Experimental study on the enhanced condensation in a double slope solar still

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Abstract Water shortage is a worldwide problem. Water scarcity has become a crucial issue in the Middle East. Brackish water desalination appears to be the useful method to secure drinkable water in desert regions. All desalination methods are energy consuming. Solar powered desalination seems to be a promising technology for obtaining potable water in most of hot climate countries having limited resources of fresh water. Solar stills are useful devices to supply fresh water to desert areas but their productivity is very low. Solar distillation systems are classified into two groups: passive and active solar stills. Enhancing the rate of condensation in a double slope solar still is the prime goal of this work. Therefore, a cost effective solar still was constructed and operated under the climatic conditions of Tabouk University to investigate the effect of cooling the glass cover on water productivity. In comparison with the passive operation, the active mode showed a significant increase on productivity to about 9450 ml/day. The increased productivity of about 180% demonstrated the merit contribution of cooling the glass cover.

Keywords: solar still; cooling; evacuated tube; Brackish Water; glass cover; Tabuk region; Saudi Arabia.

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1. Introduction

Most parts of the world receive insufficient rainfall and majority of the rural people are still unaware of the consequences of water scarcity. The demand on fresh water increases continuously because of the rapid growth of population and industrial development. It is alarming to recognize that water scarcity is a great challenge because the rate of water consumption exceeds the rate of water supply all around the world. Desalination was expanding rapidly to support the urban and industrial developments in the arid areas. Desalination of brackish water is a method of reducing the total dissolved salts in the distillate to lower levels. While on the other hand, salt separation using other technologies might be an energy intensive process. Securing a source for obtaining drinkable water in desert regions is the major objective of the present work. Considering the expanding pollution and global warming issues, the demand for developing clean and cheap sustainable energy has increased over the past decade. Solar energy is environmentally friendly; solar desalination appears to be the most economical solution when applied in the arid zones that enjoys with abundant solar radiation intensity to obtain fresh water. KSA depends mostly on seawater desalination; at the same time, it is blesses with higher levels of solar radiation. Recently, Saudi Arabia announced a significant step in advancing the solar powered technology for water desalination. The kingdom is blessed with an average of 5.5 kwh/m2/day (19.8 MJ/m^2.day) in most geographical locations, the average day light hours is about 9-10 hrs. /day equated to about 3300 hrs/year [1]. The average solar radiation varies between a minimum of 4500W/m2/day at Tabuk and a maximum of 7000W/m2/day at Bisha [2, and 3]. Solar powered desalination appears to be the best choice of producing potable water for the desert regions [4]. The lower productivity of solar stills triggered the scientists to investigate various means of improving the still productivity [5, 6]. Water productivity of solar stills increases up to 120% when coupled with evacuated tube solar heater [7]. Water productivity is strongly dependent on the incident solar radiation as well as on the enhanced design and operational conditions [8, 9, and 10]. At the same amount of energy, the decreased level of water (small mass) on the basin of the solar still requires lesser energy that in turn improves the still productivity [11, 12]. The effect of preheating the feed water showed an increase of 75 to 90%, this increase demonstrated the effect of coupling the solar still with a mini solar pond as well as of integrating the still with an evacuated tube solar heater [13, 14, and 15]. The lower depths of water showed an increase on the still productivity to about 120% [16, and 17]. Several studies reported the positive contribution of cooling the glass cover on the temperature difference between water and glass cover (Tw-Tg) [13, 15, 17 and 18]. The significant effect of cooling the glass cover showed an increase of 370% on the still productivity [19]. In fact, the improved productivity of a solar still is directly proportional to the internal mass and heat transfer coefficients (convective, radiative, and evaporative heat transfer coefficient). In this work, an attempt was made to investigate the effect of cooling the glass cover on the water productivity. Namely, to enhance the rate of condensation that in turn increases the water productivity of a double slope solar still. A double slope solar still with basin area of 0.7m^2 (100*70 cm) was constructed, operated, and tested under the climatic condition at Tabuk University, and two types of experiments were conducted. In the first set (passive mode), the solar still was exposed to the direct solar radiation. In the second set (active mode), the solar still was coupled with an evacuated tube solar collector and operated as a simple condenser, the feed water was heated externally and then introduced into the basin. Higher attention was paid the operational parameters influencing the performance characteristics solar stills. The temperature difference (Tw-Tg) is a significant parameter that improves the natural convection inside the solar still.

2. Experimental setup

Experimental setup (Figure 1) consists of single basin double slope solar still coupled with an evacuated tubes solar heater. Important modifications and adjustments were made to suit the experimental work. Key parameters such as heat losses, leakage of vapor, air tightness and insulation parameters were highly considered. The basin plate and walls are made of 3 mm thick galvanized Iron sheet; all the parts are black painted to improve the absorption of solar radiation, the basin has an area of 0.7m2 (1m×0.7m). Higher attention was paid to speed up the flow of condensate and to avoid the tendency of re-evaporation; hence, the U-Shaped collecting channel is placed on the base of the glass cover with an inclination of 10° towards the collecting header. This arrangement is made on both lengths of side walls which have a height of 20 cm on one end and 15 cm toward the collecting header. An immersed tube heat exchanger was made of copper with a total length of 22m is placed on the basin plate to heat the brackish water inside the still. The immersed heat exchanger is connected to the evacuated tube solar heater, two drilled holes (15mm) were made at the lower part of the basin to install the inlet and outlet pipes of the immersed tube heat exchanger. An airtight glass cover was made of two glass sheets (4 mm thick) and properly mounted on a steal frame with an inclination of 45°with respect to horizontal axis. The basin and glass cover are joined to each other by a number of screws. Silicon rubber sealant and rubber gasket (10 mm thick) were used to fix the glass cover with the basin to ensure the air tightness conditions. Polystyrene insulator with thickness of 5 cm placed around the basin sides and bottom and surrounded by 2cm thick wooden box to minimize heat loss. Two rubber pipes are used to collect the condensed water from both sides of the glass cover. Brackish water is introduced into the basin through a steel pipe (1/2 inch) which is placed with 5 cm above the basin plate; the pipe feeder has a number of drilled holes to ensure better distribution of feed water. A drainage hole (1/2 inch) was made at the bottom of the basin to ease the drainage of water when necessary. Two sprinklers (3/4 inch PVC pipe) with sufficient number of small-drilled holes (3mm in diameter) were installed on the top part of solar still in order to ease splashing and cooling both sides of the glass cover. Twelve thermocouples were placed at different locations on the glass cover and basin plate, eight thermocouples were used to measure the inner glass temperature for each side; and four thermocouples are used to indicate the basin temperature inside the still.

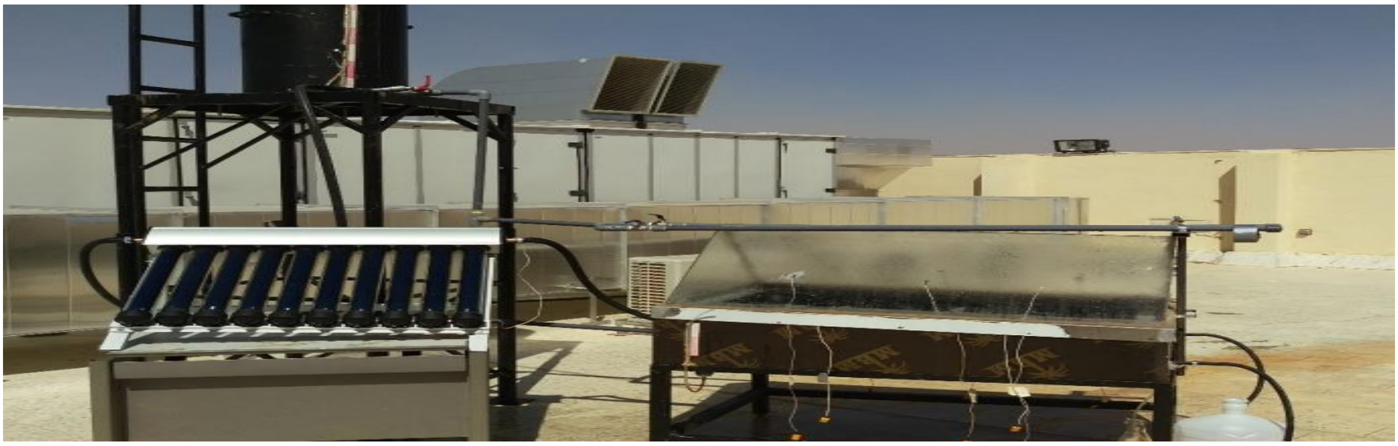

Figure 1: Solar still integrated with the Evacuated Tube Heater

A high temperature feed water was achieved in an evacuated tube solar collector, ten evacuated tubes with 50 cm length and 10 cm outer diameter were mounted on metal frame inclined at of 45˚ with respect to the horizontal axis. The still is made active by fitting a centrifugal water pump (0.5 hp) to circulate the heated feed water. A storage black tank of brackish water (250 liter) was placed at a height of 2.5 m to supply the still with feed water and water for cooling the glass cover.

3. Operating Principles

Heat transfer and heat loses are amongst the crucial parameters that characterize the still performance. The temperature variation in solar still is very crucial and the heat transfer is the most important parameter for producing distillate from solar still. Heated brackish water was fed directly into the still through the perforated steel pipe placed above the basin plate. Heat energy required to evaporate water is the latent heat of vaporization (2260 kJ/kg). In Passive mode of operation, the short electromagnetic waves passes through the transparent glass cover and absorbed by the blackened base. Brackish water begins to heat up and the moisture content between the water surface and the glass cover increases. The warmed vapor starts moving in an upward direction from the basin to the cold surface (glass cover). Finally, the water vapor condenses on the glass cover in form of small-sized droplets of fresh water that runs down under the gravitational force and collected into the storage vessel.

4. Experimental Procedure

The present study is focused on addressing the effect of cooling the glass cover on the still performance. Our experiments were conducted under passive and active moods during the period from March to May 2015 in the campus of Tabuk University. The daily experimentation was scheduled to start at 8:00 am for 10 hours under the climatic conditions of the indicated site. The major factors influencing the still such as scale formation, air-tightness, and other changing parameters were highly considered. In each experiment, proper adjustment was made and the solar still was properly oriented due south. Four levels of brackish water (0.5cm, 2cm, 3cm, and 4cm) were tested; and precisely adjusted to avoid the dry spots formation. Our measurements were carefully established and recorded on hourly basis. Temperature measurements were performed using digital temperature indicator with the aid of 12 thermocouples installed inside the solar still. The measured quantities are the glass temperature

(Tg), basin water temperature (Tw), ambient air temperature (Ta), evacuated tube outlet temperature (Tev). Temperature measurement is of crucial importance for establishing the heating history which helps in explaining the productivity variations. temperature during operation is always higher than the ambient temperature. The aim of cooling the glass cover was established on basis of keeping a higher temperature difference. A temperature difference (Tw-Tg) of about 15ºC was achieved after cooling the glass sheets. Practically, a jet of tap water (25 ºC) was used for a time interval of 2 two minutes which is sufficiently enough to provide a steady film of water for cooling and cleaning the outer side of glass sheets. Periodicity of cooling the glass sheets was fixed for each 20 operation minutes when operating under Passive mode. While for the active mode (coupled with evacuated tubes), the periodicity was fixed for each 15 working minutes. Temperature measurement is performed in each time with five minutes before cooling the glass cover. The hourly output of distillate was collected in a graduated cylinder and stored in the storage bottles.

5. Results and Discussion

Temperature variation is one of the most important elements that should be identified when performing thermal analysis of solar still. Data regarding solar energy (day light hours, and average solar radiation intensity) and temperature variation during the last 10 years in Tabuk area was collected and evaluated. The minimum and maximum temperature are presented in Figure2, the average of 36°C (April-November) is good indicator that encourages the use of solar powered desalination technique

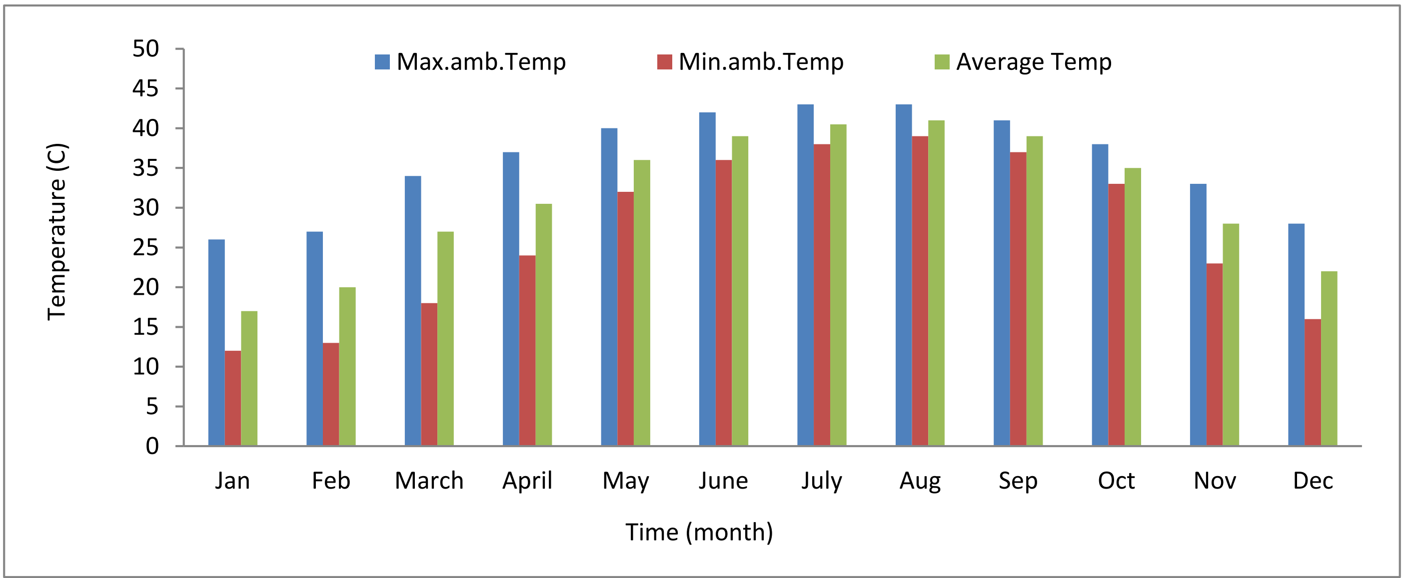

Figure 2: Time -Temperature variation in Tabuk area

The basin-type solar still is very simple and widely used for water desalination, the passive mode of solar stills can operate at low temperature, but its daily productivity is comparatively very low especially during the noon hours. Reduced productivity at the noon hours is justified by the suspended vapor film on the inner side of glass cover. A three months study showed that the water productivity is strongly dependent on the design and operational conditions. The temperature difference (T_w-T_g) is the clue secret of the reduced productivity. In absence of any cooling medium, the reduced temperature difference is considered as the suspected parameter that adversely affects the driving forces of the convective currents of evaporation and condensation. Also, the suspended thin film of vapor on the glass cover has a significant role in dissipating solar radiation falling on the glass cover. Therefore, a decision of cooling the glass cover was made to increase the temperature difference (Tw-Tg). All experiments were repeated two times to ensure the reproducibility.

The first set of experiments was conducted during the period of 15-22/April/2015 to perform the necessary calibrations and adjustments. The Passive solar still was exposed directly to the solar radiation and operated for two days (10hours/day). *In the first day*, the depth of 2cm was tested, and the system was operated in Passive mode without cooling. Two important results were obtained,

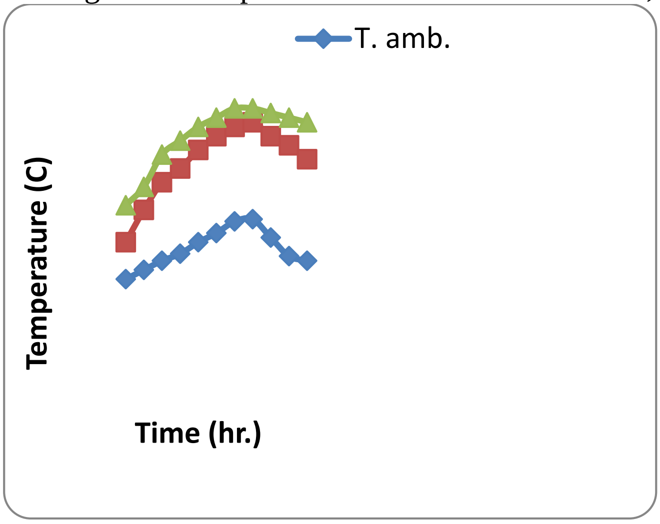

Figure 3: Passive solar still operated without cooling

In the second day, the decision was made to apply the cooling method for only one glass sheet and tokeep the other without cooling. The system was operated in Passive mode and one glass sheet was splashed three times with a jet of tap water (25ºC) for a time interval of two minutes in each time. In comparison with the first experiment, the water productivity was increased to 5.3L/day instead of 3.82 L/day, and the temperature difference (Tw-Tg) was increased to about 10ºC. The higher productivity of 38% demonstrated the significant contribution of the cooling effect even for only one glass sheet. It was concluded that the increased temperature difference contributed to empower the natural convection and improving the driving forces of vapor motion. The increased difference of temperature as a result of cooling is clearly shown in Figure 4.

namely, in absence of cooling water productivity was 3.85 L/day, and the average difference (Tw-Tg) at noon hours was ranged to 5°C. Figure 3, gives better visualization regarding the temperature difference. At noon hours the glass temperature is very close to the water temperature inside the solar still. The lower temperature of ambient air surrounding the still has an effect of increasing the temperature difference during the morning and afternoon times.

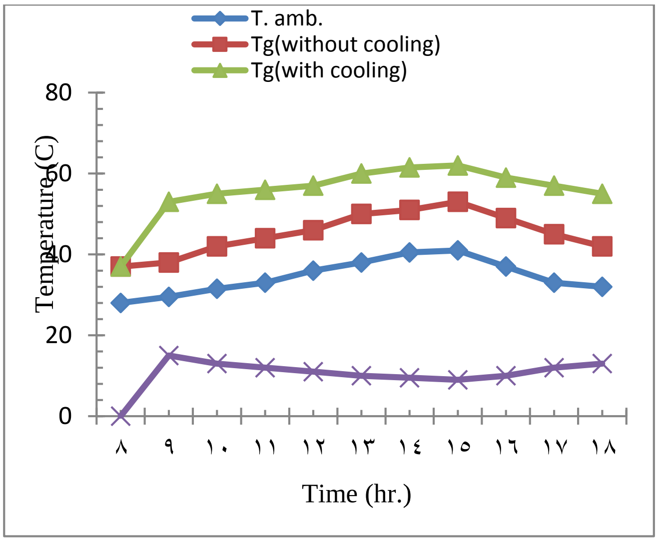

Figure 4: Effect of cooling one glass sheet on the increased productivity

The second set of eight experiments was made with a focus on exploring the effect of other changing parameters such as the water depth. Therefore, different levels of brackish water (0.5cm, 1cm, 2cm, and 3cm) were tested during the period (25 April-25 May/2015). Each water depth was tested in both modes of operation (Passive and Active), and a comparison of water productivity as before cooling (BC) and after cooling (AC) was made for both passive and active operation. A time interval of four days of experimentation is sufficiently enough to explore the effect of changing parameters on the still productivity. Improved productivity after cooling is indicated by the daily productivity (L/day) and the percentage increase for both passive and active modes. The obtained results from all tested depths of water were summarized and tabulated (Table 1). In passive mode, the effect of cooling is observed with an increase of 21 to 28% on the water productivity. In the active mode, the increased productivity after cooling is ranged from 26 to 31.2%. Another comparison was made to explore the combined effect of preheating the feed water in combination with the effect of cooling the glass cover, obtained results after cooling (AC) in the active mode showed an increase of 169-to 180% higher than those of passive mode before cooling (BC)..

Table1: Daily productivity (Passive and Active) before and after cooling

Depth In cm	Passive Mode Water productivity [L/day],			Active operation Water productivity [L/day]			
	B.C	A.C	%	B.C	A.C	%	%
0.5	5250	6695	28	7200	9450	31.2	180
2	4900	6125	25	6700	8575	28	175
3	4600	5660	23	6300	8050	27	175
4	4450	5385	21	5985	7540	26	169

The lower depth (0.5cm) was observed with the highest output than the other tested depths. The obtained results from all depths are plotted on proper time-production curves It should be mentioned that for each experiment, the system was operated in the first two days without cooling the glass cover, while in the last two days the cooling process was applied. Figure 5 provides good visualization regarding the obtained results for depth of 0.5cm. The increased productivity is directly related to the increased evaporation rate due to preheating smaller water mass, while the enhanced condensation is due to the cooling effect. The merit contribution of the cooling method is strongly observed on the increased temperature difference (Tw-Tg) which is nearly 10 to 15ºC after cooling instead of 4 to 6ºC before cooling.

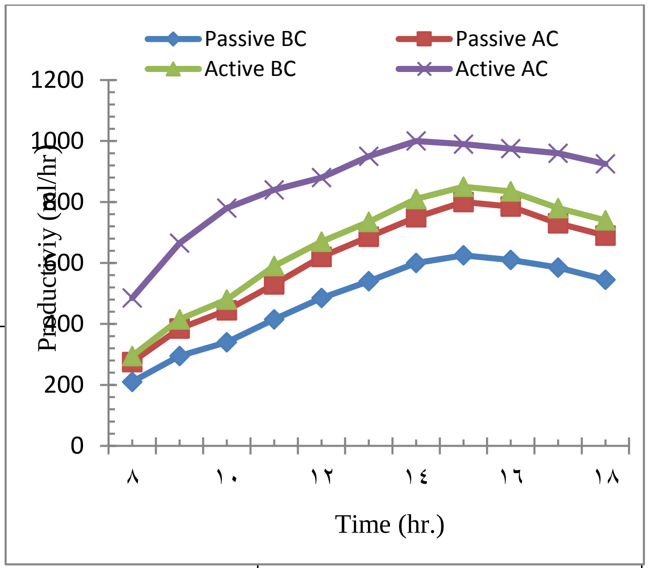

Figure 5: Daily productivity from the water depth of 0.5 cm

Another set of experiments was made to evaluate the effect of changing the water depthon the daily productivity. The same testing procedure was applied for each water depth; the obtained results from both modes of operation (Passive and Active) were recorded. Clear image regarding the obtained results from the Passive mode are presented in Figure **6**, daily productivity as before and after cooling are clearly shown.

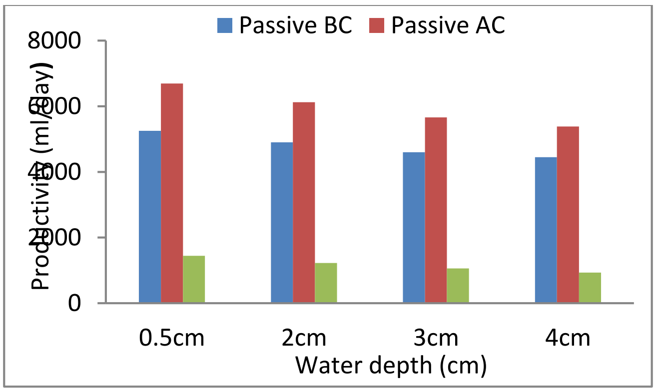

Figure 6: Daily productivity before and after cooling from the Passive mode

The experimental results have shown with no doubt that the water depth has a significant influence on the increased productivity. Changing the mode of operation from the passive to active mode has a significant effect on the increased productivity as due to the effect of preheating the feed water in the evacuated tube solar heater. The obtained results from the Active mode before and after cooling are shown in figure 7. The difference of water productivity for each tested depth is much higher than that in the passive mode; this is due to the increased periodicity of cooling. In this experiment, the glass sheets were splashed for each 15 working minutes.

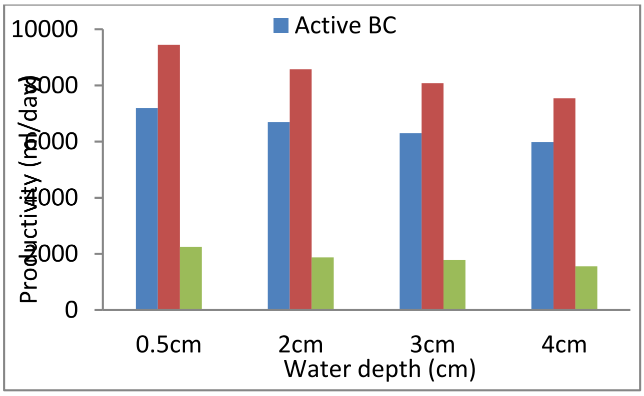

Figure 7: Daily productivity before and after cooling from the Active mode

Figure 8 provides a clear image regarding the combined effect of cooling and preheating the feed water on the daily productivity. As shown in the figure, the higher productivity is obtained from all tested depths when the system is operated under the active mode. The merit contribution of cooling the glass cover in combination with the effect of heating feed water participated to the increased productivity. For all tested depths, the higher productivity was obtained from the active mode after cooling (AC) the glass cover, while the lower productivity was obtained from the passive mode before cooling (BC). The highest productivity of 9.45L/day was obtained from the lower depth of 0.5cm

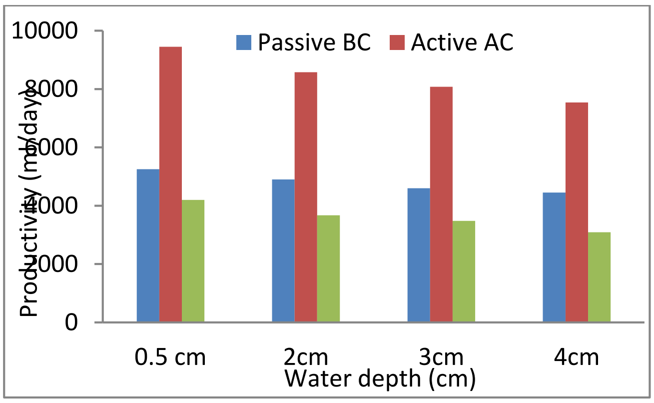

Figure 8: Combined effect of preheating feed water and cooling process

Figure 9 gives another visualization regarding the combined effect of cooling the glass sheets and preheating the feed water, the combined effect contributed to an increase of about 169-180% on the daily productivity

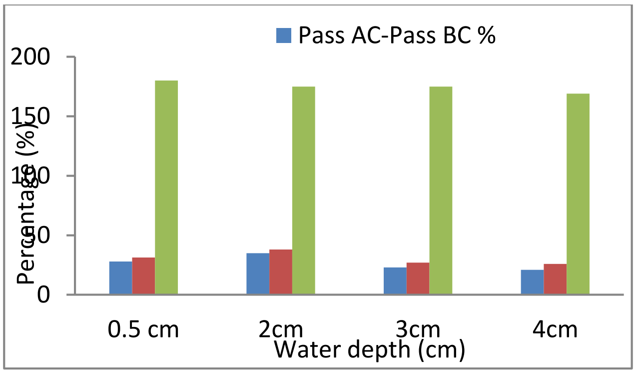

Figure 9: Comparison between water productivity before cooling in passive mode and after cooling in active mode.

More attention was paid to the depth of 0.5 which provide the highest productivity with an output of 5.25 L/day when the still is operated in passive mode without cooling and the maximum productivity of 9.45L/day from the Active mode after cooling. The increased productivity of 180% is a result of preheating the feed and the merit contribution of the cooling process.

6. Conclusions

The objective of the present work was has been achieved. The water productivity increases considerably after cooling the glass cover for both modes of passive and active solar desalination. The most important conclusions are listed as below:

- The temperature difference (Tw-Tg) is the clue secret for achieving higher productivity, and the optimized periodicity of cooling the glass sheets has the merit contribution on the increased temperature difference to about (10-15°C).
- An imbalance between evaporation and condensation processes occurs in absence of cooling medium, it can be detected by the small difference between the temperatures of glass sheets and that of basin water.
- The rapid formation of thin vapor film on the internal sides of the glass cover after few minutes is a result of preheating the feed water. While, the fast motion of water

droplets to the collecting channel is an indicator of the enhanced condensation.

- The maximum productivity of 9.45L/day is the merit contribution of combined effect of cooling and preheating the feed water.

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