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Effect of Water Depth on the Performance Evaluation of Solar Still

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Abstract

Desalination of ground brackish water by solar powered systems is a practical and promising technology for producing potable water in the regions which suffers from water scarcity especially in arid areas. In remote and arid areas in Jordan with low infrastructure and without connection to the national grid, the abundant solar radiation intensity along the year, and the available brackish water resources are two favorable conditions for using the desalination solar technology to produce the fresh water, even for domestic use. Based on these conditions, a small-scale solar powered desalination system has been constructed and operated. The present study aims to improve the solar still performance, and to increase its productivity. So it is necessary to evaluate some important parameters affecting the system productivity. The effect of water depth in the basin on the water productivity was evaluated. In the same time, the effect of the deign and operational parameters on the solar desalination process were investigated. Different depths of brackish water (0.5cm, 2cm, 3cm, and 4cm) with TDS of 5000ppm were tested under the same climatic conditions in Mutah University. A six months study showed that the still productivity is strongly dependent on the climatic, design and operational conditions. The obtained results showed that the decreased water depth has a significant effect on the increased water productivity, while the performance characteristics showed that the water productivity was closely related to the incident solar radiation intensity. The balanced conditions between the increased evaporation rate and the rapid condensation ware due to the merit contribution of the carefully applied glass cover cooling.

Keywords: Solar still; Brackish water depth; Water Productivity; Testing hours; Jordan.

1. Introduction

Desalination method has long been considered as the practical solution for the current and future demand of potable water. Desalination process is used to reduce the Total Dissolved Solids (with TDS of 5000 p.p.m and above) to an acceptable level of TDS equal to 500 p.p.m. Different desalination technologies can be applied. Desalination of ground brackish water by solar powered systems, is a practical and promising technology for producing potable water in the regions which suffers from water scarcity especially in the remote arid areas [1]. The rapid population growth, along with the expected social and economic development will increase the demand for water in such a way that the future water reserve in Jordan will not meet such a demand. Jordan in particular will face sever shortage of fresh water [2,3]. The 1998 water crisis is a good example.

In remote and arid areas in Jordan with low infrastructure and without connection to the national grid, the abundant solar radiation intensity along the year, and the available brackish water resources are two favorable conditions for using the solar powered desalination technology to produce the fresh water, even for domestic use. A small scale solar desalination technology, might to be technically and economically viable to cope with water scarcity, and it is recommended to be used in the remote and isolated communities, particularly for those areas which enjoys with abundant solar radiation intensity. Desalination of brackish water was expanded rapidly to support urban and industrial developments in the arid areas, good results were published by some researchers in the field of solar desalination [4,5].The recent sharp increase in energy prices makes the solar desalination technique a more attractive method for obtaining fresh water. Furthermore, the valuable solar radiation intensity which Jordan enjoys (5.5 kwh/m^2.day (19.8 MJ/m^2.day)), along with the high average sunshine duration (3300 hrs/year (300 days/year)), with 9-10 daylight hours for the most geographical locations encourages the use of such a solar resource. Data for the years 1960-2005 obtained from the Jordan Meteorological Department (JMD) encourages further research activities in the field of solar energy application. In order to enhance the solar stills productivity, numerous groups around the world have contributed to improve the solar desalination technology,

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by evaluating the influence of some important parameters on the system performance. The effect of climatic conditions; deign and operational conditions and geographical location on the water productivity [6,7,8,9,10, 11] were investigated. It is well known that the distillate output decreases significantly with the increase of water depth in the basin of the solar still; also, with the same solar irradiance the evaporation rate increases with the reduced mass of water on the absorber pate [12,13]. The effect of these parameters on the solar powered desalination process were evaluated before starting the experimental phase of the present work. Based on these information, the effect of water depth in the basin of solar still was evaluated. In the same time, the effect of the deign and operational parameters on the solar desalination process were investigated. Different depths of brackish water with TDS of 5000ppm (0.5cm, 2cm, 3cm, and 4cm) were tested under the same climatic conditions in Mutah University. Two greenhouse type solar stills were constructed and used. Both solar stills were utilized under the same operational conditions. The obtained results showed a significant increase in the amount of produced water especially for the tested depth of a brackish with 0.5 cm whereas; the fastest condensation rate was achieved after applying the method of cooling the glass cover.

2. System

2.1. System Description

Major handicaps which influence the still performance such as: dry spots and scale formation, air-tight conditions, glass cover inclination were investigated by different researchers; and good results were published [9,10,13,14]. The major handicaps that negatively influence the solar still productivity were taken in consideration, and some improvements on the design and operational conditions were made. In order to successfully perform the experimental investigation and to accurately evaluate the effect of water depth on the increased water productivity, it was necessary to investigate many depths of water under the same operational conditions. For that reason, two symmetrical greenhouse-type solar stills were constructed, and some improvements were made. Basically, each unit consists of the following parts as shown schematically in Figure 1:

1. The Aluminum metal is a good conductor and concentrate the heat energy at the surface layer, so the black-painted absorbing plate is made of 3 mm thick Aluminum sheet with an absorbing area of $1m^2$ (1.25*0.8), four uniformly distributed points of support are placed under the absorbing plate to provide the correct water level, as well as to prevent the tendency of deflection that can cause the formation of dry-spots.

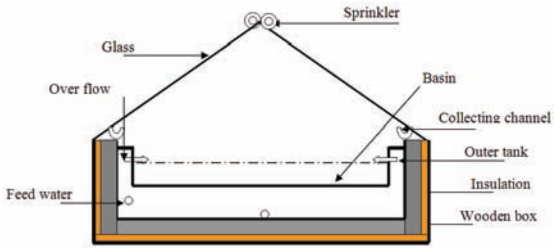

Figure 1: Schematic sketch of the testing unit (solar still) used in the present work

2. The airtight glass cover is formed of two glass sheets (4 mm thick) with an inclination of 40^o. Both sheets are supported on the steel frame and properly sealed with rubber to prevent the air leakage.
3. The insulated outer tank, in which 8 cm of rock wool is properly placed on all the basin sides and bottom, is enclosed within 2 cm wooden box and externally is surrounded by 0.3 galvanized iron-sheet.
4. In each solar still twelve thermocouples are uniformly distributed on the centerlines of the glass sheets and the basin plate in order to measure accurately the temperature variation
5. Brackish or saline water (sample of Brackish ground water collected from Al-Tanoor dam and Alkafrein-Hisban with TDS of about 5000 p.p.m). Feed water can be fed continuously or intermittently by two methods. In the first method, the feed water can be fed to the lower tank through the feed water header, after filling the lower tank, an over-flow of brackish water is fed to the upper basin through number of small drilled holes (3mm in diameter) distributed on the inside perimeter of the upper basin. While in the second method the brackish water is fed directly to the upper basin through a steel pipe that is centrally placed above the basin plate with 5 cm, the steel pipe has sufficient number of drilled hole to ensure better water distribution on the absorbing plate.
6. The collecting channel is made by PVC and placed on the base of the glass cover with an inclination of 5^o towards the collecting header in order to speed up the condensate velocity and to avoid the tendency of re-evaporation.
7. Two sprinklers are constructed and installed on the top part of each solar still in order to ease splashing method and to cool the glass cover.
8. Black plastic jackets (polyethylene) with the same dimensions of the inner basin are made in order to eliminate the maintenance cost as well as the effort of cleaning the deposited scales on the absorbing plate. The properties of selected thermoplastic polyethylene high density material (PE-HD) are indicated in Table 1

Table 1: Properties of PE-HD [-CH_2-CH_2-]$_n$

State	High density
Density [g/cm^3]	0.957
Melting temperature [° C]	130-137
Thermal conductivity [w/m.k]	0.48
Effective thermal diffusivity [mm^2/s]	0.092
Enthalpy difference [kj/kg]	650
Humidity absorption [%]	0.01

2.2. Working principle of the solar still

A small-scale hydrological cycle can be created in a well designed solar still. The air tightness and the good insulation, are two essential design parameters that should be highly considered in order to minimize the vapor leak and heat loss tendencies .

Solar stills are used to produce fresh water from brackish water by directly utilizing the sunshine. Construction and operation principle of solar stills are very simple. The black painted absorbing plate contains the brackish water which is directly exposed to the solar energy above the plate. The brackish water is completely enclosed in an air-tight conditions inside the transparent glass cover. The incident solar radiation passes through the transparent glass cover and is absorbed by the black-painted Aluminum sheet, the absorbed heat is then transferred to the water with no significant energy loss. The brackish water start heating and evaporating, the formed vapor on the water surface start moving in an upward direction as due to the created driving force (convective currents) due to the temperature difference between the water and glass cover (T_w-T_g). When the water vapor comes in contact with the condensing surface (glass cover which is externally cooled) in order to improve the condensation rate, the vapor will condense at different small-size droplets of fresh water, then the condensate starts moving down along the inclined glass cover due to the gravitational force. Finally, the condensate will be collected from the collecting channel which is connected to the collecting vessel.

2.3. Design description

Two symmetrical greenhouse solar stills were constructed, and the experimental investigation regarding the effect of water depth on the still productivity was carried out. Because the solar still productivity was strongly dependent on the design and operational conditions, the accepted thermal performance which was achieved was due to the improved design parameters and optimized operational technique.

The initial investigations were carried out in September, 2004; the negative aspects regarding the design and operational parameters were detected and treated. Practically, both stills were filled with two different brackish water depths. Each time the lower depth of 0.5 cm brackish water (above the absorbing plate) in one solar still was tested and compared with other brackish water depths (2cm, 3cm, and 3cm) in the second solar still. The solar stills were properly oriented, and directly exposed to the solar radiation. Both stills were operated during the typical days of September, 2004; the time interval of four days was sufficiently enough to execute all the necessary calibrations and adjustments. The remarkable results and visual observations during the initial investigations ware due to the accurate adjustments and calibrations. Based on these observations, the system of measurement was carefully established during the testing period, all the key quantities were carefully measured and recorded at a time interval of every 15 working minutes. The measured parameters and quantities ware; the solar radiation intensity (I), the glass temperature (T_g), the basin water temperature (T_w), and the ambient air temperature (T_a). The designed system has the following important characteristics:

1. The negative effect of scale formation on the absorption efficiency, and the increased cost of cleaning the white scale are two important causes of reducing the solar still efficiency. So, the need for using the designed black and replaceable plastic jackets having the scope of minimizing the cost of cleaning and maintenance. The plastic jackets were placed in each solar still. By using these plastic jackets, a higher absorbability can be maintained, and the scale formation become an ignored problem
2. The water surface level was precisely adjusted to avoid the dry spots, mainly at shallow water depths.
3. The proper material selection, and fabrication of the absorbing plate has a positive effect on the increased basin water temperature. In order to ensure an efficient capturing of solar irradiation, the absorbing plate is made of Aluminum sheet because of its thermal conductivity. (see Table 2)

Table 2: Thermo physical properties of Aluminum

Melting point [k]	933
Density [kg/m^3]	2706
Specific heat cp [J/kg.k]	903
Thermal conductivity [W/m.k]	237

The rapid formation of a thin vapor film on the internal sides of the glass cover was clearly observed after 25 minutes of exposing the distiller to the solar radiation. Also, the uniform distribution of the generated small size water droplets that started moving in an organized down-sliding motion to the collecting channel was observed to occur rapidly during the initial stages. The accepted thermal behavior was ensured by the last two characteristics. Unfortunately, despite the achieved performance, the water productivity was below the expected value. So, extensive efforts were made to determine the suspect reasons. Further examinations were conducted to investigate these reasons. The repeated attractive results during the start of each experiment demonstrated categorically that the design parameters had no negative effects on the reduced water productivity. The close inspection made on the data related to the measured quantities was of a great contribution in finding the suspect cause of the reduced productivity. It was observed that the sharp increase in glass temperature (T_g) because of the effect of latent heat of condensation, which having a significant role in raising the glass temperature, a temperature much higher than the ambient (T_a) and very close to the water temperature (T_w), could be the main reason of decreasing the rate of evaporation and then water productivity. Such a high temperature might have a negative effect on the condensation process and the driving force of the convective currents. Several recent studies reported that the positive contribution of cooling the glass cover [15,16,17,18]. The role of condensing cover is very important in solar distillation systems; it has to permit solar radiation to transmit, and to dissipate the heat to the ambient to provide efficient condensation [10]. Others have found the significant effect of the increased temperature difference (T_w-T_g) on the productivity of the green house solar still during the earlier night hours. They reported about 50-60% higher productivity during the early night hours than during the daylight hours. This was attributed to the positive effect of the stored heat and the increased temperature difference (T_w-T_g) [3,19]. These observations lead to the decision of applying the glass cover cooling. Based on the visual observations (faster water droplets motion) and the inspected values of the measured quantities, the periodicity of cooling the glass cover was accurately optimized to be performed every 15 working minutes. The cooling system consisted simply of two steel pipes with sufficient number of small-drilled holes (3mm in diameter). The designed sprinklers were located on the top part of each solar still to ease splashing both glass sheets at the same time. Practically, a jet of 20 ºC of water was applied to cool the glass cover. Time duration of one minute was sufficiently enough to create an accepted temperature difference of about 8 to 10º C between the glass and brackish water temperatures. Splashing of the glass cover was applied with five minutes before taking the temperature readings. The temperature readings was taken at 15,30,45,and 60 minutes. Finally, the initial stage of inspecting the design parameters and optimizing the operational technique was successfully achieved as indicated by the accepted thermal performance. The solar still productivity could be increased when an extra heat is provided from any available source of heat. Different studies with different design arrangements showed that solar still productivity can be increased when extra heat is fed to the system [20,21]

3. Results and Discussion

Practically, a number of experimental investigations were conducted to demonstrate the overall objective of the present study. All the selected water depths were tested in Mutah University at 1050 m above the sea level. The effects of water depth operational and design parameters and geographical location were evaluated.

The lower brackish water depth of 0.5cm (mass of water above the absorber) was tested in each experiment; the results were compared in each time with those obtained from the other tested water depth in the same experiment. The testing procedure was carried out during the winter of 2004-2005 and summer of 2005 as clarified in table 3.

Consisted with the planned timetable 3, the obtained results of the tested two water depths and in each experiment were compared and evaluated. The interval of four days was sufficiently enough to explore the effect of water depth on water productivity. It should be mentioned that both testing units were operated in the first two days in each experiment without cooling the glass cover while in the last two days the glass cover cooling was applied (only during the summer months of June, July, and August/2005). The effect of different parameters was evaluated through the obtained results as follow:

3.1. Effect of design and operational parameters

The same results obtained from both testing units with a water depth of 4cm showed the same thermal performance. The experiment was conducted under the solar radiation intensity of 7.73 kwh/m^2.day (27.8 MJ/m^2.day)in which both solar stills were exposed to the solar radiation for a time interval of 10 hours, the obtained results of 4.745 and 4.733 respectively showed nearly the same thermal performance and the same effect of the design parameters.

3.2. Effect of water depth on the solar stills productivity

The experimental results have shown with no doubt that the water depth has a significant influence on the increased productivity. So, the objective of the present work have successfully achieved as shown on the performance curves.

All the experiments were conducted as conform the planned timetable, and separate thermal behavior was made for each tested depth. Figure 2 illustrated the planned timetable and the experiments were conducted under the described conditions such as the average solar radiation intensity of 7.73 kwh/m^{2}day (27.8 MJ/m^2.day), and operational time of 11 daylight hours.

Table 3: Time table of testing the water depths

Tested depths of ground brackish water. 0.5 in one testing solar still, and 2,3,4 cm in the other solar still	**Summer months (2005)** Average sunshine duration is of 11.8 hrs/day. Average solar radiation intensity is 7.73 kwh/m^2.day, or (27.8MJ/m^2.day)			**Winter months (2004/2005)** Average sunshine duration is of 6-hrs/ day. Operational time of 6 hrs/day (9 am-16 pm) Average solar radiation. Intensity is 3.35 kwh/m^2.day, or (12.73 MJ/m^2.day)		
Tested depths	June	July	August	December	January	February
0.5 cm, 2 cm	15-18	10-13	3-6	5-8	9-12	10-13
0.5 cm, 3 cm	20-23	15-18	3-11	10-13	14-17	15-18
0.5 cm, 4 cm	25-28	20-23	15-18	17-20	21-24	20-23

Results are shown for all the tested water depths. It can be seen from Fig.2 that each tested depth has two values: the first value represents the obtained productivity before applying the cooling method in which the productivity from the lower water depth has 8% higher than that obtained from the tested depth of 2 cm. the same increase of 12% higher than that obtained from the depth of 3 cm, and an increase of 14%in water productivity than that obtained from the depth of 4 cm.

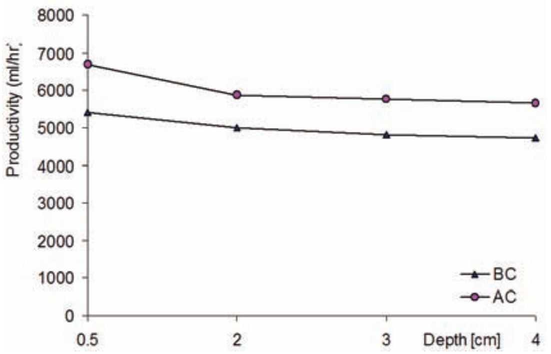

Figure 2: Productivity versus water depth before cooling (BC) and after cooling (AC)

3.3. Effect of cooling the glass cover

In comparison with the previous results which obtained before cooling the glass cover The significant effect of cooling the system is strongly observed on the increased productivity. The effect of cooling the glass cover shows an increase on the water productivity with about 17-23%. The increased productivity is achieved for all the tested depths under the effect of cooling. In each experiment, the lower depth was observed with the higher output than the other tested depths. Also Figure 2 shows the results before and after cooling for all the tested depths. The lower depth as compared with the other depths has 14% higher than that of 2 cm, 16% than that of 3 cm, and 18% higher than that obtained from the tested depth of 4cm, To explore the merit contribution of the applied cooling method, a comparative evaluation was made separately for each water depth as shown in figures (3,4,5, and 6). The obtained results before and after cooling the glass cover are tabulated in table 4.

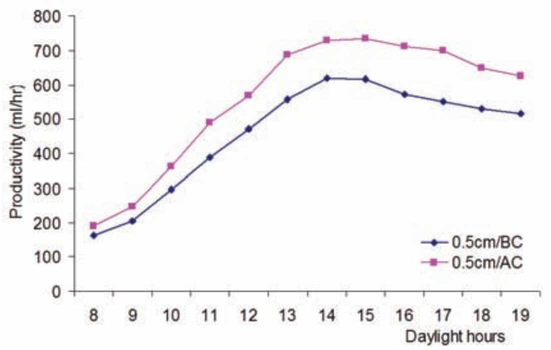

Figure 3: Productivity versus sunlight hours of depth of 0.5 cm, with 5.400 Lit/day before cooling and 6.693 Lit/day after cooling (an increase of 23%)

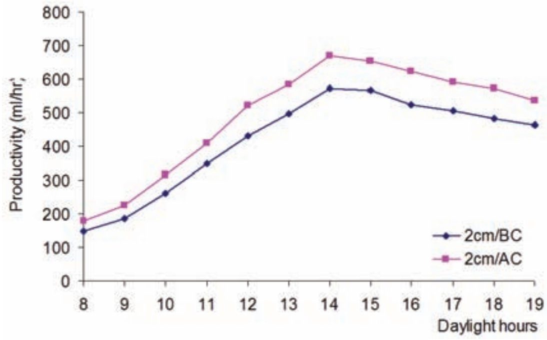

Figure 4: Productivity vs. sunlight hours of the depth of 2 cm, with 4.990 Lit/day before cooling and 5.883 Lit/day after cooling (an increase of 18%)

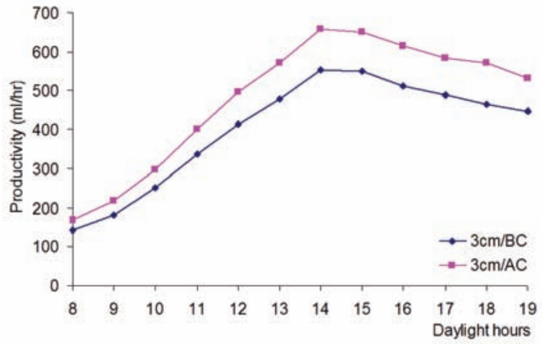

Figure 5: Productivity vs. sunlight hours of the depth of 3 cm with 5.756 Lit/day after Cooling and 4.817 Lit/day before cooling (an increase of 19%)

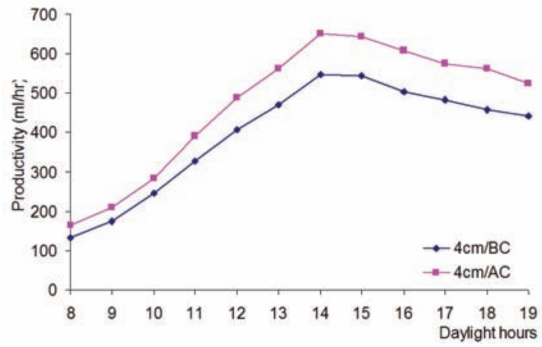

Figure 6: Productivity vs. sunlight hours of the depth 4 cm with 5.660 Lit/day after cooling and 4.733 Lit/day before cooling (an increase of 19%)

Table 4: water productivity before and after cooling for each water depth

	Water depth [cm]	Productivity before cooling [lit/day]	Productivity after cooling [lit/day]	Percentage of increase [%]
Figure 3	0.5 cm	5.400	6.693	23
Figure 4	2 cm	4.990	5.883	18
Figure 5	3 cm	4.817	5.756	19
Figure 6	4 cm	4.733	5.660	19

The tabulated data gives a clear image about the effect of the decreased depth on the increased productivity. The same observations can be made on the positive effect of cooling the glass cover and the resulting increase on the temperature difference (T_w-T_g).

The increased productivity from the lower depth (small mass) is directly related to the increased evaporation rate as well as the faster condensation which is due to the cooling effect. The merit contribution of the cooling method is strongly observed on the increased temperature difference (T_w-T_g) which is nearly 10 ºC after cooling instead of 4 ºC before cooling. A separate thermal behavior is made to show the increased (T_w-T_g) for each tested water depth, and the results are properly represented on the time-temperature curves as shown in Figure 7, (0.5 in comparison with 2cm). The results show the positive effect of cooling the glass cover as indicated by the increased temperature difference (T_w-T_g), and nearly the same increase is obtained for all the tested depths. The last figure (Fig.8) shows a clear image of the created difference after cooling as well as before cooling for all the tested depths. Figure 8 shows the time temperature variation before and after cooling for both tested depths of 0.5 and 2 cm. The ambient temperature, glass temperature and water temperature before and after cooling were measured for every 15 minutes. The obtained results were used to compute the temperature difference for each tested depth and plotted in Figure 7.

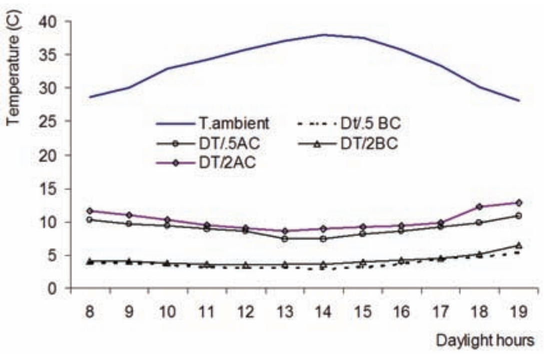

Figure 7: Temperature difference (T_w-T_g) vs. the sunlight hours, for the depths of 0.5 and 2 cm before and after cooling

Actually the thermal performance of the other tested depths are nearly the same, but with different values. Practically, figure 8 can be considered as a sample for the other time-temperature variation regardless the other tested depths.

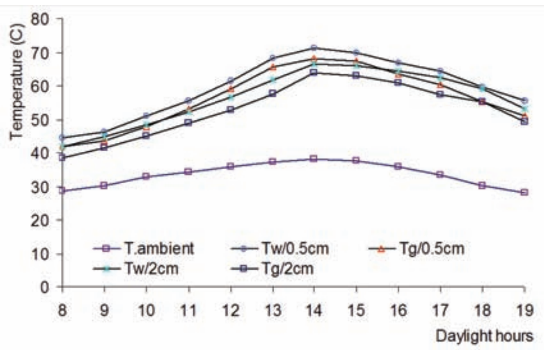

Figure 8: The time vs. temperature variation of ambient, water and glass temperature (before and after cooling) for the depths 0.5 and 2 cm

The obtained productivity from the lower depth with 6.699 Lit/Day shows an accepted agreement with the theoretical productivity of 8.6 lit/day that can be produced under the available climatic conditions. Dividing the experimental output of the lower depth by the theoretical one, the efficient percentage efficiency of solar utilization comes to be about 75%.

4. Conclusions

The major interesting results of the present work can be summarized in the following points:

1. The accepted thermal performance of the constructed solar still with an increased evaporation rate and the faster condensation was achieved due to the appreciated contribution of the improved design parameters and the operational.
2. The merit contribution of using the plastic jackets had a significant role for minimizing the effort of cleaning the deposited scale (by using a new jacket when needed) and maintaining efficient capturing of solar irradiation.
3. The deciding role of cooling the glass cover was strongly observed on the increased temperature difference (T_w-T_g) as well as on the increased water productivity. Higher attention must be spent to the times of applying the cooling method.
4. The concept of using the greenhouse solar stills was found to be very attractive method for obtaining the fresh water even for a small-scale demands, because of several economic and technical advantages such as, the inexpensive technology including the material prices and manufacturing.
5. An efficient utilization of the solar energy could minimize the need for using the expensive conventional sources of energy and meet the energy saving requirements.
6. The efficient utilization of the solar energy with a percentage of 70% was reached and demonstrated by the good agreement between the obtained productivity of 6.7 Lit/day and the theoretical productivity of 9.5 Lit/day that could be obtained under the available climatic conditions.
7. The possibility of increasing the water productivity could be reached by lowering the water depths on the basin- absorbing plate. It is necessary to investigate the effect of all the operational parameters before taking the decision of installing the solar distillation plant.
8. It was found that the geographical location may having a significant positive effect on the increased water productivity, especially for those locations with an abundant solar irradiation and situated at higher elevations above the sea level, where the reduced boiling point of water and the corresponded saturation pressure are below the standard atmosphere.

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