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Efficiency Improvement of the Condensation Pipes in the Soil for a Basin Type Solar Desalination Unit

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Abstract

A solar desalination unit consisting of a set of conventional basin-type solar stills, and a set of condensation pipes buried in the soil was investigated in this study. The effects of soil moisture and condensation pipes length, depth, diameter and material of the pipes in improving the efficiency of the solar still was studied. Compared to the traditional condensers used in conventional basin type solar stills, it was found that using buried metallic pipes as condensers led to an increase in the freshwater production rate by up to 136%.

Additionally, increasing the soil moisture led to improvements in the effectiveness of the buried condensation pipes in condensing more freshwater.

Compared to conventional solar stills the freshwater production rate in this study increased by about 54% for a soil moisture level of 30%. Furthermore, metallic pipes produced more freshwater compared to plastic pipes of the same heat transfer surface area. Compared to the plastic pipes, fresh water production rate increased by 98% when metallic pipes were used.

Keywords: Solar Desalination; Condensation Rate; Solar Still; condensation pipes; Freshwater production

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Efficiency Improvement of the Condensation Pipes in the Soil for A basin Type Solar Desalination unit

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تحسين كفاءة أنابيب التكثيف داخل التربة لوحدة التحلية بالطاقة الشمسية

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ملخص

بهدف انتاج المياه العذبة تم عمل نظام لتحلية المياه تألف من مجموعة من المقطرات الشمسية التي تم داخلها تسخين الماء المالح بواسطة اشعة الشمس المباشرة وانتاج الهواء الرطب الذي نقل مباشرة بواسطة مراوح إلى انابيب مدفونة تحت التربة عملت كمكثفات. لتحسين كفاءة النظام وبالتالي انتاج كميات أكبر من الماء العذب تمت دراسة تأثير اطوال، اقطار واعماق الأنابيب الموجودة تحت التربة وكذلك رطوبة التربة على معدل التكثيف داخل تلك الأنابيب.

لقد تبين من هذه الدراسة أن زيادة اقطار، اطوال واعماق الأنابيب وكذلك زيادة رطوبة التربة قد قامت بتحسين كفاءة نظام التحلية مما زاد في كمية المياه العذبة الناتجة، حيث كانت الزيادة بمقدار 136% عندما استخدمت الأنابيب المدفونة تحت التربة كمكثفات للهواء الرطب مقارنة بالمكثفات التي تستخدم عادةً في المقطرات الشمسية التقليدية. كما كان لمادة الأنبوب تأثير على معدل التكثيف داخل الأنابيب حيث كان المعدل اعلى عند استخدام الأنابيب المعدنية مقارنة بالأنابيب البلاستيكية.

الكلمات الدالة: تحلية شمسية، معدل التكثيف، مقطرات شمسية، أنابيب تكثيف، انتاج ماء عذب.

Introduction

With the dramatic growth in population and increase in living standards, freshwater supplies are deteriorating (Kuylenstierna , Björklund, & Najlis, 2009., Fritzmann., Löwenberg., Wintgens, & Melin, 2007., El-Kady & El-Shibini, 2001). Solar desalination of brackish and impure water, as well as seawater, seems to be a promising solution to this problem. It has been used for many years to provide freshwater and represents the most attractive and simple technique among existing desalination processes. It is suitable for small-scale units at locations where solar energy is abundant. It has been studied as a preferred process because of its energy efficiency and low environmental impact. In the Middle East, Jordan has one of the highest solar intensities; the mean value of the radiation density can reach 200W/m2 (Abdallah, Abu-Khader, & Badran, 2009, Etier, Al Tarabsheh & Ababneh, 2010). Moreover, Jordan is considered the fourth poorest country in the world in terms of water resources (Denny, Donnelly, & McKay, 2008) The use of solar desalination and improvements in the efficiency of solar devices could be a suitable solution for desalinating water in remote areas with poor water quality and a lack of other treatment options. Basin type solar stills are an option that can be used for water desalination and are considered one of the cheapest solutions for purifying brackish water. They are suitable for the Middle East and Africa due to their low cost and ease of maintenance (Salah, Omar, & Abu-Khader, 2008, Shanmugasundaram, 2016). The main drawback of the conventional basin type solar still is its low productivity, which is about 4 l/m2/d. This low level of productivity makes it impractical for many uses. Many basin type solar still designs have been developed and constructed (Akash, Mohsen, & Nayfeh,2000, Al-Hayek & Badran, 2004; Kabeel & El-Agouz, 2011; *et al.*, 2013; Malik, Kumar & Sodha, 1982) while others evaluated the performance Hanson, Zachritz, Stevens, Mimbela, & Cisneros, 2004, Maalej, 1991, Sharma, & Mullick, 1993; Tiwari, Minocha , Sharma, & Khan,1997). Efficiency improvements by cooling of the solar still condenser was also reported (Abu-Hijleh, 1996, Abu-Arabi, Zurigat, Al-Hinai, & Al-Hiddabi, 2002, Mamkagh and Anderson, 2018).

The efficiency of the conventional solar still can be improved by using buried metallic pipes that are connected to the still, and using these pipes as a condenser to produce more freshwater. Lindblom & Nordell (2007) and Lindblom & Nordell (2006), studied two types of condensation systems for drinking water production and for subsurface irrigation. The systems were theoretically analyzed by numerical simulations of the mass and heat transfer in the soil and pipe system for 90 days. It was found that the freshwater production rate was improved by decreasing the surrounding air temperature and increasing the humidity and velocity of the air. Bagher et al. (2012) also studied condensation systems for subsurface irrigation and drinking water production. Their systems produce approximately 0.5 l/m2/h. Hexigeduleng & Yixin (2010) used perforated pipes placed inside the soil to irrigate greenhouse tomatoes. The effect of the pipe depth on desalinated water production was studied by Lindblom (2012) and found that it had a negative effect on condensation rate.

The main objective of the present study was to connect the buried condensation pipes to the conventional basin type solar stills to serve as a condenser for enhancing the still productivity. The effects of soil moisture and the buried piping parameters (length, depth, diameter, and material of the pipes) on improving the condensation effectiveness are also investigated.

Materials and Methods

Experimental Site

The field experiment was carried out in a region with soil consisting of sandy clay loam in the southern part of Jordan at Agricultural Research Station, Faculty of Agriculture, Mutah University (31°16′N, 35°44′E, and 962 m above mean sea level). The site was chosen in the center of the field where the solar stills would be exposed to sunlight most of the time without obstacles. The solar radiation levels and number of sunny hours per day for the 5 month duration of the experiment were measured and are presented in Table1.

Table (1) Average monthly solar radiation and sunny hours per day for the 5 months of the experiment

	May	June	July	August	September
kWh/m^2	223	249	248	226	177
Average daily Sunny hours	13:47	14:12	13:59	13:15	12:20

Design and construction

A solar desalination system (Figure 1) designed and constructed and consisted of two main sections, the first section was a set of simple solar stills and the second section was a set of condensation pipes buried in the soil.

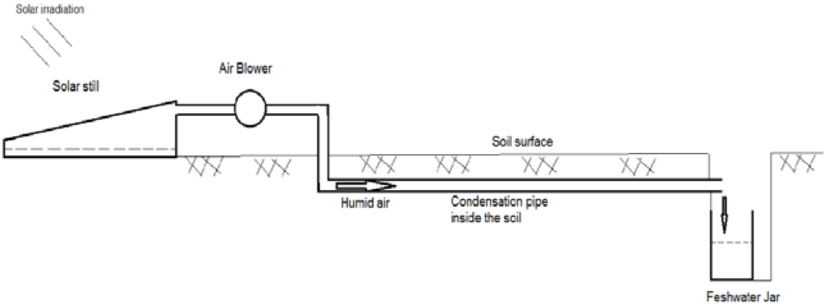


Figure (1) Profile of the solar desalination system

The solar desalination unit consisted of 13 conventional single slope basin-type solar stills. Each still consisted of the following sections: a wooden framework, a transparent cover, a float, an inlet from the brackish water tank, and an outlet to the air blowers. Figure 2 show the schematic diagram of one solar still where the framework of the still was made of wood for ease of construction and good isolation from the external environment. It was fabricated in a box type shape of 80 cm x 80 cm and 1 cm in thickness. The height of the front side was 10 cm and the back side was 20cm high. One conventional basin type solar still was used separately as the reference case for experimental control. It was tested separately under the same conditions as the proposed solar still unit and its daily freshwater production rate was found to be 4 l/m^2.

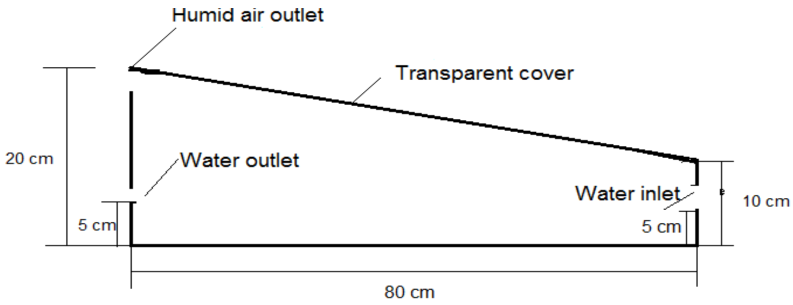


Figure (2) Schematic diagram of the solar still.

As shown in Figure 3, brackish water flows from the water tank to the solar stills by gravity. To ensure that the depth of the water remained around 5 cm, small floats were installed inside the solar stills.

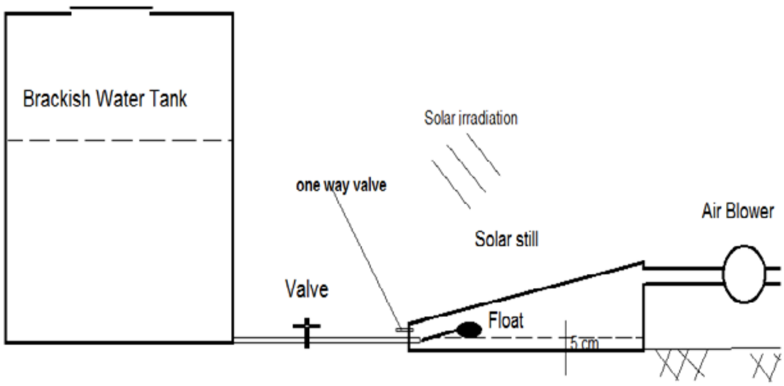


Figure (3) Solar still with brackish water tank and air blower

The water depth used was based on previous studies showing that this depth increases the evaporation rate inside the solar still (Wasil & Altamush, 2012; Tiwari & Tiwari, 2007; Bilal, Akash, Mohsen, & Nayfeh, 2000). One-way valves were used to vent the solar still so air can enter the still but vapor cannot exit. The air blowers then transfer the vapor formed from the stills through plastic pipes to the condensation pipes that are buried in the soil.

The condensation pipes

The condensation pipes were chosen based on what was locally used for water distribution. To determine the effect of length, depth, diameter, and material of the pipes affected on condensation rate, metallic and plastic pipes with different diameters and lengths were buried in the soil at different depths. The condensation areas of the pipes were calculated from the pipe lengths and diameters. The lengths of the condensation pipes used in this experiment were 2m, 4m, and 6m. The diameters were 0.5" and 1" for the metallic pipes and 1" for the plastic pipes.

The productivity of conventional basin type solar stills (Kalogirou, 1997). needed to be referred to because each square meter of pipe condensation area requires at least one solar still to produce the required quantity of vapor. Because pipes have different condensation areas, valves were used to connect each pipe to an adequate number of stills.

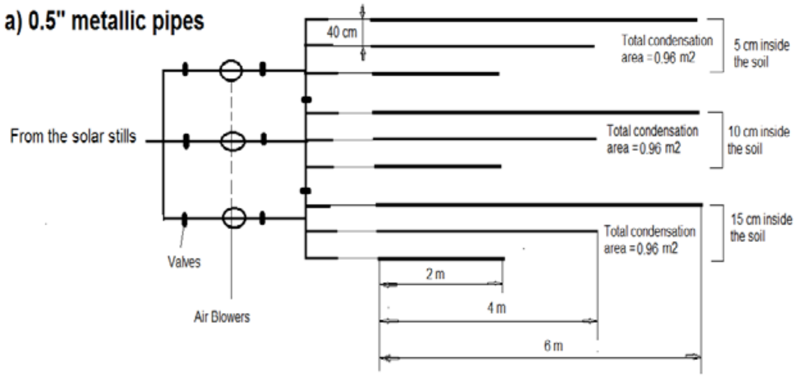
Because the condensation rate decreases with the pipe depth (Bagher, Boroomandnasab & Thameur, 2012, Mikielewicz & Mikielewicz, 2010) in this study the pipes were not buried very deep in the soil. The depths of these pipes for the experiment were 5cm, 10cm, and 15cm.

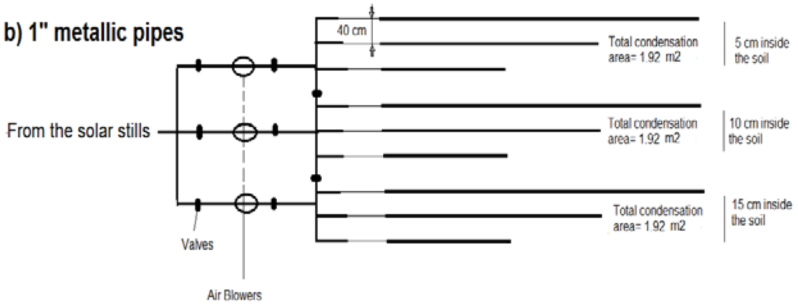
Evaporation in solar stills is the process of turning brackish water into vapor by applying heat from sunlight. The reverse process is condensation, which takes place in the pipes and converts vapor into liquid water. The necessary condition for this process to occur is that the temperature of the condensation pipes should be lower than the vapor temperature (Tromp-van, & McDonnell, 2006). For the experiment, the soil temperature at the pipes was about 23^{o}C, the temperature of the condensation pipes was 30^{o}C, and the vapor temperature was 60^{o}C, so the proper condition for condensation to occur on the inner surface of the pipes was established.

The solar stills were tightly sealed to prevent heat and vapor leakage. Air blowers were used to transmit the vapor from the solar stills to the metallic and plastic pipes in the soil. The daily freshwater that was produced could then be collected at the pipes outlets.

Thermocouple probes were used to measure the temperature of the soil around the pipes, the temperature of the pipes, and the temperature of the vapor. The solar radiation levels and exposure times were also measured.

To control the direction of the vapor flow from the solar stills to the condensation pipes, several valves were used. This enabled the delivery of the vapor to any condensation pipe or group of pipes as needed.





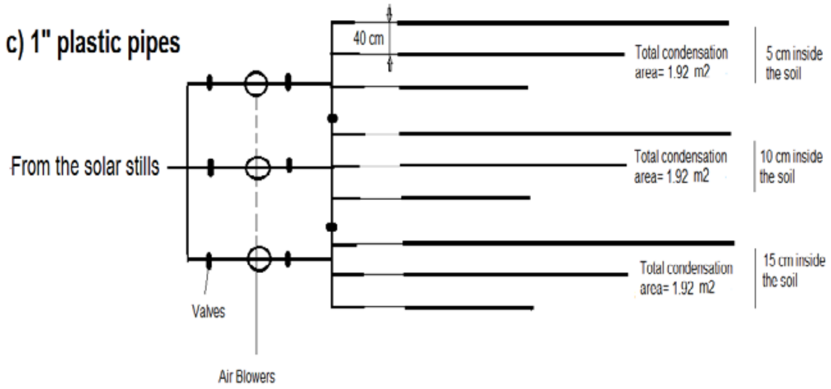


Figure (4) Design of the experiment with: a) 0.5" metallic pipes, b) 1"metallic pipes and c) 1"plastic pipes.

Figure 4 shows the final design of the experimental setup. The design was divided into three groups with different parameters. The first group contained nine metallic pipes with diameters of 0.5"and lengths of 2 m, 4 m, and 6 m. The first three pipes of this group were buried at a depth of 5 cm, the second three pipes at 10 cm, and the other three pipes at 15 cm. The second group contained nine metallic pipes with diameters of 1", which also had lengths of 2m, 4m, and 6 m. These pipes were divided similarly and buried at the same depths as the first group. The third group contained nine plastic pipes with diameters of 1" and lengths of 2m, 4m, and 6 m. This group of pipes were also divided similarly and buried at the same depths as the first and second groups. A pipe spacing of 40 cm was used in this study because it was considered optimum spacing for peak condensation rate production (Lindblom, 2012).

Soil moisture around the condensation pipes

Increases in soil moisture around the condensation pipes can improve the pipe efficiency because it increases the temperature difference between the soil and the pipes. The moisture level was brought to the desired level at the end of September by adding a known quantity of water.

Soil moisture sensors were used to measure the moisture level. Three levels of soil moisture, 10%, 20%, and 30%, were established around the condensation pipes. For each level of soil moisture, the condensation rate was also measured by collecting the freshwater at the pipe outlets.

Results and Discussion

Factors influencing the condensation rate

Figure 5 shows the relationship between the time of the experiment and the freshwater production rate of the solar desalination system. It shows no significant differences in the freshwater production rates between May, June, July, and August. A significant decrease to 5.01 l/m2/d occurred in September constituting over 20% relative to June. This was because September had lower solar radiation levels and fewer sunny hours than the other months, as shown in Table 1. Compared to the reference case of 4 l/m^2/d) for the conventional solar still, the amount of freshwater production rate in any of these months was much higher. This demonstrates the superiority of the solar desalination system used in this study. This increase was obtained because buried pipes were used as the condenser for the solar stills instead of the traditional solar still condenser consisting of the transparent cover.

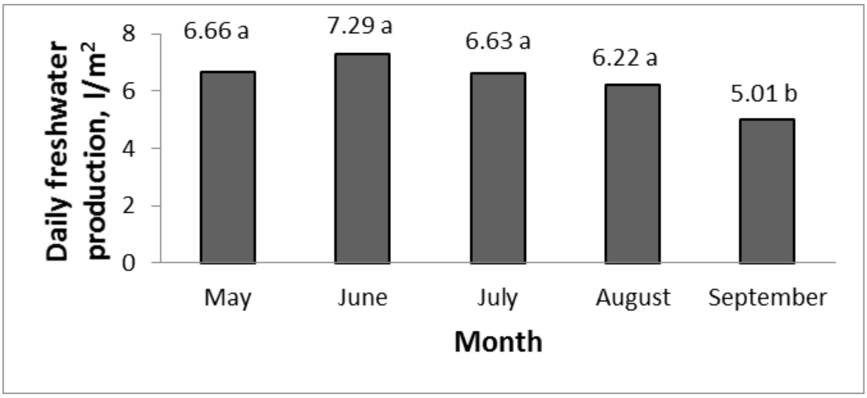


Figure (5) Monthly freshwater productivity of solar desalination unit by months

Means marked by the same letters are not significantly different at the 0.05 level.

Figure 6 shows the effect of pipe material and diameter on the freshwater production rate. Compared to the plastic pipes the fresh water production rate increased by 98% when metallic pipes were used. The metallic pipe with a diameter of 1"produced about 9.46 l/m^2/d while the plastic pipe with a diameter of 1"produced about 4.76 l/m^2/d. This indicates that there is a significant difference in the freshwater production rate due to the pipe material. The difference in production rate could be caused by the thermal conductivity difference between the plastic pipe (PVC), which has a thermal conductivity of 0.19 W/(mK), and the steel pipe, which has a about 54 W/(mK) thermal conductivity (John & Ronald, 2010). The higher thermal conductivity of the steel pipe allows it to transfer heat to the surrounding soil more effectively, enabling faster cooling.

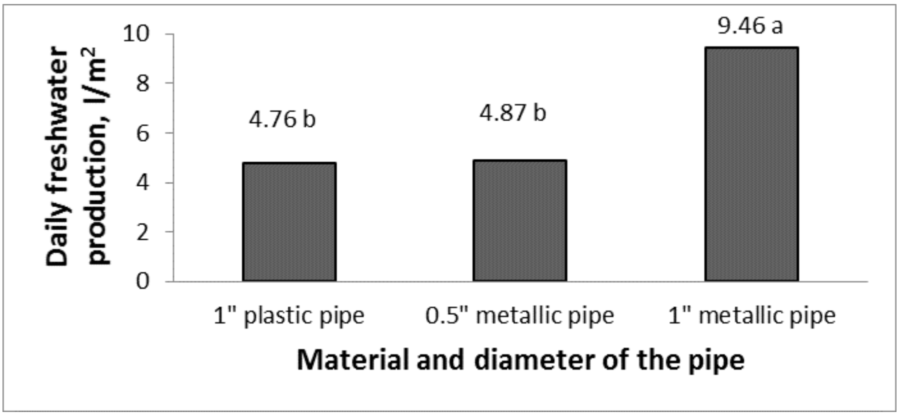


Figure (6) The effect of the pipes material and diameter on their freshwater production rate. Means marked by the same letters are not significantly different at the 0.05 level.

The metallic pipe with a 1" diameter produced significantly more freshwater compared to the pipe with a 0.5" diameter. It produced 9.46 l/m^2/d compared to 4.87 l/m^2/d for the 0.5" diameter pipe. This is because the larger diameter increases the pipe's ability to cool more rapidly. Compared to the reference case the freshwater production rate increased by about 136% when the 1" diameter metallic pipe was used.

Figure 7 shows a linear proportional relationship between the length of the pipe and the condensation rate due to larger heat transfer/condensation area. It produces more freshwater when there is a sufficient amount of vapor available. The condensation rate in longer pipes cannot be predicted because the humid air becomes colder and drier while passing through the pipe, thus negatively affecting the freshwater production rate (Lindblom & Nordell, 2006). Because the pipes used in this study are not very long, there is a need for additional studies focusing on longer pipes and their effects on condensation rate.

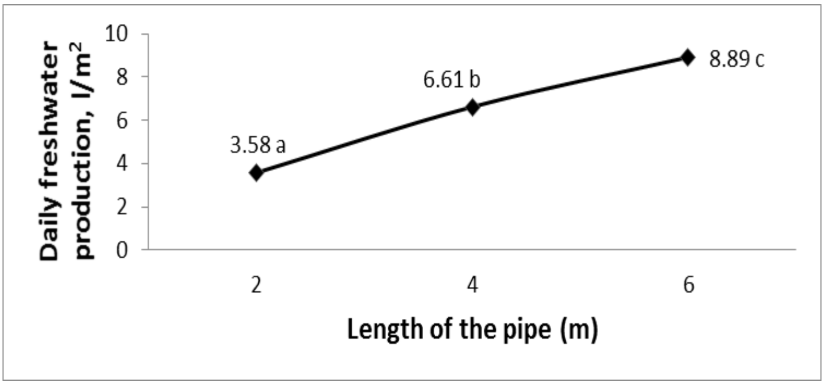


Figure (7) The effect of the pipe length on its freshwater production rate.

Means marked by the same letters are not significantly different at the 0.05 level.

The pipe with a 2m length produced freshwater at a rate of about 3.58 $l/m^2/d$. The production rate for the 4 m length of pipe was about 6.61 $l/m^2/d$, while the rate for the 6 m long pipe was about 8.89 $l/m^2/d$. These levels of freshwater production rates were considered significant improvements. Compared to the reference case of 4 $l/m^2/d$, the freshwater production rate increased by about 65% and 122% for the 4 m and 6 m pipes, respectively.

Figure 8 shows the effect of the pipe depth on freshwater production rate. When the pipe was buried at 5 cm, 10 cm, and 15 cm, the freshwater production rates were 5.91 $l/m^2/d$, 6.39 $l/m^2/d$, and 6.79 $l/m^2/d$, respectively.

The figure shows a significant increase in production rate when the pipe was buried at a depth of 15 cm. Compared to the reference case, the freshwater production rate increased about 59% and 69% for buried depths of 10 cm and 15 cm, respectively. Referring to Tromp-van Meerveld and McDonnell [30], this is because the soil near the surface dries faster than the deeper soil, which results in less soil thermal conductivity and a decrease in the pipe condensation rate.

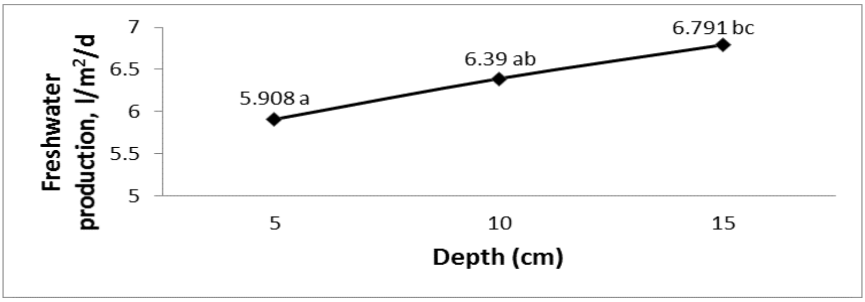


Figure (8) The effect of the pipe depth inside the soil on its freshwater production rate.

Means marked by the same letters are not significantly different at the 0.05 level.

Condensation pipes efficiency

As shown in Figure 9, when the soil moisture around the condensation pipes was 10%, the freshwater production rate was 3.46 $l/m^2/d$, but by increasing the soil moisture to 20% the freshwater production rate increased to 5.02 $l/m^2/d$. A significant increase in the freshwater production rate occurred when the soil moisture around the condensation pipes was 30%. The production rate for the 30%moisture level was 6.16 $l/m^2/d$, which was an increase of about 54% compared to the reference case.

The main reason for this could be due to an increase in the soil thermal conductivity (Nidal, & Randall, 2000, Venkat, Jackson & Zehrfuhs, 2003).The water in the soil enabled a quicker removal of heat, which results in an increase in temperature difference between the soil and the condensation pipes, thus improving the pipe condensation rate.

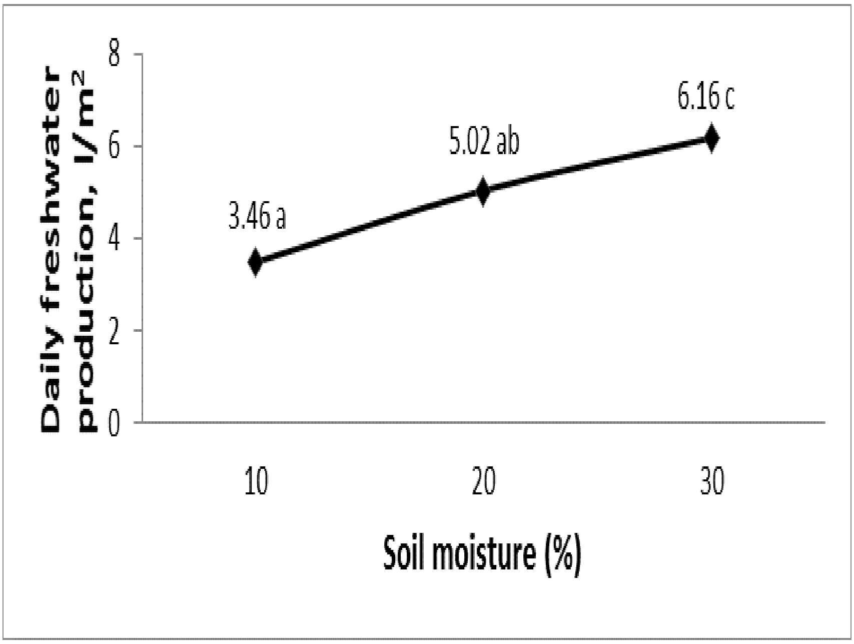


Figure (9) Effect of soil moisture on the pipe freshwater production rate

Means marked by the same letters are not significantly different at the 0.05 level.

Conclusion

The use of buried metallic pipes as condensers instead of the traditional solar still condensers led to an increase in freshwater production rates up to 136%. This shows the superiority of the solar desalination system used in this study over the conventional solar still.

The solar desalination system produced more freshwater than the conventional basin type solar still when the length, diameter, and depth of the pipe were increased. The improved production was due to the greater efficiency of the buried condensation pipes.

The metallic pipes produced more freshwater compared to the plastic pipes even when they had the same condensation area. Compared to the plastic pipes, the fresh water production rate increased by 98% when metallic pipes were used.

Seasonality also affects the freshwater production rates due to the variability in solar radiation intensity and the number of sunny hours per day.

Increasing soil moisture around buried pipes led to efficiency improvements in the buried condensation pipes and was a good way to condense more freshwater on the inner surface of the pipes. This effect was because water in the soil helped to transfer heat from the pipes to the surrounding soil, leading to more rapid cooling of the pipes. Compared to the conventional still, freshwater production rate increased about 54% when the soil moisture was 30%.

Acknowledgment

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