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Full Length Research Paper

Seasonal performance evaluation of solar stills connected to passive external condensers

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In recent years, investigations and research has focused on exploring methods and finding ways to enhance solar stills efficiency and increase the production rates. In this study, experiments were carried out for 24 h during summer, autumn, and winter in order to investigate the affect of incorporating passive external condensers to a single-slope, single basin type solar still. Therefore, three identical solar stills were designed and constructed with the glass covers mounted on the stills at an inclination of 20° to the horizontal plane, with an effective area of 1 m^2. The first still was used for reference; the other two were connected at the back by means of pipes to passive cylindrical condensers in two different ways. One still was connected only, through the upper part of its back, while the other still was connected from both upper and lower parts of its back. The distilled (condensed) water was collected either through the condensers or by running down the inclined glass cover into a trough. It has been found that the average production rate obtained from the experiments conducted during the summer season is about 42.9% higher than that obtained during the autumn season and 117.4% higher than that obtained during the winter season. It has also been found that the still connected through the upper part only yielded an increase in its production rate of 15.1, 15.08 and 16.6% for the summer, autumn, and winter respectively in respect to the conventional simple solar still. The still connected to the condensers through its upper and lower parts yielded an increase in its production rate of 30.54, 33.6 and 35.8% for the summer, autumn and winter respectively, in respect to that produced by the conventional simple solar still. The overnight production rate was found to represent an average ratio of 10.8, 13 and 19.7% of the total daily production rate, for the summer, autumn, and winter respectively.

Key words: Solar still, solar distillation, water desalination, solar still efficiency.

INTRODUCTION

A fresh water supply has become one of the major problems in many parts of the world, especially in arid and remote areas (Varun, 2010). Bahrain and other Gulf regions lie in the high solar band region and therefore can be exploited to convert saline water to potable water. The most economical and easy way to accomplish this objective on a small scale is by using solar stills (Ahmed et al., 2010; Murugavel and Srithar, 2011). Solar still distillation represents the foremost attractive and simple technique among distillation processes, and it is particularly suited for production on a small scale, where the intensity of solar energy is considerable. It is easy to set up and needs little and cheap maintenance (El-Zahaby et al., 2011). A Solar still usually consists of a shallow, airtight basin with an inclined top cover made of clear transparent material (Glass covered Solar Stills are rather more rugged and trouble free and are able to withstand climatic and environmental conditions far better than plastic). The inside surface of the bottom of still, is usually painted black to maximize the absorption of sun's heat (Ighodalo and Ebhodaghe, 2011).

The basic principles of solar water distillation are simple, yet effective, as it exactly replicates the heating, evaporation and condensation processes occurring in nature to purify water (Al-Hayeka and Badran, 2004). It represents a direct simulation process of the green house effect. The suns rays penetrate the transparent inclined cover heat up the water. The heated water evaporates and condenses on the inner side of the transparent surface. The condensate which is distilled water runs down the inner side into troughs from where it can be collected in storage containers (Panchal and Shah, 2011).

There are several types of solar stills, the simplest of which, and the most common, is the single basin solar still. Despite the advantages of this device, its low productivity is recognized (Badran and al Tahaineh, 2005). The solar still productivity and efficiency was found to be dependent on key parameters such as solar radiation intensity, ambient temperature, location, glass cover material, its thickness and its inclination, wind velocity and the basin water depth of the still (Kabeel and El-Agouz, 2011). The yield of a single basin single slop solar still is usually in the range of 2 to 4 L/day/m² (Kumar and Bai, 2008). For this reason the solar still is not popular (Ismail, 2009). Kabeel and El-Agouz (2011) conducted a literature review and reported that in most cases, even under optimized operating conditions, the efficiency of the conventional single slop single basin solar still was in the range of 30 to 45%, with less than 5 L/m^2/day of fresh water production. Therefore, the main goal of this research is to explore new concepts and examine different designs to enhance the solar still productivity (Dev et al., 2011). They have investigated the effects of climatic, operational and design parameters on the performance of a basin type solar still in order to improve the productivity (Arjunan et al., 2009).

The main driving force for the distillation process is the temperature difference between the water and the still cover. The heat produced by condensation is transmitted from the condensed vapor to the cover, increasing the cover temperature, and consequently, reducing the condensation rate in the conventional still, and resulting in relatively low efficiency (Madhlopa and Johnstone, 2011).

Minimizing water depth is always regarded as one of the key parameter to enhance day time still output (Khalifa and Hamood, 2009; Tiwari and Tiwari, 2008).

El-Zahaby et al. (2011) introduced a new approach to control water depth through creating a thin re-established film of saline water in a particular manner in the solar still. They reported that a high efficiency of 77.35% was achieved. Boubekri and Chaker (2011) found that integrating external and internal reflectors in a solar still has the impact of increasing the solar productivity by up to 72.8% in the winter, 40.33% in the spring, and 7.54% in the summer. They also found that using a thermal storage tank with the solar still will increase the still productivity by 27.5, 21 and 23.2% in the winter, spring and summer respectively. Abdallah et al. (2008) found that the installation of reflecting mirrors on all interior sides of a single slope solar still enhanced its productivity by 30%. Tanaka (2010) performed a theoretical analysis of a basin type solar still with internal and an external reflectors. They used a flat plate which extends from the back wall of the still as an external reflector. They reported that the average daily production rate of the still throughout the year increased, compared to a conventional basin type still, and was predicted to be 29, 43 or 67% when the glass cover inclination was 10º, 30º or 50º and the length of external reflector was half the still’s length. Dev et al. (2011) carried out experiments using an inverted absorbing solar still and a single slope solar still. They found that the inverted absorbing solar still produced 6.302 kg/.m² days in comparison with the simple solar still which produced 2.152 kg/m²-day less in the same working conditions. Abdulla and Badran (2008) found that introducing a sun tracking system to a fixed conventional solar still enhances its productivity by 22%. Abdallah et al. (2008) found that replacing the flat basin of the still by a stepped basin enhanced its performance by 180%. They also found that coupling this design with a sun tracking system will further enhance the still's thermal productivity by 380%. Kabeel et al. (2012) found that introducing a stepped basin to the conventional solar still increased its productivity by up to 57.3%, depending on the tray depth and width. El-Sebaii et al. (2000) added a suspended plate within the basin water of a conventional single basin solar still in order to decrease the preheating time required for evaporating the still basin water. They found that to be around 18.5 to 20% higher than that of the conventional solar still.

Ghoneyem and Ileri (1997) found that that a solar still with a glass cover of 3 mm thickness yielded 16.5% more production than a cover 6 mm thick. Akash et al. (1998) found that using black ink and dye increases the still productivity to 45 and 60% respectively. Velmurugan et al. (2008) tried to increase the still productivity, by enhancing the evaporation rate, using sponges and fins. They reported that productivity increased 15.3% when sponges were used, while the productivity increased by 45.5% when fins were used. Nafey et al. (2002) reported that using a floating perforated black aluminum plate in a solar still increased the productivity by 15% at a brine depth of 3 cm and to 40% at a brine depth of 6 cm. Badran and Al-Tahaineh (2005) reported that the coupling of a flat plate solar collector to a conventional single slope solar still with mirrors fixed to the interior sides coupled with a flat plate collector enhanced its productivity by 36%. Badran (2007) found that the use of asphalt in the basin of a conventional solar still improved its production rate by 29%. The use of a sprinkler combined with the asphalt improved the still productivity by 51%.

Abu-Hijleh and Mousa (1997) found that the use of a water film to cool down the still cover increased the productivity by up to 20%. Ahmed et al. (2010) found that integrating a cooling tube attached to the inner surface of the glass cover of a conventional solar still will decrease its productivity by about 4%. Madhlopa and Johnstone (2009) fitted a separate condenser to a conventional solar still and calculated its performance. They found that the solar still productivity increased by 62% in comparison to a conventional solar still without condensers. El-Bahi and Inan (1999a) found that coupling a conventional solar still to an outside passive condenser increased its productivity by 75%. El-Bahi and Inan (1999b) used direct and reflected solar radiation utilizing a double glass cover and an integrated separate condenser. They reported that the efficiency was increased by 48% and it exceeded 70% when the condenser cover was cooled down. Sakthivel et al. (2010) introduced a medium of jute cloth into the conventional single slop solar still, in an effort to increase the evaporation surface and to utilize the latent heat of condensation. They found that still productivity increased by 8%. Abdallah et al. (2009) used three different types of absorbing materials in an attempt to improve the thermal performance of the single solar still. They found that the overall average gain in the collected distilled water was 28% when coated metallic wiry sponges were used and by 43% when the uncoated metallic wiry sponges were used. The gain was 60% when the black rocks were used. A.E. Kabeel (2009) found that using a concave jute wick surface had the effect of increasing the amount of absorbed solar radiation and consequently enhanced the evaporation surface area. This resulted in an increase in the solar still productivity of 30%. Arjunan et al. (2009) found that using blue metal as a storage medium in a conventional solar still improved its productivity by 5%. Sakthivel and Shanmugasundaram (2008) found that using a black granite gravel material as a thermal energy storage medium improved its productivity by about 17 to 20%.

Nijmeh et al. (2005) found that using potassium permanganate as an absorbing material increased the single basin double cover solar still productivity by 26%, while using violet dye improved the productivity by 29%. Mahkamov and Akhatov (2008) performed experiments on a multistage solar thermal water desalination system. They found that the productivity was twice as high as that of conventional solar stills. Nassar et al. (2007) performed experiments on a concave mirror, which reflected the suns rays to focus inside the still. The still was put under vacuum pressure. A condenser was used to condense the outlet vapor. They found the still productivity increased by 303%. Al-Karaghouli and Alnaser (2004) investigated the performance of single and double-decker basin stills. Both stills have the same basin area. They found that average production for the double-decker basin still is about 40% higher than the production of the single basin still. Arunkumar et al. (2012) introduced a new design of solar still with a hemispherical top cover for water distillation with and without water flowing over the still cover. They reported that the solar still efficiency increased from 34 to 42% with the top cover cooling effect.

In the present work, outdoor experiments have been conducted during July 2011 (representing the summer season), October 2011(representing the autumn season), and January 2012 (representing the winter season), to evaluate the seasonal effect of connecting external passive condensers to the conventional single slope basin type solar still using two different methods of connection.

METHODOLOGY

In this investigation, three identical single slope basin type solar stills were designed and constructed from 1.4 mm galvanized steel with a net basin area of 1 m² (1x1m). A 4 mm thick glass cover was fixed at an angle of 20º to the horizontal to each solar still. In order to maximize the absorption efficiency of solar radiation and the insides of the galvanized basins were painted black.

To prevent or minimize heat lose from the base and the sides of the galvanized basins, each galvanized basin was fitted inside a wooden basin of an identical shape, but of a slightly larger size.

The gaps between each wooden and galvanized basin were packed with 50 mm thick glass wool with an insulation thermal conductivity of 0.045 (W/m² °C). The first still was used as a reference. The schematic diagram of the first still is shown in Figure 1.

Four identical passive cylindrical condensers were designed and constructed from 1.4 mm galvanized steel. Each condenser had a diameter of 30 cm and a height of 80 cm. The condensers were fixed to the back of the other two solar stills by 10 cm diameter, 20 cm length galvanized pipes using union connections (to facilitate connecting and disconnecting the condensers). The first two condensers were fixed in parallel to the upper part of the back of the second solar still as shown in Figure 2. The other two condensers were fixed, in parallel, to the back of the third still at both upper and lower parts, as shown in Figure 3. A short pipe fitted to a half inch valve and to a 30 cm flexible hose was fitted at the lower end of each condenser and was used to drain and collect the condensed water. During the experimental tests, wooden boards were used to shield the condensers from direct sun radiation to prevent heating up the condensers surfaces.

A suitable frame was built and all three stills were mounted adjacent to each other as shown in Figure 4. A level meter was used to ensure that they were precisely horizontal. A feed water tank was fixed at the same level as the stills with a float to feed and control the water level inside the three stills to a fixed value of 1 cm. As an extra precaution, to ensure that the water level inside the stills is exactly horizontal, and the brackish water is at the same constant level in all three stills, white lines one cm from the bottom of each still basin were painted all round the inner side of the basins. The water level was checked before and throughout the tests. A trough of suitable shape and size was fitted at the lower edge of each glass cover and was used to collect the condensed fresh water which ran down.

A half inch diameter pipe was fitted to a valve and a 30 cm flexible hose which was then connected to the bottom of the trough of each still. They were used to collect the condensed water running down the glass cover into the troughs. The flexible hoses lead to plastic bottles, where the collected condensed water was be measured in a graduated flask. All three stills had drainage pipes and valves fitted to the lower part of the stills. Other sets of half inch pipes and valves were fixed at the lower end of the back of the still and were connected to the feeding tank through the main pipe. Silicon rubber was used to seal all the stills. The sealant is an

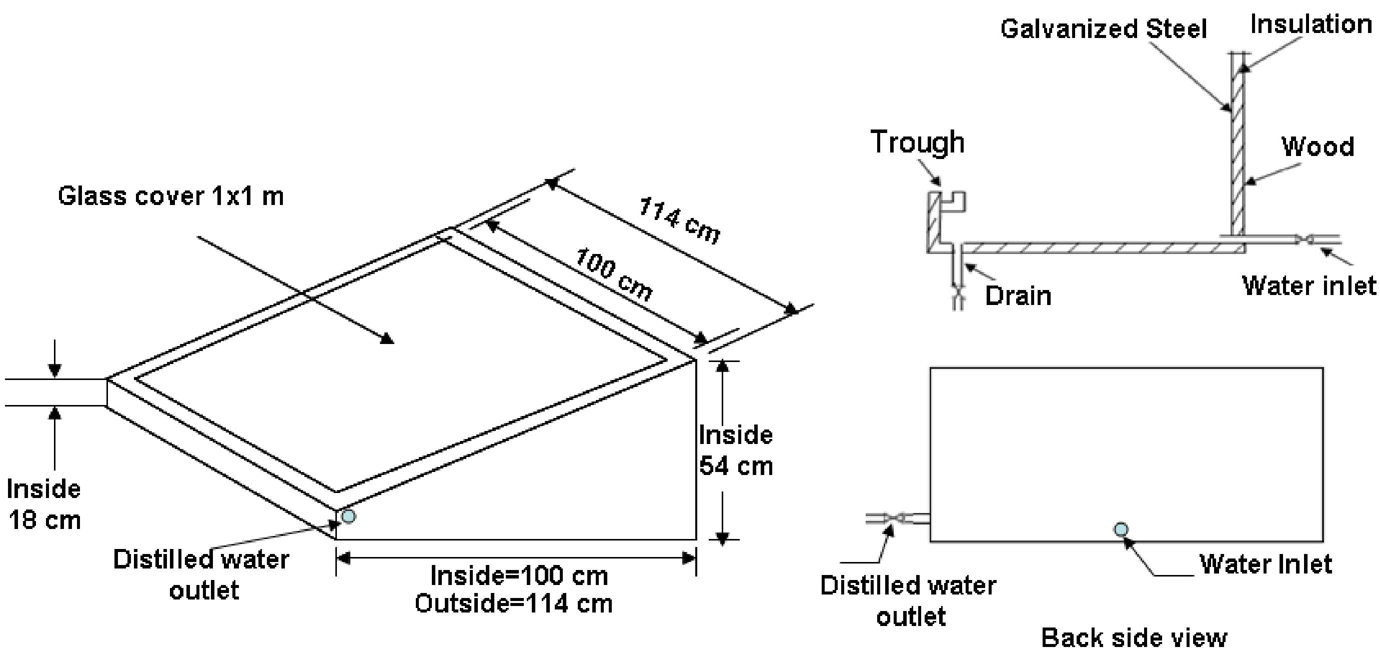

Figure 1. Schematic diagram of conventional solar still.

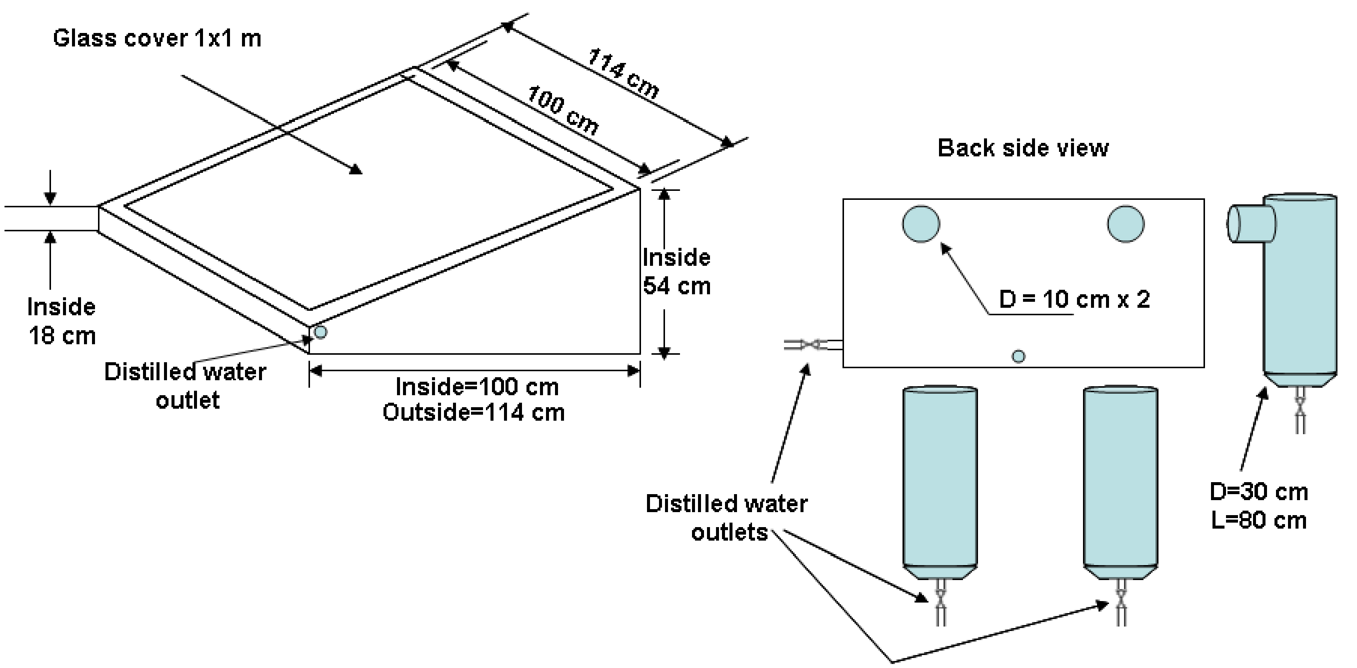

Figure 2. Schematic Diagram of Solar still linked to passive condensers by single connection.

essential factor for efficient operation. The three stills were positioned adjacent to each other facing south as shown in Figure 4.

In the present study a solar intensity meter was used to measure the solar radiation intensity in w/m² (its range was from 0-1.999 kw/m²). The wind speed was measured using a digital wind anemometer with a range of 0-15 m/s and an accuracy of ±0.2 m/s. Copper-Constantan thermocouples were used to measure the ambient temperature, the galvanized tanks basin temperatures, the water temperatures, the vapor temperatures inside the stills, the glasses inner and outer temperatures, the condensers inside temperatures and the condensers outer surface temperatures.

The experiments were conducted on days with clear skies at the Gulf University, in the city of Sanad in the Kingdom of Bahrain

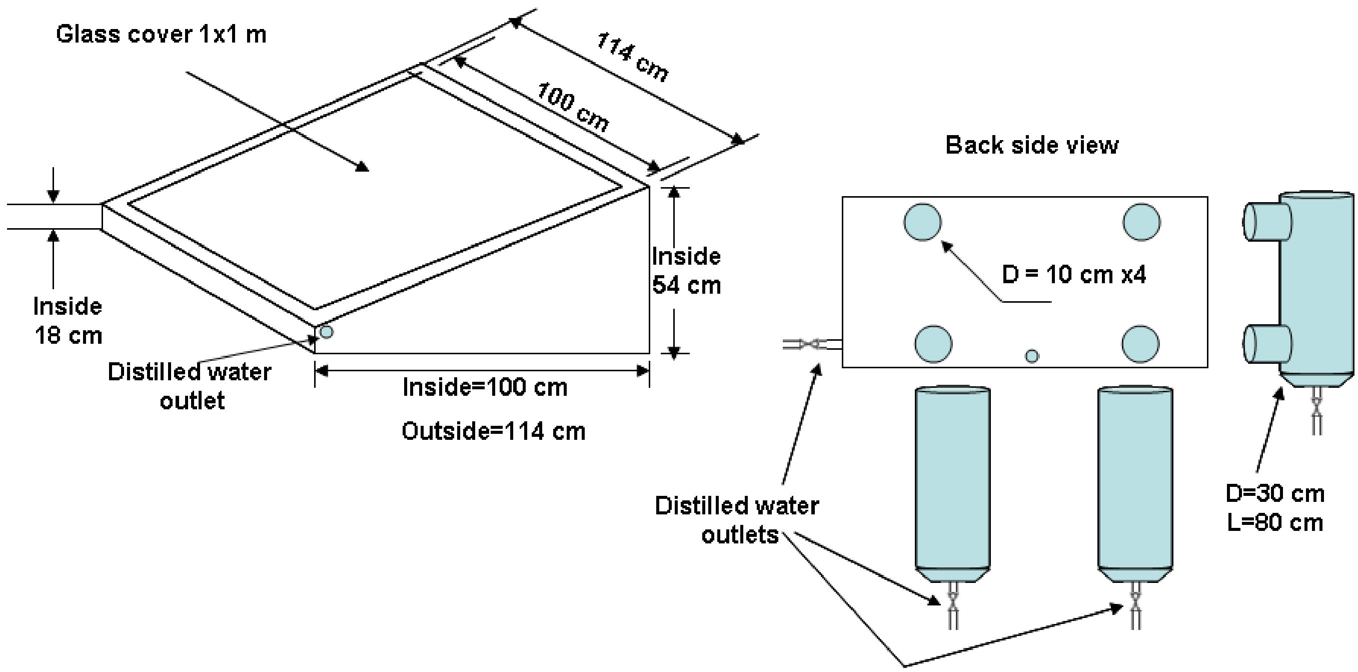

Figure 3. Schematic Diagram of Solar still linked to passive condensers by double connections.

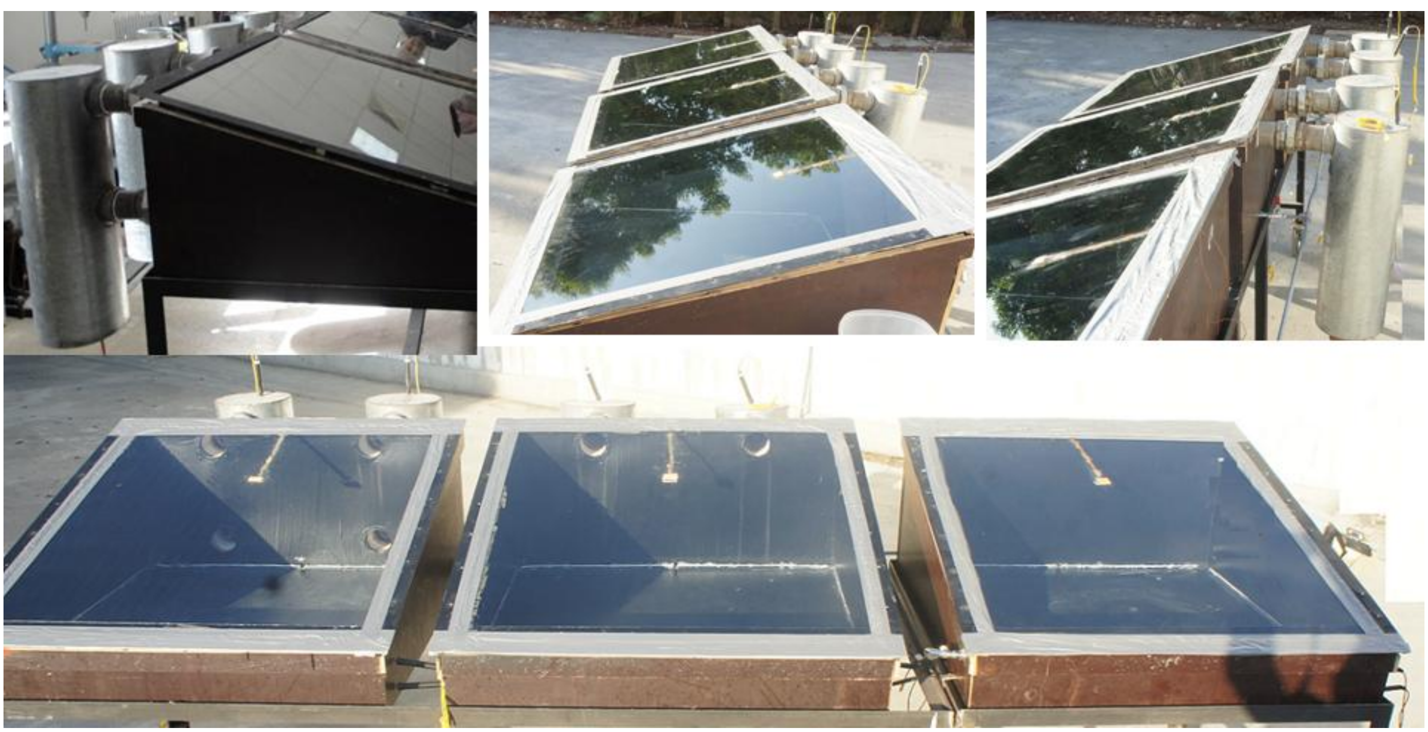

Figure 4. Different views of the solar stills.

(32.4º E 26.1º N) during the month of July 2011 (which represented the summer season), October 2011 (which represented the autumn season), and January 2012, which represented the winter season). Preliminary tests were conducted for two days to make sure that the system was ready. Then the experiments were conducted for another two days and the average values taken.

RESULTS

In this research, experiments were conducted at Gulf University in the city of Sanad, in the Kingdom of Bahrain in July and October 2011 and January 2012 to investigate the seasonal comparative performance of linking passive condensers to conventional single basin, single slop solar stills. The methods of linking the condenser to the solar stills were also investigated. For the purpose of ensuring the stability of the cells and to verify the results obtained, each experiment was repeated three times. Three simple solar stills were used. The first was a conventional, single basin, single slope solar still which was used as a reference, that is, for comparison with the other two stills. In the second still, two cylindrical condensers were linked in parallel, only to the upper part of the back of the still. In the third solar still, another two condensers of an identical shape and size were connected to both upper and lower parts of the still back. The three stills were set up level and adjacent to each other facing south. Wooden boards were placed on the top and sides of the condensers to shield them from direct sunlight reach them. The water depth inside the three stills was leveled and controlled to one centimeter by means of a float fixed in the feeding tank. The readings of solar intensity, wind speed and the temperatures at various locations in the three stills were taken from 6:00 am in the morning till 6:00 pm in the evening at two hour intervals. At the same time the condensed water from the condensers which ran down the glass covers, was collected and measured individually. The first collections at 6:00 am represented the overnight condensation.

It was found that the conventional solar still's daily production of distilled water was 3.340 liter/day, 2.320 liters/day, and 1.510 liters/day for the summer, autumn, and winter respectively. All condensates were collected by the trough at the lower side of the glass cover. Summer production rate is about 44% higher than the autumn production rate, and 121% higher than the winter production rate.

The solar still that had the condensers connected to only the upper part of its back yielded a daily production rate of distilled water of 3.845 liters/day, 2.670 liters/day, and 1.760 liters/day for the summer, autumn, and winter respectively. The summer production rate was 44% higher than the autumn production rate, and 118.4% higher than the winter production. The solar still that had the condensers connected to both upper and lower part of its back yielded a daily distilled water production rate of 4.360 liters/day, 3.100 liters/day, and 2.050 liters/day for the summer, autumn, and winter respectively. The summer production rate was 40.6% higher than the autumn production rate, and 112.7% higher than the winter production rate. The comparison between the summer, winter, and autumn distilled water production rates for the three stills are shown in Figures 5, 6 and 7 respectively. The average production rate, for the three solar still, in the summer season was 42.9% higher than that produced in autumn season and 117.4% higher than that produced in winter season.

DISCUSSION

In order to find out the effect of incorporating the condensers to the solar stills, the data obtained for the three seasons has been studied and analyzed. Comparing the productions rates of the three stills during the month of July (the summer season), it was found that the solar still that had the condensers connected, in parallel, to only the upper part of its back produced total of 3.845 liters/day, representing an increase of 15.1% in comparison to the conventional, reference solar still. 1.490 liters of the produced distilled water was collected from the condensers, while the other 2.355 liters were collected from the trough located at the lower end of the glass cover. The still that had the condensers connected, in parallel, to, both, the upper and lower parts of its back produced a total amount of distilled water of 4.360 liters/day, representing an increase of 30.54% in comparison with the conventional solar still production rates. 1.885 liters of the produced distilled water was collected from the condensers and the other 2.475 liters was collected from the trough located at the lower end of the glass cover.

A comparison of the production rate during the month of October revealed that the solar still that had the condensers connected, in parallel, to only the upper part of its back produced a total of 2.670 liters/day, representing an increase of 15.08% in comparison to the conventional, reference solar still. 1.010 liters of the produced distilled water was collected from the condensers, while the other 1.660 liters were collected from the trough located at the lower end of the glass cover. The still that had the condensers connected, in parallel, to, both, the upper and lower parts of its back produced a total amount of distilled water of 3.100 liters/day, representing an increase of 33.6% in comparison with the conventional solar still production rates. 1.290 liters of the produced distilled water was collected from the condensers and the other 1.810 liters was collected from the trough located at the lower side of the glass cover.

A similar trend was obtained when the production data obtained from the experiment conducted during the month of January (winter season) was compared. The solar still that had the condensers connected, in parallel, to only the upper part of its back produced a total of 1.760 liters/day, representing an increase of 16.6% in comparison to the conventional, reference solar still.0.640 liters of the produced distilled water was collected from the condensers, while the other 1.120 liters was collected from the trough located at the lower

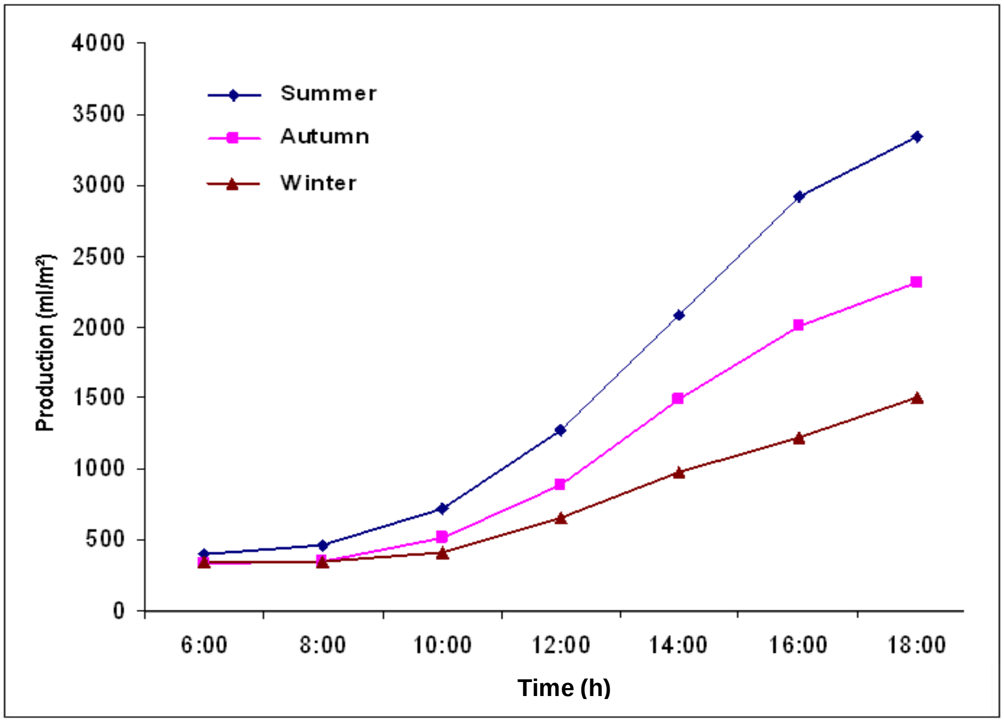

Figure 5. Comparison between summer, autumn, and winter production rate for the solar still without condensers.

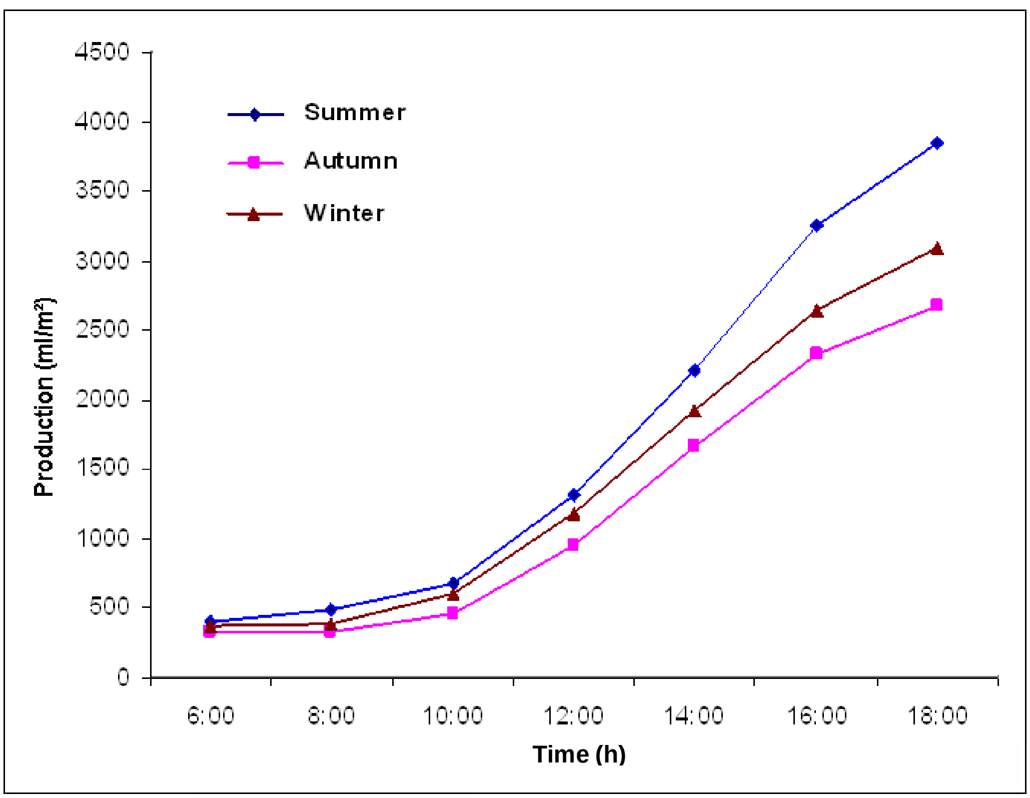

Figure 6. Comparison between summer, autumn, and winter production rate for the solar still linked to condenser by one connection.

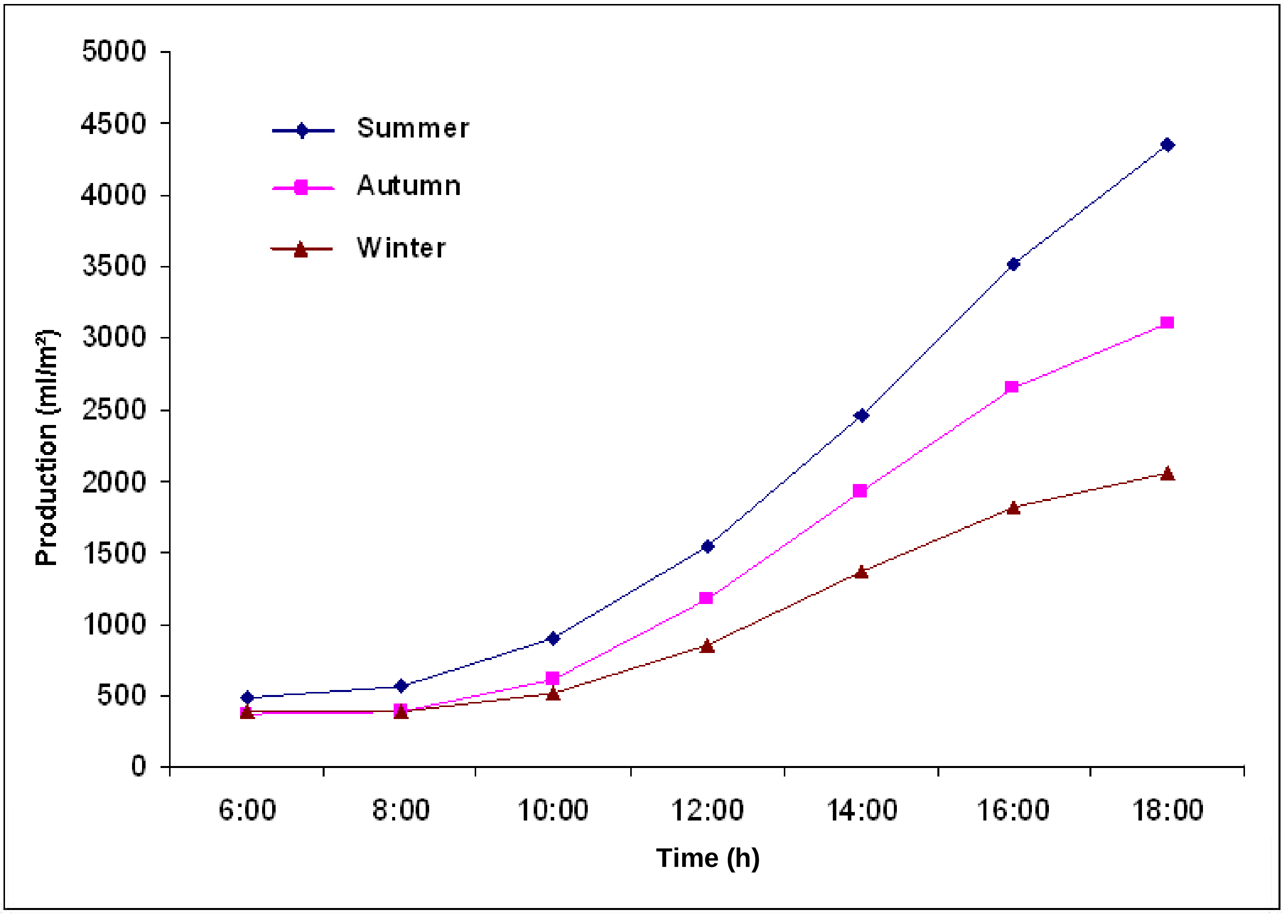

Figure 7. Comparison between summer, autumn, and winter production rate for the solar still linked to condenser by two connections.

end of the glass cover. The still that had the condensers connected, in parallel, to, both, the upper and lower parts of its back produced a total amount of distilled water of 2.050 liters/day, representing an increase of 35.8% in comparison with the conventional solar still production rates. 0.900 liters of the produced distilled water was collected from the condensers and the other 1.150 liters was collected from the trough located at the lower end of the glass cover.

Therefore, the experiments conducted during the summer season gave an average higher production rate of 42.6% than that obtained during the autumn season, and 117.6 % higher than that obtained during the winter season. Figures 8, 9, and 10 shows the comparison of the accumulated production rate for the three stills for the summer, autumn, and winter respectively.

Figures 11, 12, and 13, show the comparisons on an hourly basis, and for the three seasons respectively.

It has also been found, that in the experiments which have been conducted during the summer season, the three stills yielded an average amount of overnight condensation of 0.430 liters/day.

This represented 10.8% of the total summer daily production. In the autumn experiments, the average amount of overnight production for the three stills was 0.347 liters/day. This represented 13% of the total autumn daily production rate. In the winter experiments, the average amount of overnight production rate of the three stills was 0.346 liters/day. This represented 19.7% of the total winter daily production rate. The increase in the night percentage of production rates over the three seasons, summer, autumn, and winter, may be attributed to the increased temperature drop during the night. This may have enhanced the heat transfer rate and consequently, increased the night production percentage.

The glass covers of the solar stills heated up due to absorbing the suns rays and also due to the given latent heat of vapor condensed on the inside surface. The glass covers have a very low thermal conductivity. On the contrary, the condensers are made of galvanized steel which has a much higher thermal conductivity. In addition the condensers are kept in the shade. Never the less, it has been found that the amount of condensed water collected from the condensers is about 40%, while the

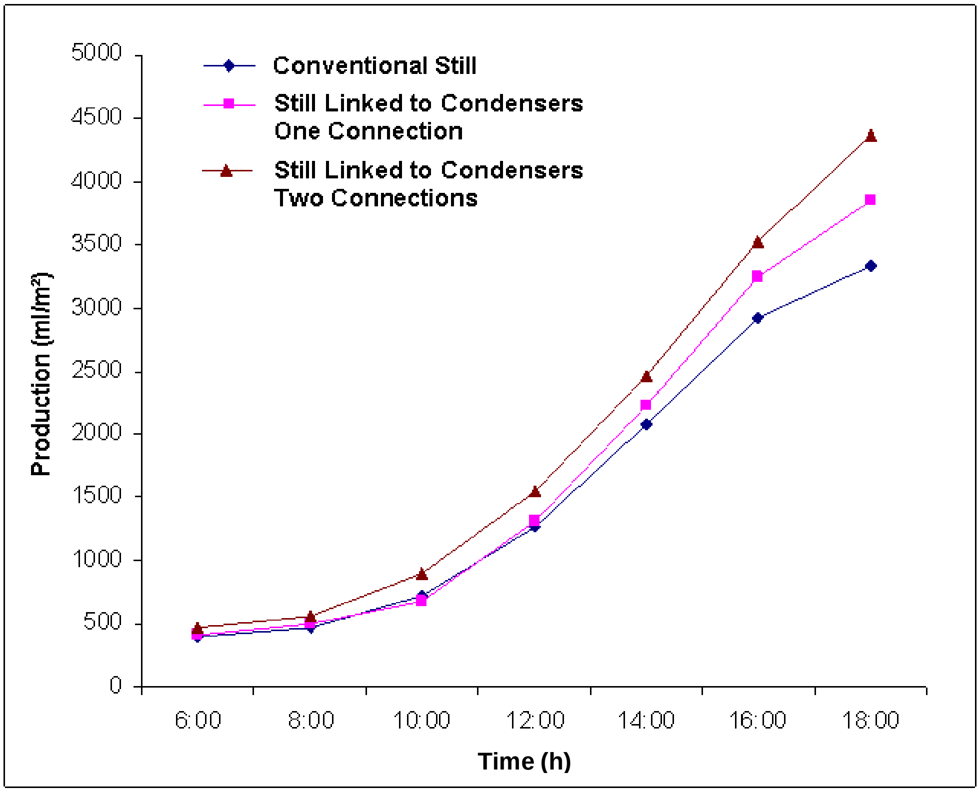

Figure 8. Comparison between accumulated productivity of the three stills- summer season.

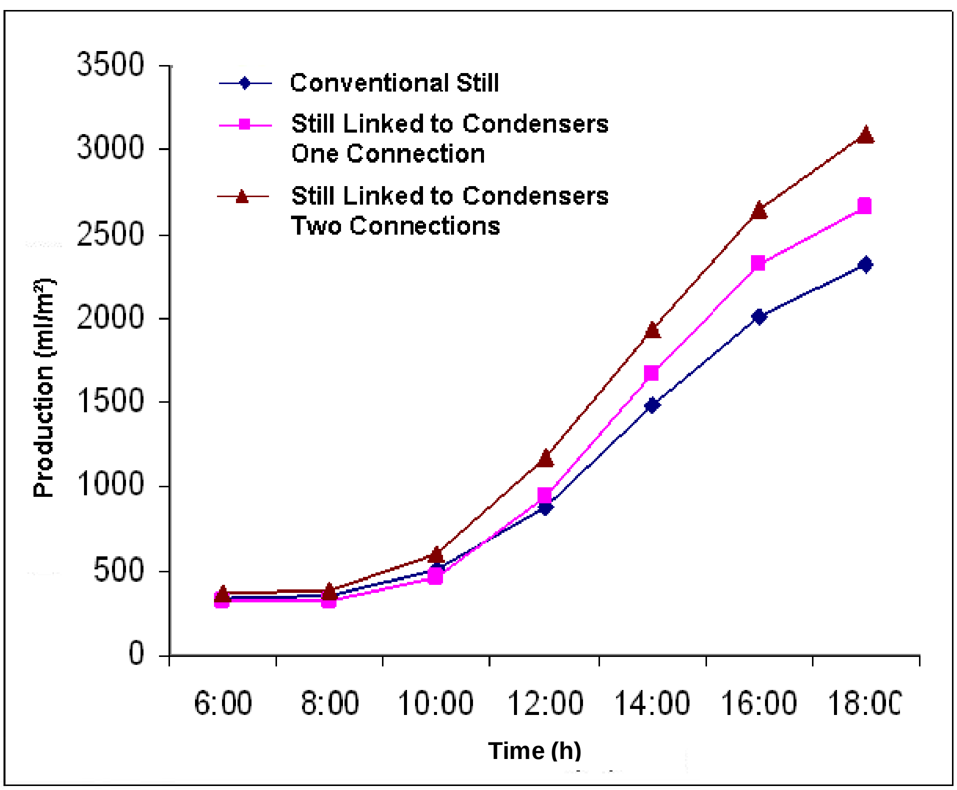

Figure 9. Comparison between accumulated productivity of the three stills- autumn season.

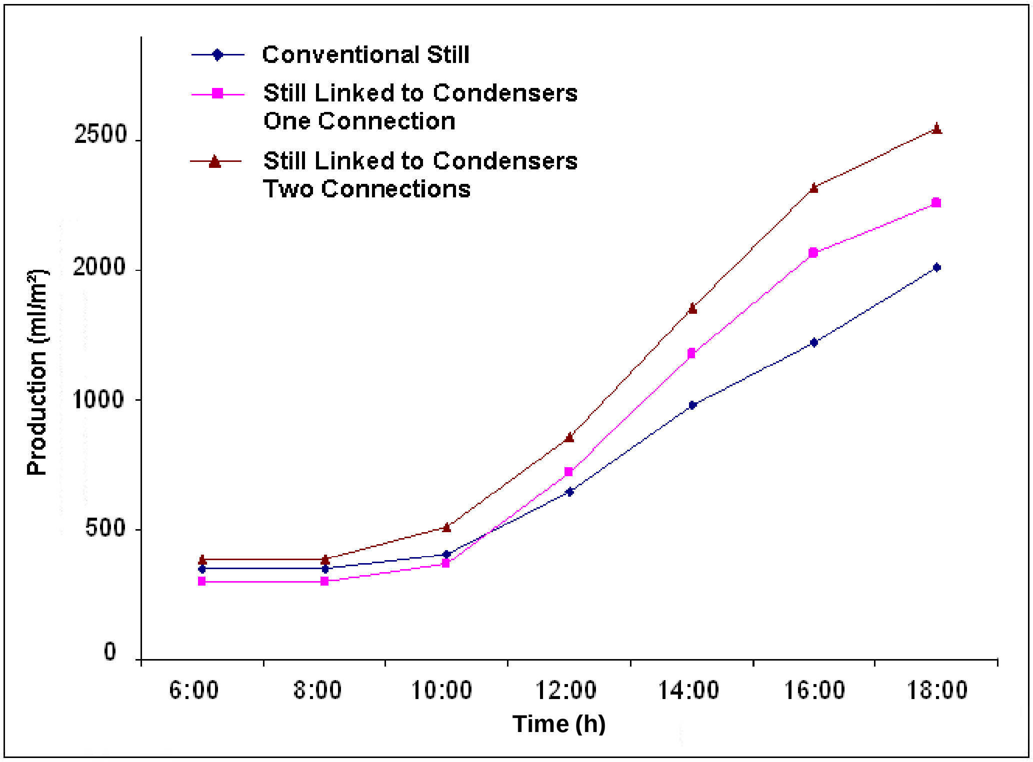

Figure 10. Comparison between accumulated productivity of the three stills- winter season

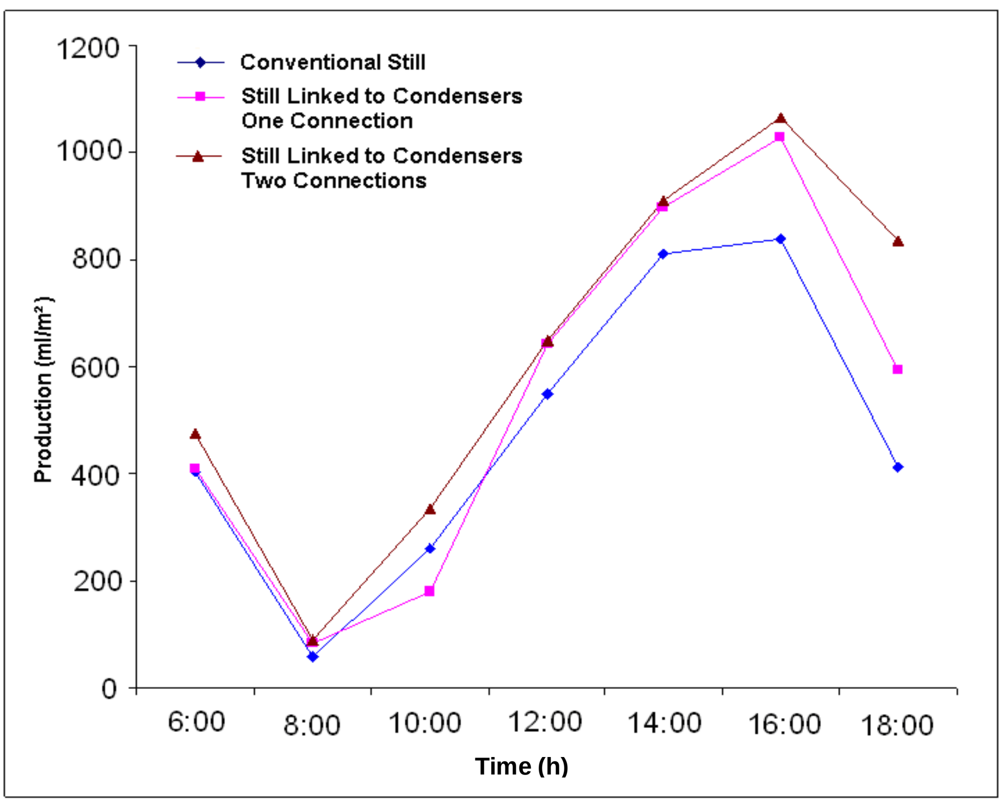

Figure 11. Comparisons between productivity of the three stills on hourly basis- summer season.

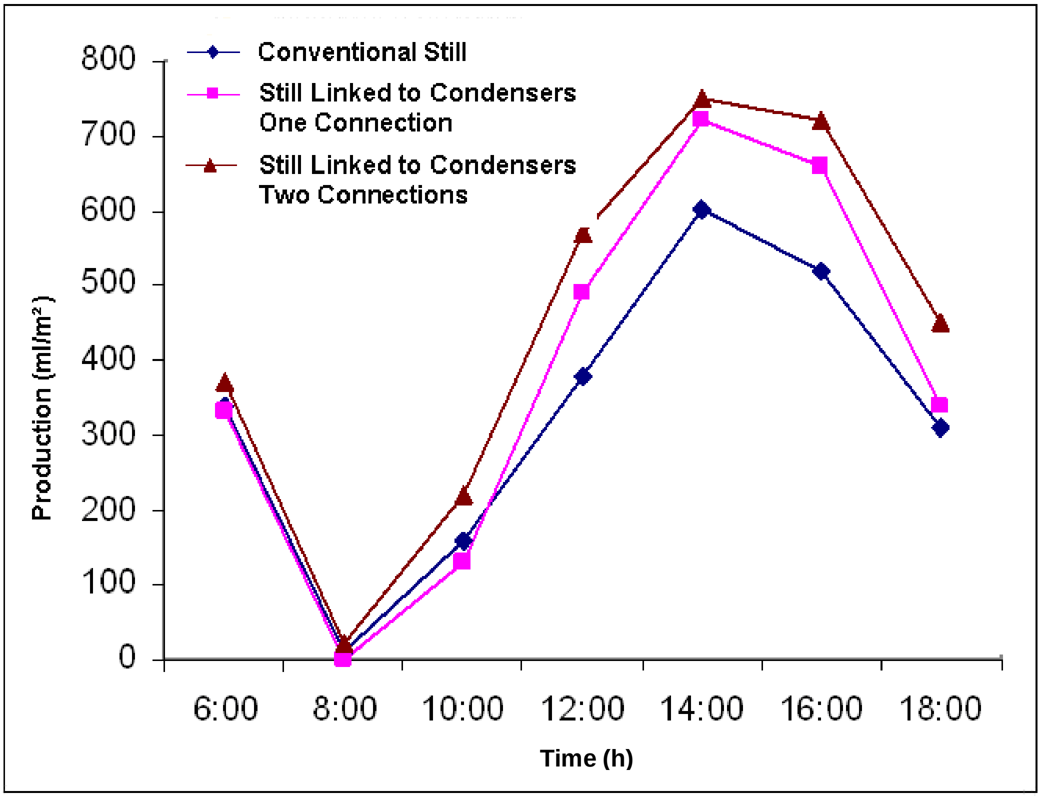

Figure 12. Comparisons between productivity of the three stills on hourly basis- autumn season.

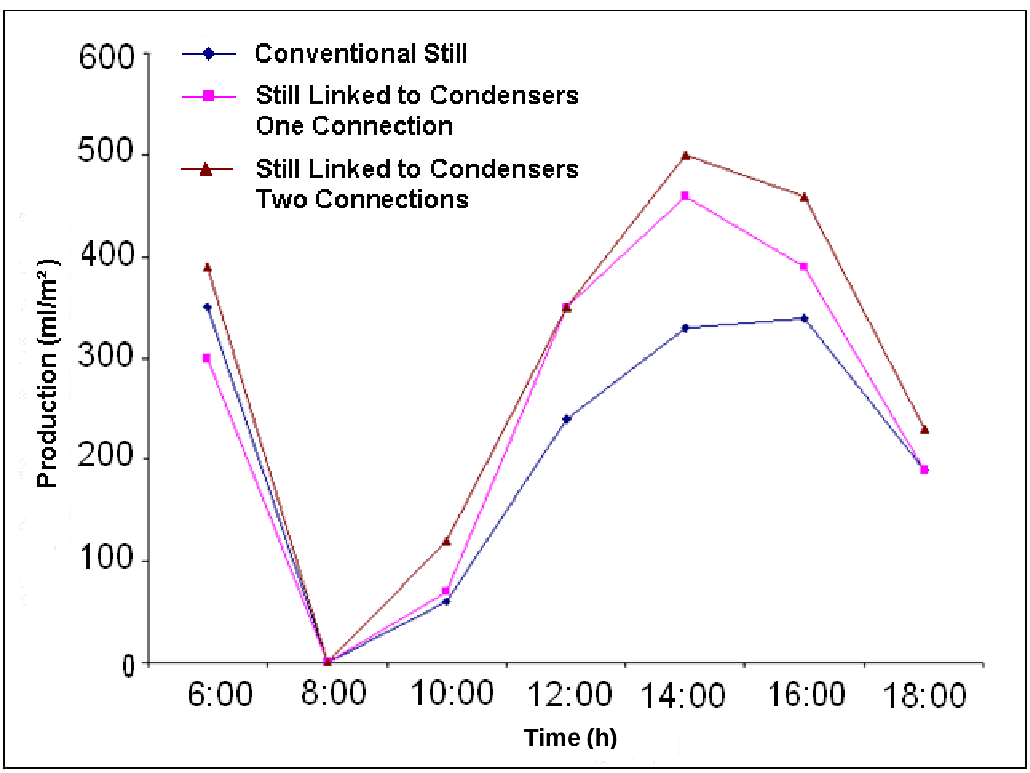

Figure 13. Comparisons between productivity of the three stills on hourly basis- winter season.

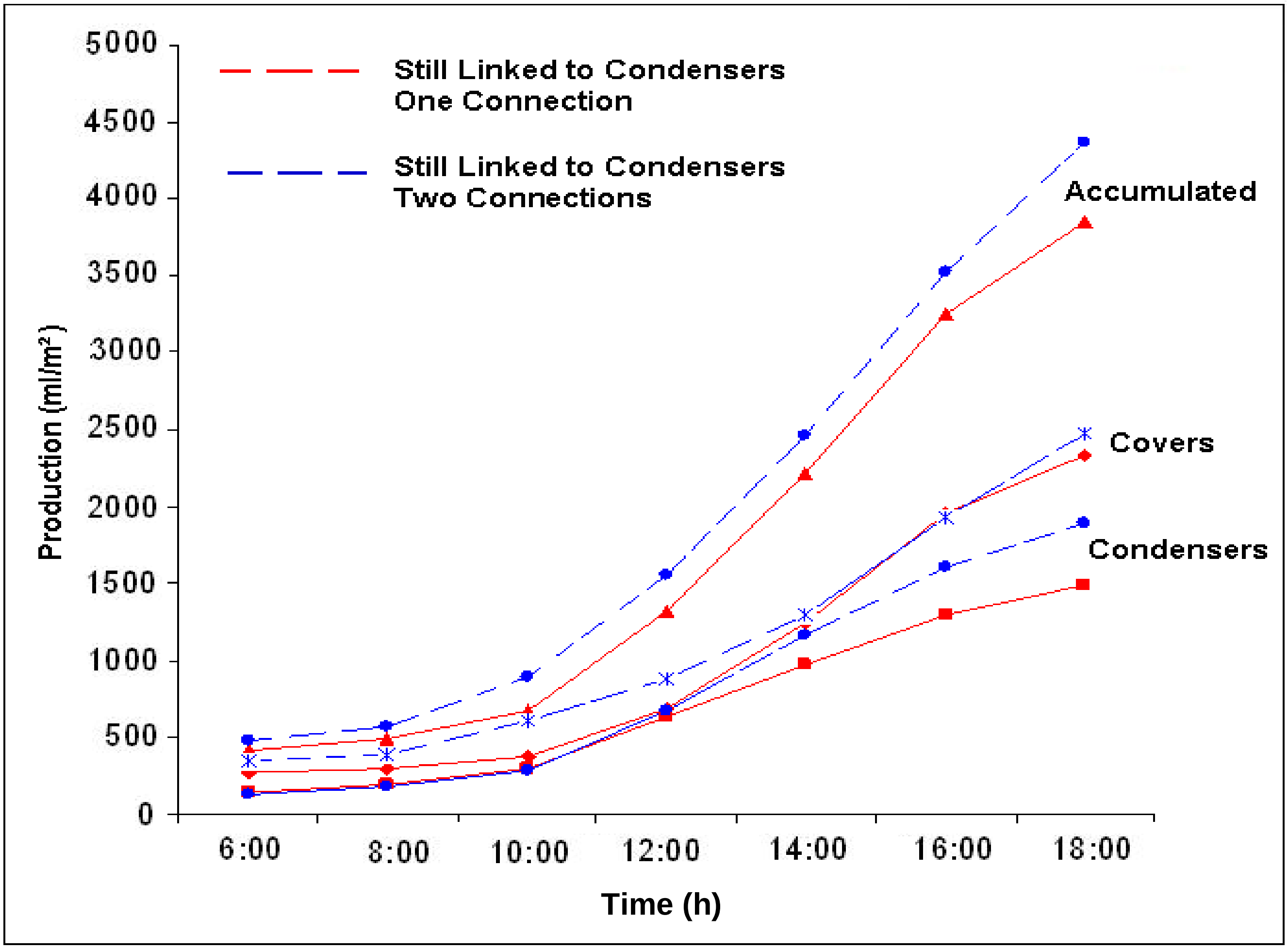

Figure 14. Comparison between distilled water obtained by stills covers and condensers- summer season.

amount collected from the trough down the glass cover represents about 60% of the total production rates. This may be attributed to the fact that condensers were connected through 10 cm diameter pipes diameter which affected the amount of vapor that can purge from the still to the condensers. This analysis is supported by the fact that the condensation yield obtained from the still that has the condensers linked by two connections (at the upper and lower parts of the back) gave a better yield than the still in which the condensers were connected only to the upper part of the back.

The two connections set up, increased vapor purge and circulation and consequently, gave a better condensation yield. A comparison between the production rates obtained from the condensers and the glass covers, for the three seasons are shown in Figures 14, 15 and 16 respectively.

For the same reasons, it has been found that the vapor temperatures inside the conventional still which was not linked to external condensers is, slightly, higher than the vapor temperatures inside the other two stills which were linked to external condensers. This can be seen in Figures 17, 18, and 19, which shows the vapor temperature distribution inside the three stills for the summer, autumn, and winter respectively. A similar trend was observed when the water temperature of the three stills were compared for the three season respectively , as shown in Figures 20, 21, and 22.

During the experimental investigation, the wind speed was in the range of 0-3 m/s. the maximum solar radiation intensity (perpendicular to the stills' covers) was 1040 W/m², 914 W/m², 805 W/m² for the summer, autumn, and winter seasons respectively.

Conclusion

Outdoor experimental tests have been carried out to study the effect of incorporating and connecting external passive condensers to the conventional, basin type, single slope solar still on a seasonal basis. It can be concluded that:

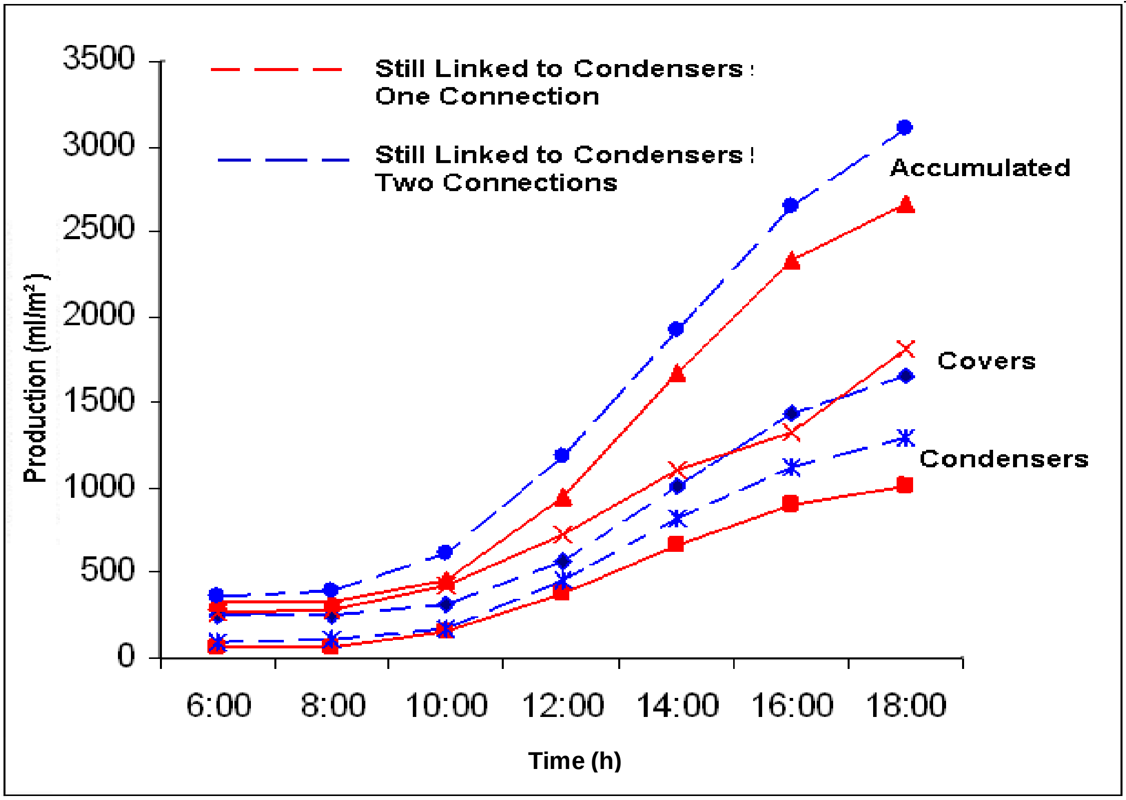

Figure 15. Comparison between distilled water obtained by stills covers and condensers - autumn season.

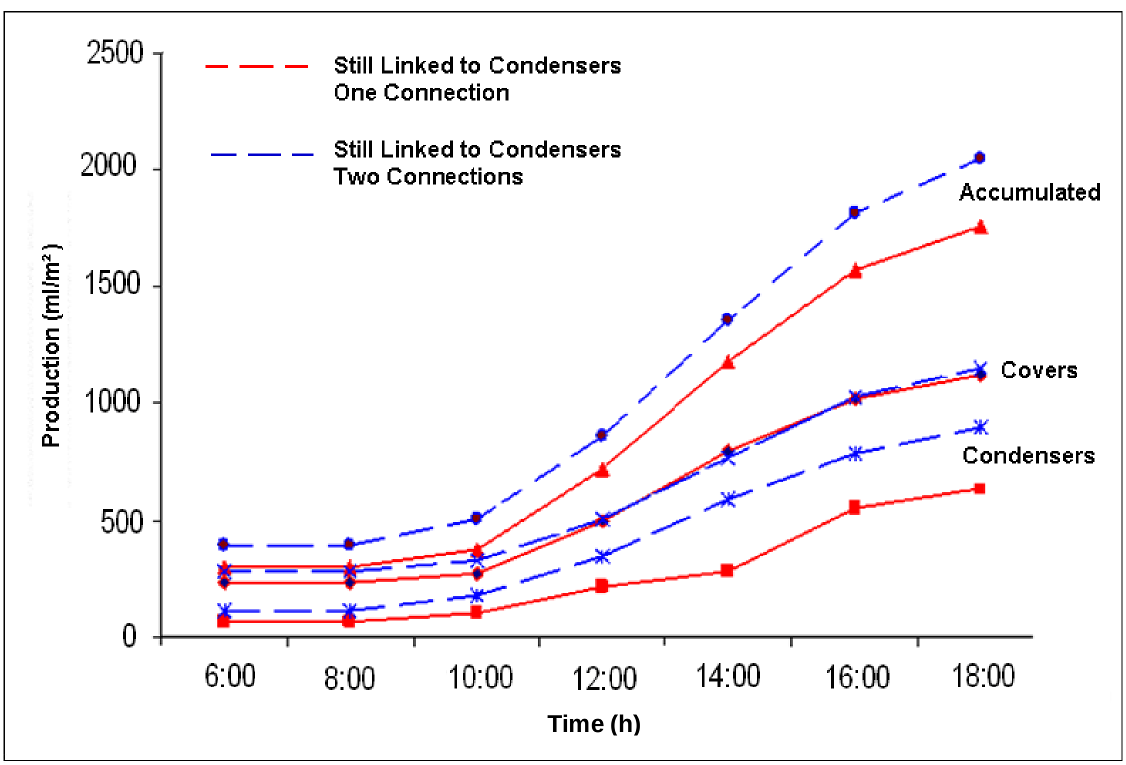

Figure 16. Comparison between distilled water obtained by stills covers and condensers- winter season.

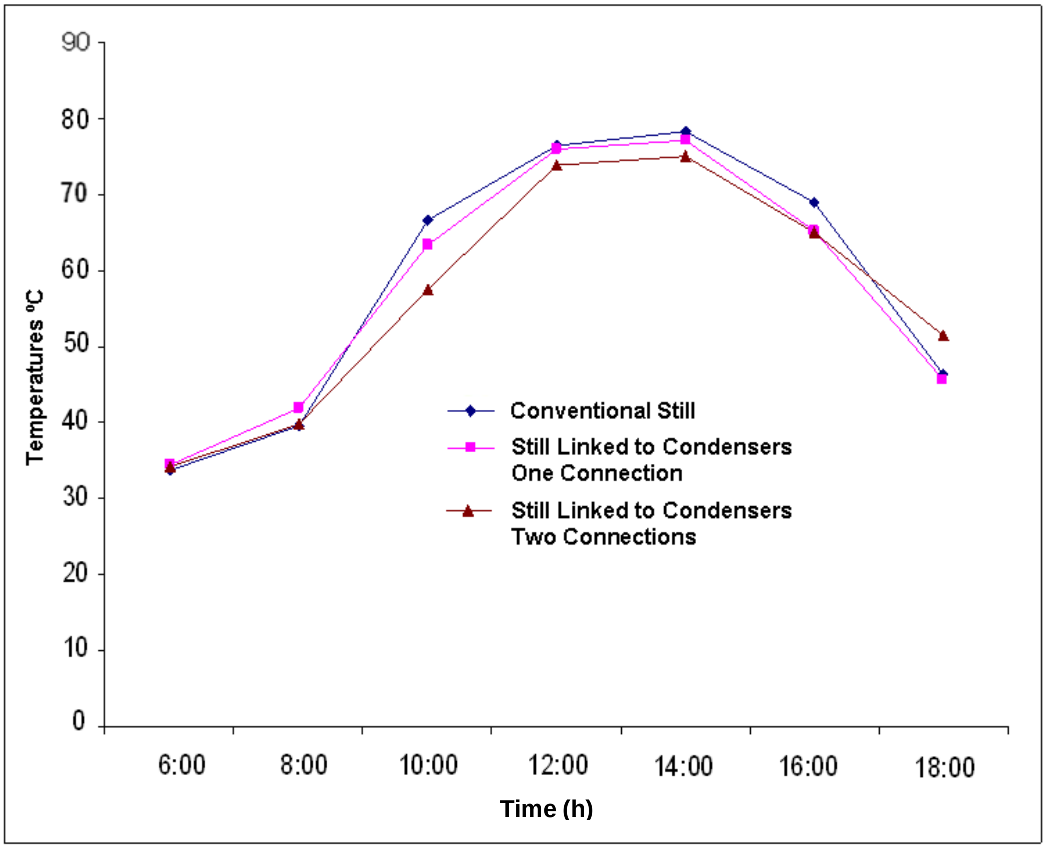

Figure 17. Still vapor temperature distributions - summer season**.**

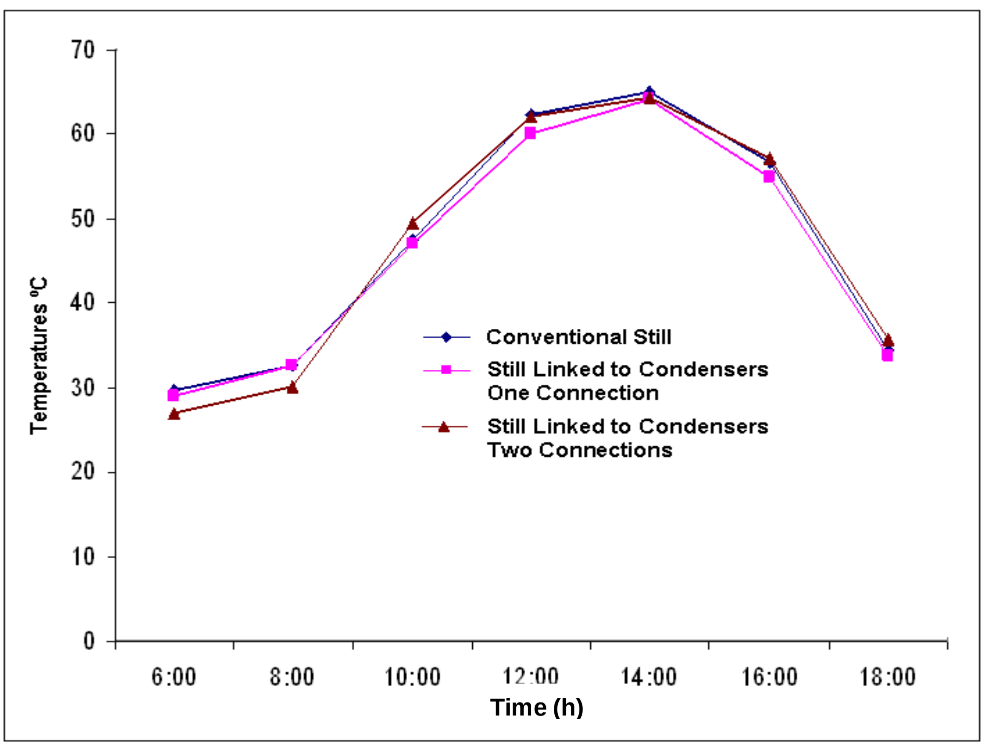

Figure 18. Still vapor temperature distributions - autumn season.

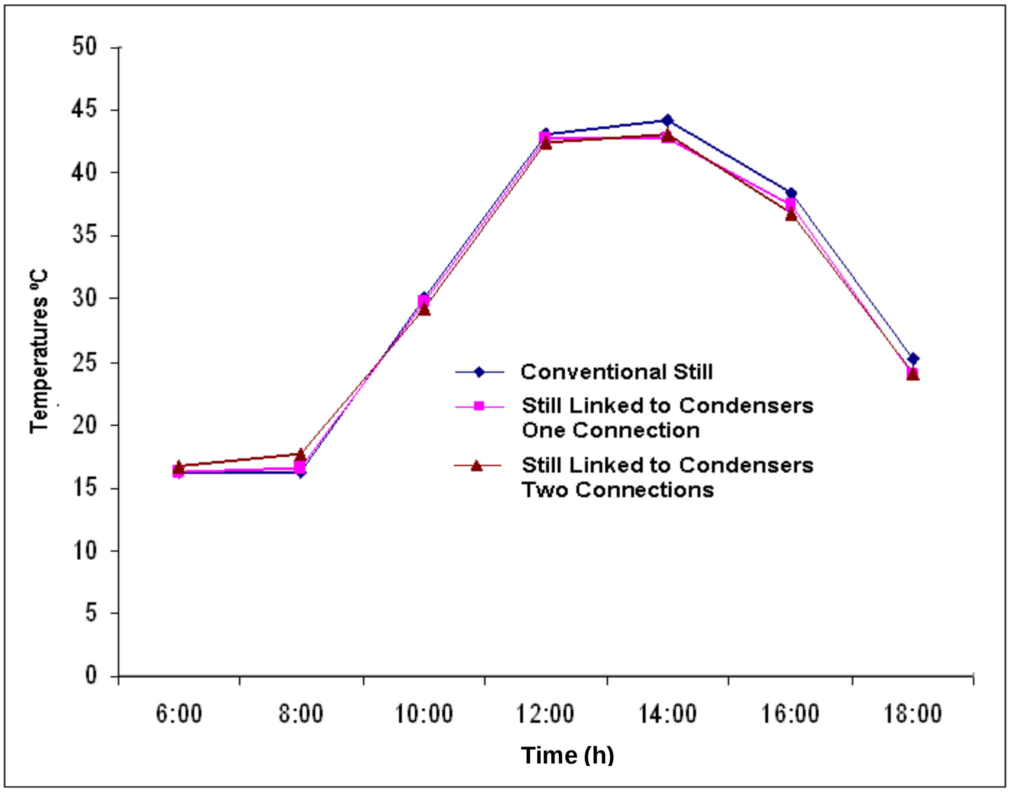

Figure 19. Still vapor temperature distributions - winter season.

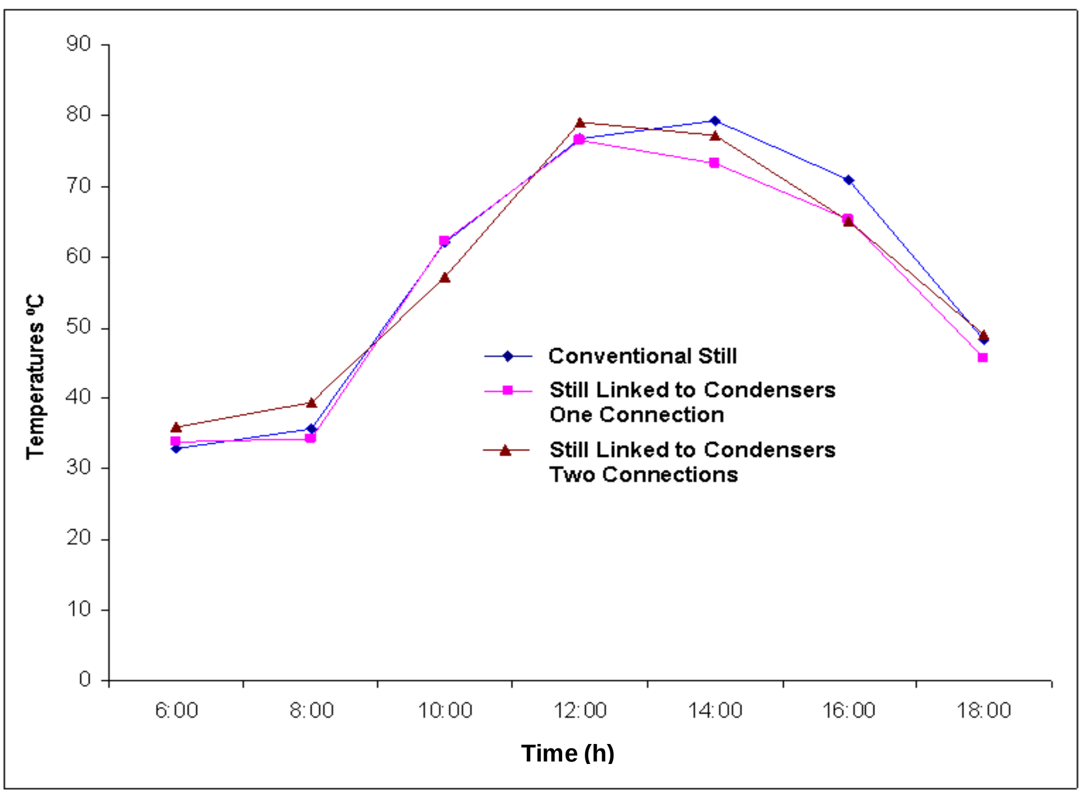

Figure 20. Still water temperatures- summer season.

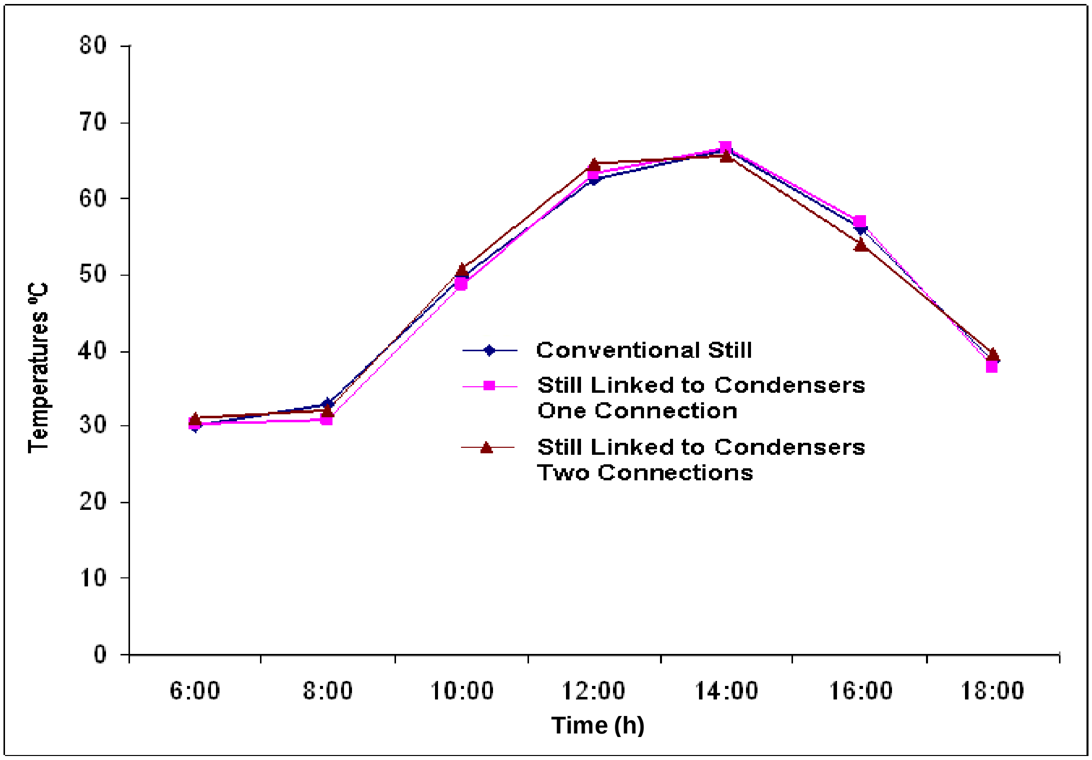

Figure 21. Still water temperatures - autumn season.

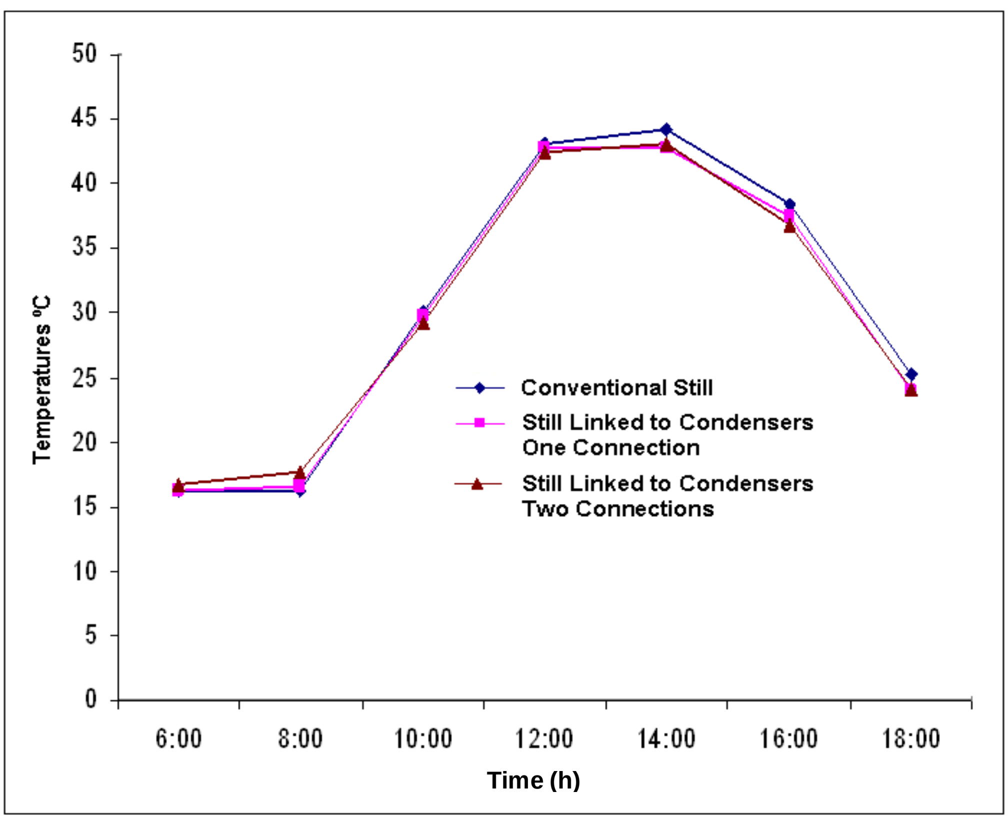

Figure 22. Still water temperatures - winter season.

1. The experiments conducted during the summer season yielded an average of 42.9% more distilled water than that obtained in the autumn season, and 117.4% more than that obtained in the winter season.
2. Incorporating external passive condensers enhances the production yield of the conventional, basin type, solar still.
3. The methods of incorporating and connecting the condensers to the conventional solar still have a significant effect on enhancing the still productivity.
4. The still connected through the upper part only to the external condensers, yielded an increase in its production rate of 15.1, 15.1, 15.08 and 16.6% for the summer, autumn, and winter respectively, compared to the conventional simple solar still.
5. The still connected through its upper and lower parts to the condensers, yielded an increase in its production rate of 30.54, 33.6 and 35.8% for the summer, autumn and winter respectively, compared to that produced by the conventional simple solar.
6. The overnight production rate was found to represent an average ratio of 10.8, 13 and 19.7% of the total daily production rate, for the summer, autumn, and winter respectively.

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