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Experimental Study on Direct Water Distillation System using Solar Evacuated Tube Collectors

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Abstract

In this work, experimental study and investigation are carried out to examine a solar distillation system that uses solar evacuated tube collectors. The proposed thermal distillation system is based on the use of heat pipes solar evacuated tube collectors, which is very efficient in absorbing solar thermal energy and with high thermal insulation efficiency. The energy produced by the condensed steam is reused by a heat recovery system to serve as an additional input of energy to preheat the inlet water stream. The evacuated tubes collector is an array composed of 20 evacuated tubes, and a heavily thermally insulated manifold header, stainless steel support frame, and standard mounting frame package. Each tube has a diameter of 58mm and a length of 1800mm, and the overall dimensions of the panel are 1760x1500x180mm. The distillation system is monitored and controlled through Arduino electronics and a waterproof temperature sensor. The passage of water inside the manifold is done through a control process is based on thermocouple sensors and a water pump. The experiment was carried out in June and for several days. The system was operated from sunrise to sunset and data recorded from 9:00 am to 2:00 pm every day. The collected pure water quantities were 52, 51, 32, and 54 L/day during four consecutive days. These produced quantities indicate the feasibility of using this method in the distillation of water in different applications in reasonable commercial quantities.

Keywords: solar distillation, heat pipes, solar thermal, heat recovery

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دراسة تجريبية على نظام تقطير مباشر للمياه باستخدام مجمعات أنابيب الطاقة الشمسية المفرغة

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ملخص

في هذا العمل، يتم إجراء دراسة تجريبية وفحص لنظام تقطير شمسي يستخدم مجمع اشعة شمسية مكون من أنابيب طاقة شمسية مفرغة. يعتمد نظام التقطير المقترح على استخدام أنابيب تجميع الطاقة الشمسية المفرغة المضمنة بأنابيب حرارية، وهو فعال للغاية في امتصاص الطاقة الحرارية الشمسية وذو كفاءة عزل حراري عالية. يتم إعادة استخدام الطاقة الناتجة عن البخار المتكثف في عملية التقطير من خلال نظام استرداد الحرارة ليكون بمثابة مدخل إضافي للطاقة لتسخين تيار الماء الداخل. يتكون مجمع الاشعة الشمسية من مصفوفة أنابيب مفرغة مكونة من 20 أنبوبًا، ومشعب معزول حراريًا بشكل كبير، وإطار دعم من الفولاذ المقاوم للصدأ. يبلغ قطر كل أنبوب 58 ملم وطول 1800 ملم، والأبعاد الكلية لمصفوفة التجميع الشمسي هي 1760 × 1500 × 180 ملم. يتم مراقبة نظام التقطير والتحكم فيه من خلال إلكترونيات Arduino ومستشعرات درجة الحرارة مقاومة للماء. يتم مرور الماء داخل المشعب من خلال عملية تحكم تعتمد على استشعار الحرارة ومضخة مياه. تم تنفيذ التجربة في شهر يونيو ولعدة أيام. تم تشغيل النظام من شروق الشمس حتى غروبها وسجلت البيانات من الساعة 9:00 صباحًا حتى 2:00 مساءً كل يوم. كانت كميات المياه النقية التي تم جمعها 52 و 51 و 32 و 54 لتر / يوم خلال أربعة أيام متتالية. تشير هذه الكميات المنتجة إلى جدوى استخدام هذه الطريقة في تقطير المياه في تطبيقات مختلفة بكميات تجارية معقولة.

الكلمات الدالة: تقطير شمسى، تقطير المياه، مقطرات شمسية، أنابيب شمسية مفرغة، انتاج ماء مقطر.

Introduction:

Due to the fast growth of the world population, improving living standards, changing consumption patterns, and expansion of irrigated agriculture, the need for freshwater has been raised globally (Ercin & Hoekstra, 2014). The Middle East, especially Jordan, is facing great challenges due to limited natural resources of drinking water. By the year 2025, if current trends continue, per capita water supply will fall by 50 %, putting Jordan in the category of having an absolute water shortage, Mohsen (Mohsen, 2007). To solve the problem of freshwater resources, several desalination technologies have been employed. Among these; Reverse Osmosis (RO), Vapor compression (VP), and Electrodialysis (ED) are the most common method (Mahian et al., 2015). Distillation is the most developed method and can be applied for the production of large quantities of water. The phase change of water from liquid to vapor is the basis of all forms of distillations. The methods commonly used are the multi-effect (ME) and multi-stage flash (MSF) processes (Mohsen & Al-Jayyousi, 1999). Solar distillation can be used to produce distilled water for industrial and laboratory applications, and also for small communities at average daily water consumption around 0.4 m^3/ per person (Howe, 1986). Many researchers have been investigating solar desalination systems. (Hunashikatti et al., 2014) developed a desalination unit using solar still coupled with evacuated tubes for domestic use. (Kalogirou, 2005) studied seawater desalination using renewable energy sources. He also makes a review of various desalination systems that use renewable energy sources. (Jafari Mosleh et al., 2015) proposed a new desalination system, which makes use of a heat pipe, ETC, and a sun-tracking PTC system. They verified that the efficiency can be increased to up to 65.2%. (Kedar et al., 2019) carried out an experimental investigation for the softening of hard water by using a solar desalination system with an evacuated tube collector. They reported that the evacuated tube solar collector system gives 27-28 liters of soft water per day. (Shafii et al., 2016) present a new passive solar desalination system, which benefits from twin-glass evacuated tube collectors. In this system, results show a significant increase in the rate of desalinated water production, and the highest production reaches up to 0.83 kg/(m2·h). A solar still for water distillation using an evacuated tube collector was designed and developed by (Kalbande et al., 2016). In this study, the radiative and convective heat transfer coefficient was calculated and discussed. The paper of (Kedar et al. 2018) mainly focuses on thermal analysis of evacuated tube collectors as well as the design and analysis of compound parabolic concentrators. Recently, (Nabil et al., 2019) investigated experimentally the effect of water film thickness inside the ETC, the condenser's diameter and the condenser's inclination angle on the performance of the system considering the daily desalinate yield and the system's efficiency.

Finally, researchers may find in the great work of (Ali et al., 2011) a full and comprehensive review, 118 references, of all the indirect solar desalination technologies. They also reviewed a lot of publications addressing the economic feasibility and parameters that affect the cost of each desalination technology.

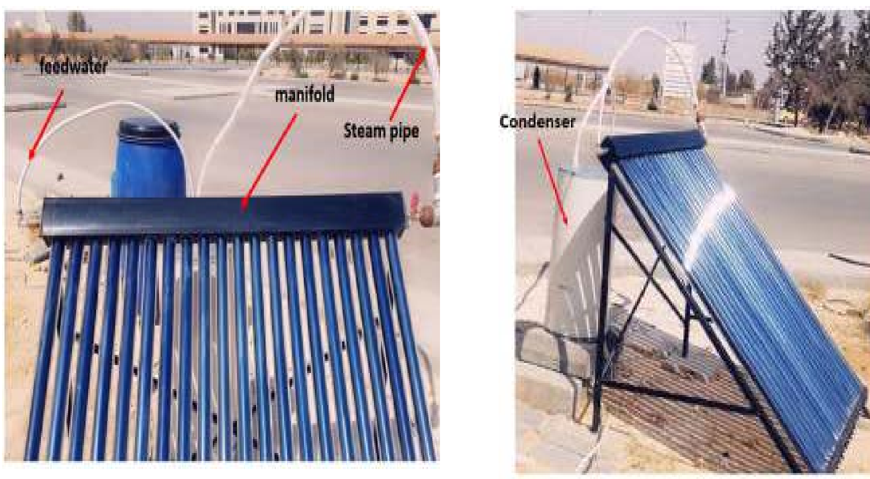
In this study, a new non-complicated and efficient solar distillation system coupled with a set of 20 evacuated tubes are employed with one manifold. The direct transfer of the absorbed solar energy to the tab water, with heat recovery principle to improve the performance of the system, is aimed to be verified experimentally. To this end, this work is divided into four sections: Introduction, Experiment and Measurements setup, Results and Discussion, and finally Conclusions.

Experiment and Measurements Setup

Solar distillation system

The system in the experiment mainly consists of evacuated tubes array, supply tap water tank, distilled water collecting jar, coil and shell condenser, Arduino electronics-based measurement components, water circulation pump, and power supply batteries.

A commercial evacuated tube solar collector with a heat pipe allows for rapid heat transfer. The heat pipe itself is a copper tube that maintains a vacuum and contains a small amount of liquid. In this work, we utilize a commercial collector consists of 20 tubes array, a heavily insulated single manifold header through which steam passes to the coil and shell condenser, stainless steel support frame, and standard mounting frame package with rubber gaskets. Each evacuated tube has the dimensions of 58mm x 1800mm, for radius and length respectively. The overall dimensions of the solar collecting panel are 1760x1500x180mm. Figure 1 shows two different views demonstrating the main components of the system: Solar radiation collecting tubes, manifold, condenser, and feedwater tank.



(a) (b)

Figure (1)Different views of the solar distillation system showing the main components: tube collector and the heat exchanger (condenser)

The heat recovery heat exchanger has been designed, fabricated, and integrated with the distillation system. Coil and shell-type heat exchanger is designed and manufactured with a coil diameter of 12.7 mm and a length of ~10,000 mm, and the shell dimension 70*36*31 mm. In this manner, the condensed steam will pass its heat to the relatively cold feedwater in the heat recovery heat exchanger.

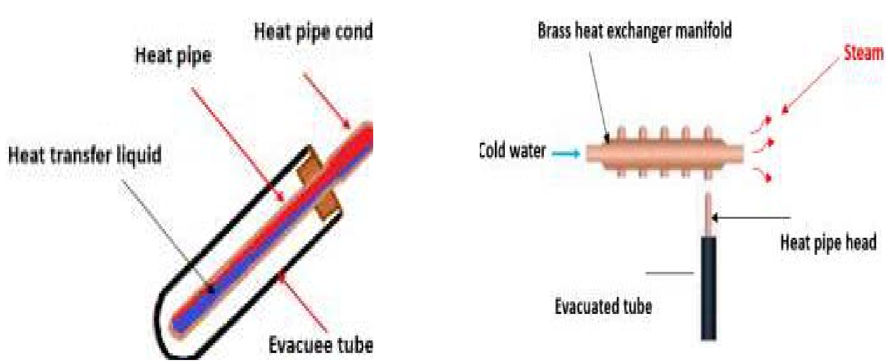
Measurement’s devices and electronics

Arduino Mega board equipped with a chip microcontroller is used for signal processing. A data storage module that using an SD card shield with an embedded time clock and a display module of LCD are used for monitoring and registering the acquired data. The card adapter stores the data of sensor readings every 30 seconds in the form of text files (*.txt). Such equipment is quite enough for conducting reliable measurements on the different physical quantities in this work, where more details about using Arduino for such research can found in (Louis, 2016)

A lead-acid battery,12-volt with and 7.2Ah capacity, is utilized to operate the Arduino electrical system and also to run a 12-volt DC water pump. The hardware implementation of the system has been done on the breadboard.

System components and the principle of operation

The working principle of the system depends on the absorption of solar radiation by the evacuated tubes collectors, where the absorption layer of the collectors absorbs solar radiation and converts it into heat. This generated heat is absorbed by the heat pipe liquid which in turn evaporates at a temperature below 32 degrees Celsius due to decreased pressure inside the pipe. The collected heat is transferred to the radiation bulb at the end of the pipe which serves as a condenser and heat radiation element, as Figure 2 illustrates.



(a) (b)

Figure (2) A schematic diagram shows a depiction of the: (a) The evacuated tube with heat pipe, and (b) the assembly of the heat pipe, the evacuated tubes, and the steam generator manifold.

The passage of water inside the manifold is done through a control process and this process is based on a thermocouple sensor and water pump, the sensor is connected inside the manifold to measure the water temperature. When the water temperature reaches 100 degrees Celsius, the controls give the pump a command to start pumping the water. By this control method, the pump will stop working if the solar radiation decreases, and the water temperature in the manifold becomes less than 100 degrees Celsius. Rising water temperature and changing its states from liquid to vapor state requires a sufficient quantity of gained energy obtained from solar radiation. In this design shown in Figure 3, the condensed steam exchange energy with the feed water through the heat exchanger. The energy recovery is the reason for increasing the amount of produced distilled water.

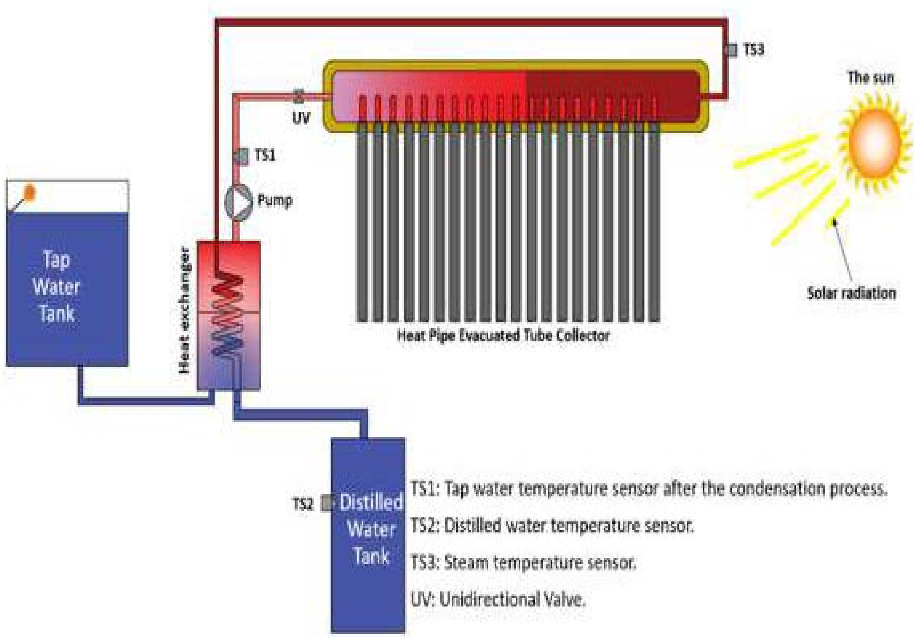


Figure (3) Layout and components of the distillation system, where TS1 is temperature sensor number 1, TS2 is temperature sensor number 2, TS3 is temperature sensor number 3.

Results and Discussion

The experiments were carried out on the premises of Al al-Bayt University, Mafraq- Jordan. The measurements were taken for four days from 3/June to 6/June as per the environmental and climatic conditions of Mafraq city which is located 80 km to the north from the capital Amman. Mafraq located at the latitude of ~32.3429^{o} North, the longitude of ~36.208^{o} East, and the altitude of 686 m.

To select the optimal tilt angle of the evacuated tube collector, the conventional estimation method which equates inclination angle to latitude angle is not adopted here. Reasonably, the tilt angle was calculated analytically using the equations in (Duffie and Beckman, 2013). The optimum tilt angle is defined at the maximum averaged efficiency. The yearly averaged maximum efficiency was calculated by a C++ program, developed for this purpose, and the results are shown in Figure 4. Based on these calculations, the evacuated tubes array optimal tilt angle is ~40^{o} with azimuth angle to true south.

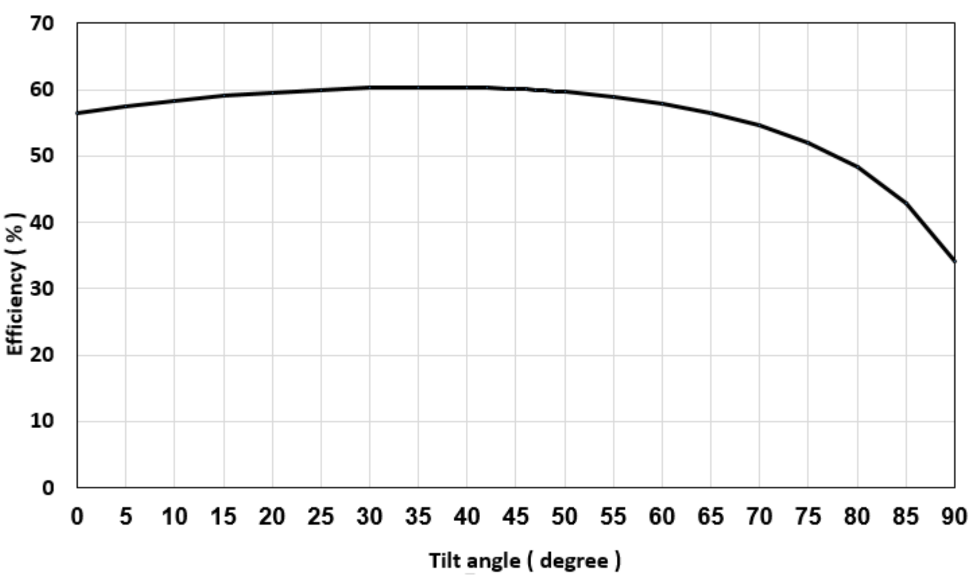


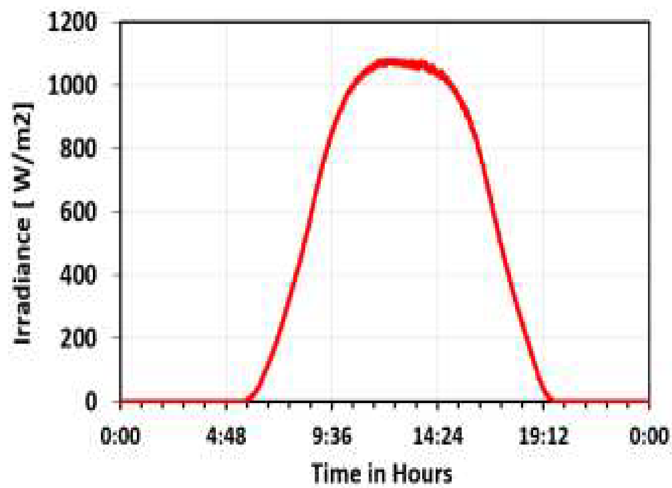
Figure (4) The average yearly efficiency of the evacuated tube collected as a function of tilt angle calculated at Mafraq location: Latitude of ~32.343º N, and Longitude of ~36.208º E.

Experiments were carried in June 2019 and the results of various parameters recorded for several days. The system is installed under realistic conditions, and real-time measurements of temperature are conducted. Thermocouples of K-type are installed at points as shown in Figure 3. Temperature sensor 1 (TS1) is assigned for tap water temperature, the temperature sensor 2 (TS2) is assigned for distilled water temperature (TS2), and the temperature sensor 3 (TS3) is assigned for steam temperature. The measurements have been recorded for approximately 4-5 hours daily with sampling intervals of 10 seconds. The obtained results from the period of observation of the experiment are summarized in Figures 6-9. It can be observed from Figures (6-9) that the heat recovery process is very efficient. The produced distilled water temperature remains ~40 C^o which is ~12 C^o above the supply water temperature, (the measured ambient temperature is 28 C^o). The recovered energy is transferred into the feedwater during the implied heat exchanger. As a result, the preheated feedwater temperature raised from ~28 to ~50 C^o.

To investigate the irradiance and the amount of distilled water the solar irradiance is measured. Figure 5 shows the global irradiance measurements during the experiment observation days. One can see that quite a large amount of irradiance, and hence energy, is available in the location experiment, as expected. If this amount of energy gathered and recycled efficiently, it would be sufficient and effective to produce a large amount of clean water by solar distillation.

It can be seen that even in the cloudy days, the distillation process continues with some reasonable amounts of water being produced. This can be seen by correlating Figure (5,c) and Figure (8), where the cloudy weather during the morning hours does not prevent the distillation to proceed. However, the amount of collected distilled water is not as that on sunny days. Despite this, system production of distilled water continues afternoon due to partially cloudy weather.

(a)


Irradiance [W/m2]
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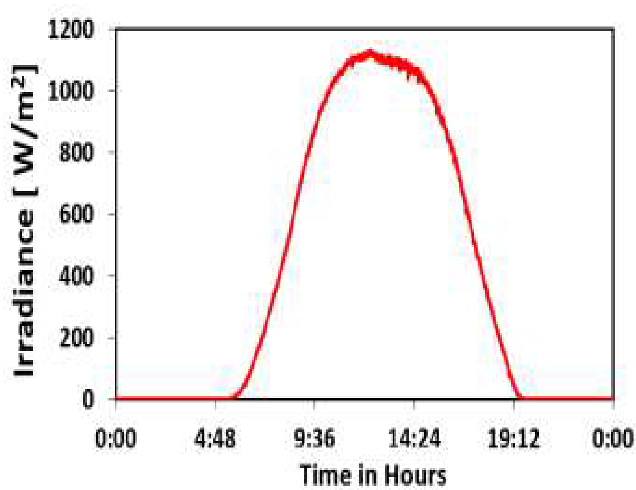
Time in Hours

(b)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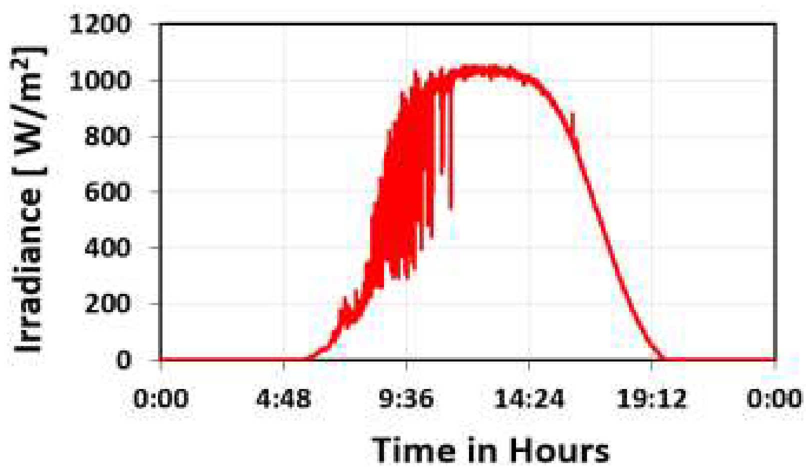
(c)



(d)

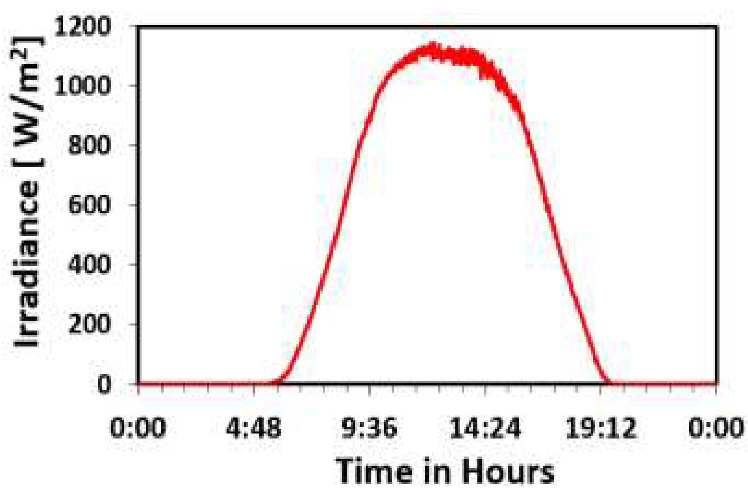


Figure (5) The global irradiance measured at the location of the experiment, Latitude of ~32.343º N, and Longitude of ~36.208º E. (a) 3rd of June/2019, (b) 4th of June/2029, (c) 5th of June/2019, and (d) 6th of June/2019.

Comparing the amount of the produced amounts of distilled water on different days, we can see that approximately in the sunny days, similar amounts of water would be produced. Whereas, in a partially cloudy day ~ 64% of that of the sunny day production can be achieved. These observations, readings, and measurements shed a light on the performance of the system. Since the scope of this work is to prove the concept, as mentioned earlier, we focused on providing observations that support the scope of the work.

The most important observation is the temperature of water vapor in the manifold. It is known that the temperature of water evaporation at atmospheric pressure is equal to ~100 ^{o}C. Therefore, the recorded temperatures range is between ~90- 130 ^{o}C is an indicator of the success of the system to generate steam because it reaches the necessary evaporation degrees. This steam is condensed later through the condensing unit and flows to the collecting tank.

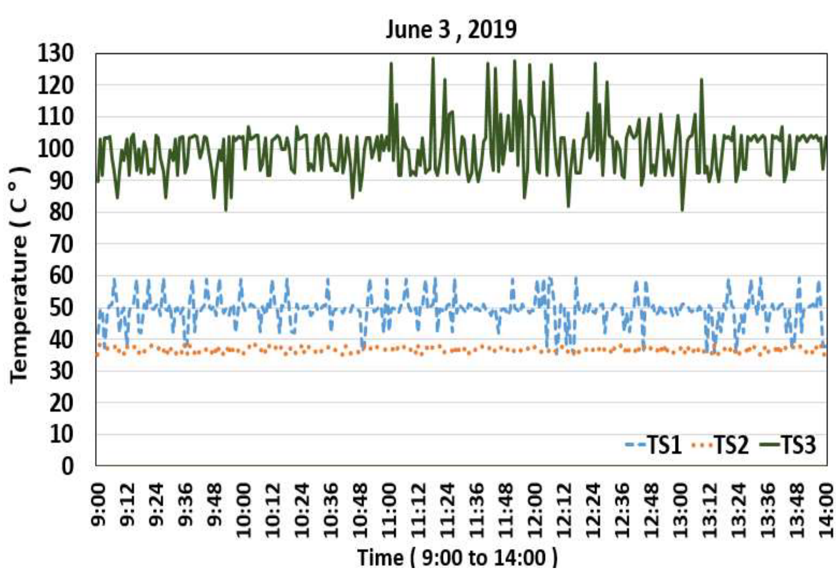


Figure (6) The temperature readings at different locations in the system: temperature sensors 1(TS1), temperature sensors 2 (TS2), and temperature sensors 3 (TS3).

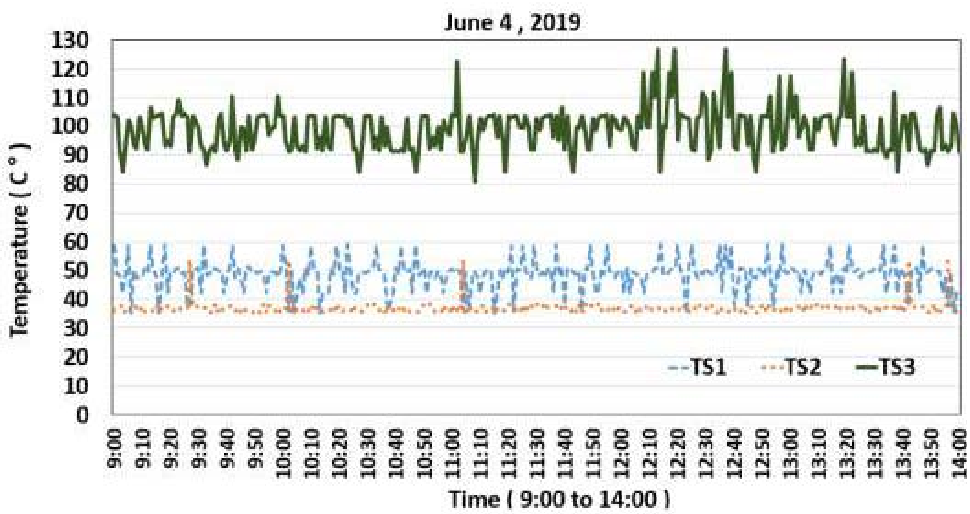


Figure (7) The temperature readings at different locations in the system: temperature sensors 1(TS1), temperature sensors 2 (TS2), and temperature sensors 3 (TS3).

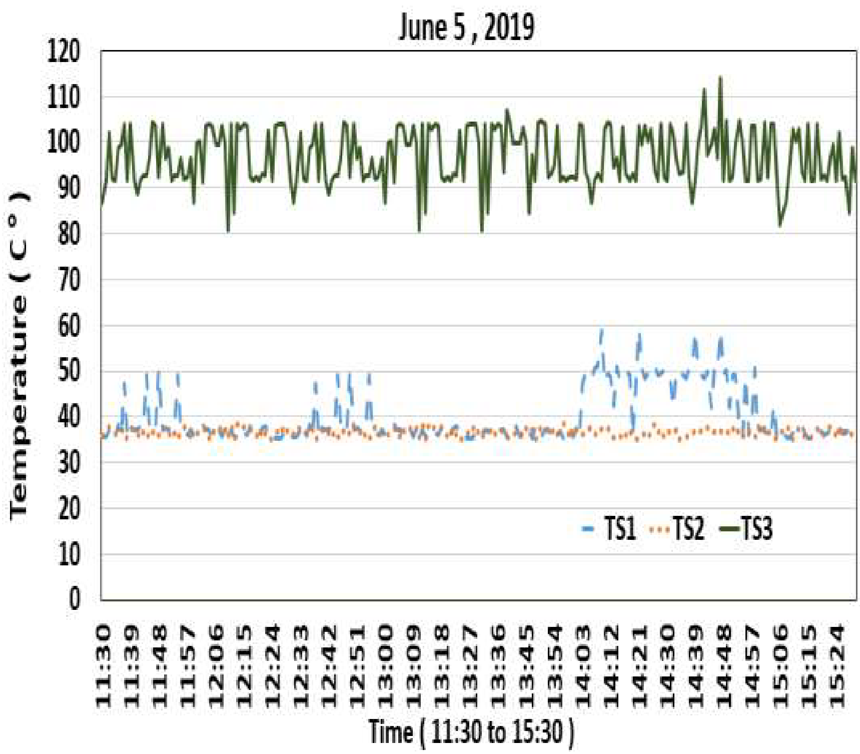


Figure (8) The temperature readings at different locations in the system: temperature sensors 1(TS1), temperature sensors 2 (TS2), and temperature sensors 3 (TS3).

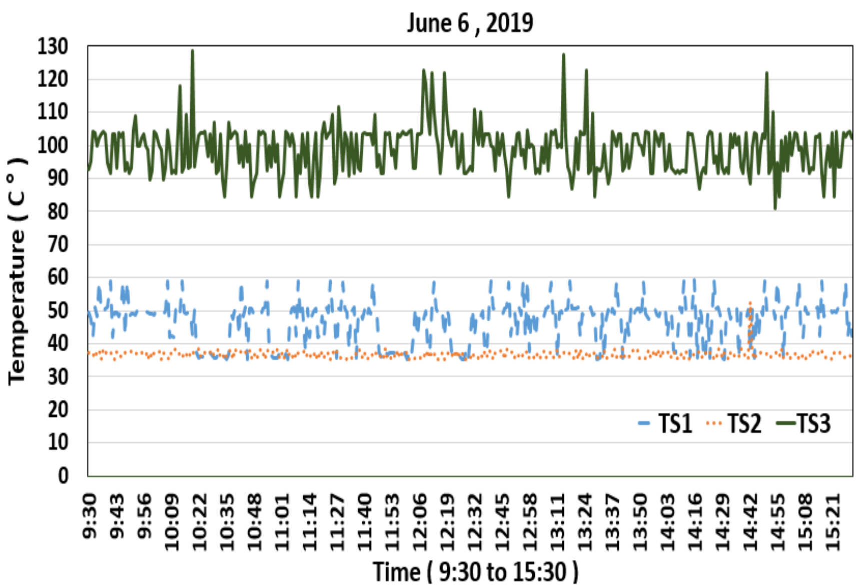


Figure (9) The temperature readings at different locations in the system: temperature sensors 1(TS1), temperature sensors 2 (TS2), and temperature sensors 3 (TS3).

It is worth noting that the recorded temperature depends also on the flow rate of both streams. As mentioned earlier, the flow rate of the fed water was controlled by the feed pump which is governed by the temperature of the water inside the manifold to ensure that the collected energy is sufficient to cause vaporization of the supplied amount of water. The flow rate amount value of the feed water stream is not so significant in these measurements, only the total amount of the collected distilled water is measured daily. It is obvious from the theory that the rate of the distilled water production is in variations with the solar intensity during the day hours as well as weather conditions. Studying the effect of this variation is not in the mind of the authors in this work because it is well addressed in the literature (Shafii et al., 2016). The main aim of this study is to prove the performance of the newly suggested approach for distillation and to measure the daily amount of produced distilled water. For this purpose, the amount of the collected distilled water is tabulated in Table 1. The results in Table 1 inevitably indicate and prove that the introduced distillation approach and system in this work are effective for producing distilled water in reasonable commercial amounts. The main idea of this system and its almost costless production can be used commercially due to the effective quantities of distilled water produced. Therefore, after proving that this system can work and produce distilled water, it is possible to build a system consisting of, for example, 500 evacuated tubes with an estimated monthly production of ~37000 Liter/month of distilled water.

Table (1) The daily collected amount of distilled water during the observation period

Date	Climate	Sunset to sunrise	Hours	Quantity of distilled water
3/June	Sunny	05:29 to 19:36	14.07	~52 L/day
4/June	Sunny	05:29 to 19:37	14.08	~51 L/day
5/June	cloudy	05:29 to 19:37	14.08	~32 L/day
6/June	Sunny	05:29 to 19:38	14.09	~54 L/day

Conclusions

A new simple and efficient solar distillation system were presented. The idea of using an evacuated tube collector to directly produce distilled water from the tap water augmented by the heat recovery principle was verified to work effectively. The recovery of energy raised by condensation has improved the efficiency of the system and the leadership of the amount of distilled water produced. The introduced system can operate efficiently in a similar environment of Mafraq. A commercial version of the system would be produced for different applications.

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