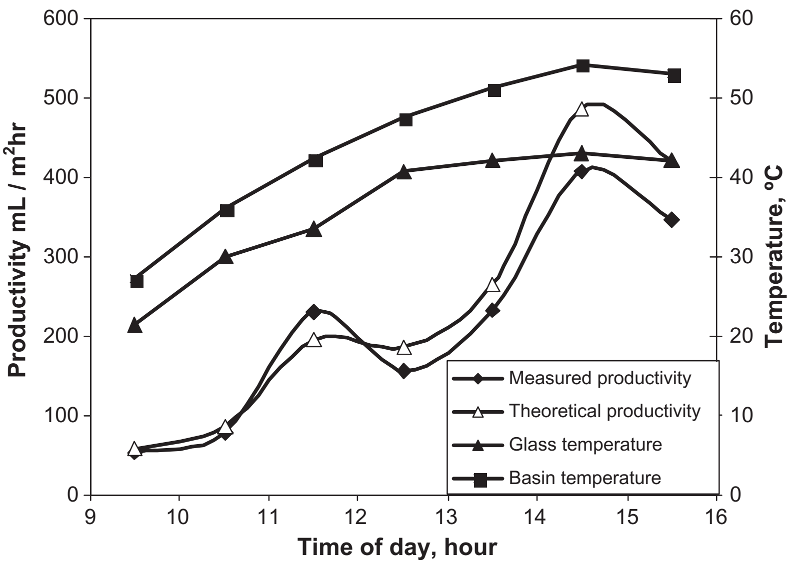

Fig. 4. Comparison of the theoretical and measured hourly productivities of the still.

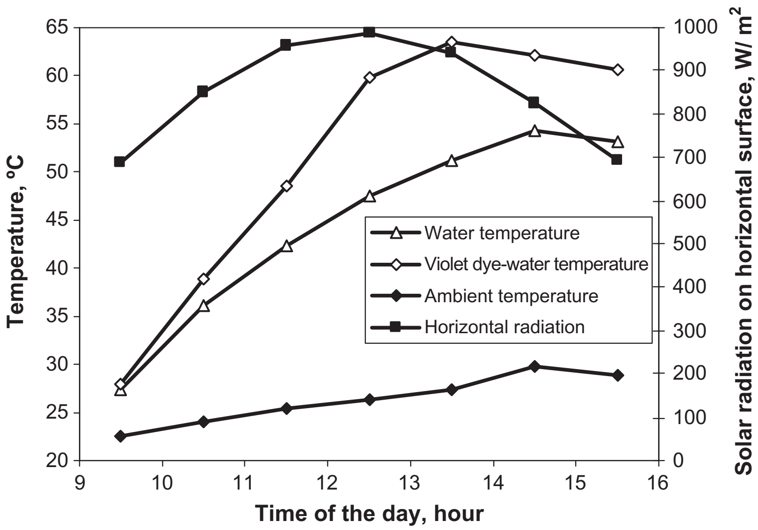

Fig. 5. Comparison of basin temperature for water–dye and water systems.

50%. A higher proportion resulted in decrease in efficiency due reduction in water surface area caused by charcoal floating on the surface.

5. Conclusion

Solar still is an attractive option to overcome fresh water-shortage problems in remote areas in Jordan. The performance of solar stills can be improved by using non-conventional designs and techniques. In

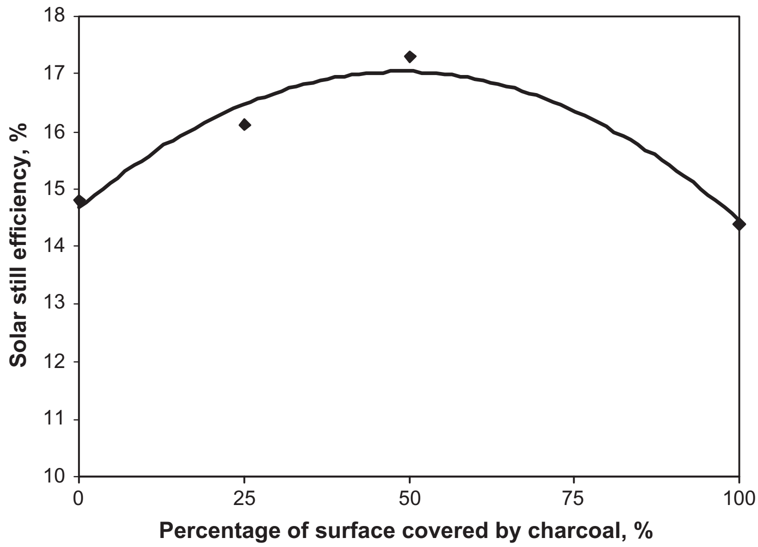

Fig. 6. Effect of proportion of the covered surface area by charcoal on efficiency of the still.

this study, experimental results of a single-basin solar still using various absorbing materials to in Amman, Jordan during the months of April and May were presented. The materials used to study enhancement of water productivity were dissolved salts (i.e., potassium permanganate: $KMnO_4$ and potassium dichromate: $K_2Cr_2O_7$), violet dye, and charcoal. The addition of the dissolved salts is a novel method in improving the performance of solar stills. It produced significant increase in still efficiency and productivity. It was found that the addition of $K_2Cr_2O_7$ (70 mg/l) and $KMnO_4$ (50 mg/l) produced an enhancement in solar still daily efficiency of 17% and 26%, respectively. The best result was obtained by using violet dye with an increase of about 29%. The effect of charcoal with different concentrations was also studied. It was found that the optimum efficiency and productivity were achieved when it covers 50% of basin surface area (17.3% and 5290 ml/day). Also, the theoretical hourly productivity of the solar still was computed and compared with the experimental values. In general, experimental results were in good agreement with theory.

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