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Improvement of the performance of a solar still by utilizing the sorption thermal storage of natural zeolite

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ABSTRACT

The effect of natural Jordanian zeolite (NJ zeolite) as a thermal energy storage material on the thermal efficiency of solar still was experimentally tested under Jordanian climatic conditions. The zeolite samples were obtained from northeast of Jordan. In this study, two similar solar stills with basin of 0.95 m^2 and a pyramid glass cover have been designed and constructed by local materials. One of the solar still is filled up with NJ zeolite beneath the basin liner surface of average grain-sized particles between 0.4 and 4 mm. The experimental results illustrated that adding the NJ zeolite beneath water basin and using a centrifugal fan working with photovoltaic solar panels become applicable in increasing the productivity of freshwater. The research was conducted for the range of zeolite mass starting from 500 to 1,500 g. It was found that the amount of zeolite played a major role toward increasing freshwater production. The performance evaluation indicated that the daily productivity was enhanced by 43% when using NJ zeolite.

Keywords: Jordanian zeolite; Solar still; Storage material; Water distillation

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1. Introduction

The accelerated demand on proper quantity, quality, and reliability of drinking water is increasing continuously in developing countries. The inappropriate access to water resources that is commonly containing significant dissolved salts and/or harmful bacteria is inadequate for drinking and harmful for humans. Therefore, improving the availability of freshwater resources and its quality with simple technological innovations will lead to a rapid growing in the livelihoods of these countries. Jordan is classified among the countries that suffer from sharp shortage of drinking water according to the World Health Organization (WHO). But Jordan has high global radiation and more than 300 sunny days annually. A small scale of drinking water can be realized for such locations using solar stills, which boast abundant of solar energy and high sources of brackish water. Building solar stills are relatively inexpensive, simple to operate, construct, and yielding freshwater at low cost. The principle of the conventional solar still (CSS) is a simple one in which a certain area of glassed-over wooden frame evaporated the impure water and condensed it again into freshwater [1–4].

A lot of experimental and theoretical works are being carried out to enhance the performance of stills. Researchers have tried to determine the dependency of the productivity in terms of different structure, weather conditions, and operation factors [5–10]. Solar

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stills are commonly classified according to energy supply. Passive solar stills use only the direct solar energy incident on the glass actual area i.e. CSSs. In active solar still, an external thermal energy is supplied to still unit for faster evaporation and thereby, enhance the productivity [11–13].

Heat storage medium and phase change materials (PCMs) have become important issues in the present solar energy application research. It has long been known that there are different systems of storing solar energy. These thermal systems are based on sensible, latent, and chemical reaction energy storage. Latent and sensible heat are types of energy released or absorbed in the thermal system. There are a large number of advantages that are provided by the latent heat storage system compared with the sensible heat storage systems such as large energy storing per unit volume, longer periods of storage, and greater repeating capabilities [14–17].

Tabrizi and Zolfaghari [16] investigated experimentally the effect of using sand as a heat storage media on the performance of the still. They used sand in solar still as heat storage media and showed that it produced distillate during off-shine hours and its productivity was 75% higher than the conventional still.

Abdullah et al. [17] carried out experiments in a still using three different absorbing materials (coated metallic wiry sponges, uncoated metallic wiry sponges, and black volcanic rocks). The stills used in experiments were loaded with different absorbing materials. The temperature of the outer surface of the glass, water vapor, basin water, was measured using digital thermometer in the range of 50–150°C. The productivity of the still loaded with black rock, coated and uncoated metallic wiry sponges was 60, 43, and 28% higher than the conventional still, respectively.

Much more attention has been paid in the literature to PCMs that used as a thermal energy storage medium combined with some several solar technology systems; such as solar distillation, solar domestic hot water systems, promoting solar cookers, and greenhouses. The advantage of PCM materials is that they can store solar energy to compensate fluctuations in the solar energy [18–21].

PCM materials are substances capable of melting and solidifying at a certain temperature. They are also able to store and release large amount of thermal energy. There are a large number of PCMs available in wide temperature range. By coating the basin of the solar still with a certain PCMs, a significant amount of heat will be stored within PCM in the sunshine hours instead of losing it to surroundings. In evening, when the PCM solidified, the stored energy releases to maintain the basin water at appropriate temperature to produce freshwater. This in turns enhances the freshwater productivity during off-shine hours [22–24].

It is well known that using adequate thermal energy storage in solar still, high potential in energy utilizing as well as freshwater productivity will be achieved. Natural zeolites have advantage over many others PCMs. Their high heat storage density and ability to hydrate and dehydrate while maintaining structural stability makes zeolites becoming a futuristic material for storing solar energy. Natural zeolites are aluminosilicate minerals of alkali or alkaline earth metal which includes crystal water. Zeolites are composed of three-dimensional networks of AlO_4 and SiO_4 tetrahedra joined together by having one or more of oxygen atoms. The voids form 20 to 50% of the total crystal volume of most common zeolites. When the temperature of zeolites is increased, water molecules getaway and replaced with heat stored energy, when water comes again in contact with zeolite, the heat energy is released. The natural zeolites have significant advantage over other form of thermal heat storage (latent and sensible). They have large energy storage density. Zeolites unlike water which gradually cools off retain a hundred percent of the heat for an unlimited amount of time. It can store up to four times more heat than water (see Table 1) [25,26].

Taamneh and Taamneh [26] designed and fabricated simple pyramid-shaped solar still, which has been adopted in this work, and its performance was experimentally evaluated under Tafila climatic conditions. They used a forced convection fan that improved the evaporation and condensation rate. The productivity of the solar still equipped with fan was enhanced by 25% compared with solar still without fan.

The purpose of this research is to present NJ zeolite as sorption thermal storage with pyramid solar still (which has been designed and constructed by Taamneh and Taamneh [26]). By adding zeolite beneath the basin of the solar still, the enhancement of evaporation rate is expected over a day. There seems to be lack of study on the solar still using natural zeolite as thermal energy storage. Therefore, in this paper, the influence of NJ zeolite on the pyramid-shaped solar still performance will be investigated experimentally.

2. Experimental approach and setup

The experiments were carried out for 3 d in June under the outdoors of Tafila climatic conditions, Jordan. Seawater was used in all experiments with salinity in the range of 35 g/l. The experiments were

Table 1
Physical properties of modifies and CSS components (0–100˚C)

	Thermal conductivity (W/m K)	Bulk density (g/cm^3)	Porosity (%)	Specific heat (kJ/kg K)	Heat of absorption (kJ/kg)	Storage density (kWh/m^3)
Zeolite	0.32–38	0.9–1.1	30–47	0.87–0.91	1,019-1,132	180–300
Brackish water	0.67	1.022	–	4.19	420–840	65–82
Glass	1.02	2.53	–	0.8	600–800	22–80
Absorber (aluminum)	204	2.7	–	0.89	500–900	27–70

conducted for different particle sizes of NJ zeolite which was obtained from Al Mafraq, the northeast of Jordan. As shown in Fig. 1, the unit consists of metallic container, occupied by the raw saline water to a certain level below the exit. Pyramid solar still of area 1 × 0.95 m is constructed.

It has been designed and constructed in such a way that four similar triangles made of glass are being held on to the supporting structure container by adhesive silicon. The thickness of glass cover was 4 mm with relative transmissivity of 0.88. These glass triangles covered a square base container to form the pyramid shape. The purpose from the design is to increase the surface area used for condensation. The triangle shape glasses are inclined to an angle of 38˚ in order to make dripping water run down on the channel adjacent to the container and to increase the amount of solar radiation reaching the surface more frequently during the day. For sealing purpose, an adhesive silicon as rubber gasket was used and placed between the glass cover and the container support structure where they were tightened and held in around the periphery of the still. Two holes with diameter of approximately 1 inch were drilled into the container to provide accessibility of saline water into the basin during initial filling and installing the centrifugal fan as well as pipe vent. Also, a vent pipe is connected to the tee-pipe in order to prevent overflowing of the saltwater when the water comes in contact with NJ zeolite (valve 1 opened) and ensure the air flow induced by a centrifugal fan when valve 1 is closed. The bottom section of basin and the side wall of the container were insulated to reduce thermal losses to the surroundings. The condensed water runs down into a gutter, which is made of galvanized steel and connected to the outlet (drain pipe) and frequently collected using a plastic container. A black plate is used to cover the base of the solar still, fabricated from a black painted galvanized iron sheet of thickness 0.15 cm. A vertical gap (5 cm) under the horizontal portion of the basin liner is left. This gap can be loaded with the NJ zeolite about 3 cm in depth or less whose base is also black flat. The NJ zeolite is separated by the base liner. A schematic diagram of the investigated solar still with NJ zeolite is shown in Fig. 2.

Fig. 1. Photograph of pyramid-shaped solar sill.

Two identical solar stills were manufactured and tested under the same weather conditions. The NJ zeolite sample which was obtained from Al Mafraq, the northeast of Jordan, sieved into different particle sizes and washed by distilled water to remove surface dust (see Fig. 3). Then, it had been dried at 120˚C for 12 h. One of the solar still is filled with NJ zeolite beneath the basin liner surface of average particles grain size between 0.4 and 4 mm.

Zeolite is family of chemical compounds that are capable of reversible absorption. Under the influence of a heat supply, water is desorbed from the material and is then stored separately (an endothermic phenomenon referred to as the charging or activation of material). When water and sorbent are put into contact (opening valve 1), there is a heat release (an exothermic phenomenon referred to as a material's discharge or deactivation). Now, during the sunless hours (night time and cloudy days), the dry zeolite

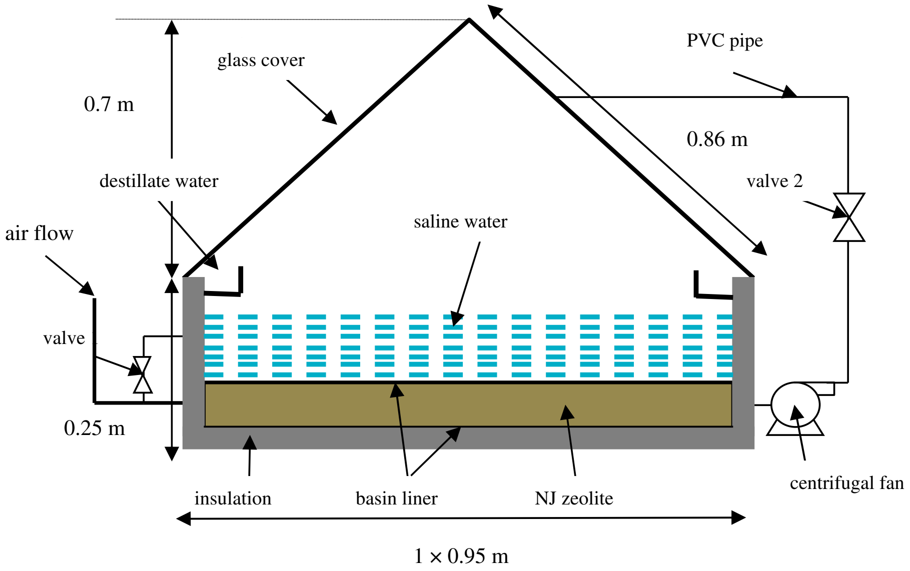

Fig. 2. A schematic diagram of pyramid-shaped solar still with NJ zeolite.

bed beneath the basin liner is a source of stored chemical energy which is readily changed into thermal energy by allowing water and zeolite into contact (in the sunless hours). The physical properties of zeolite, brackish water, glass, and aluminum absorber that have been used throughout all experiments are given in Table 1.

The zeolite is also warmed by it is own absorption of the solar energy. Continuous heating by the sun causes the zeolite to release the water vapor. The water undergoes a phase change. The water vapors then rise and blown through the solar still by the centrifugal fan; the centrifugal fan works with photovoltaic solar panels and low power consumption (~10 W). In order to ensure that blowing occurs at atmospheric pressure, a simple vent pipe is connected to the solar still container as shown in Fig. 2. Therefore, air will fill the space—where the NJ zeolite is placed—when the centrifugal fan is operated. Hence, during this phase of the process, solar energy is stored in the form of heat absorption in the NJ zeolite. At night, or on cloudy days, this stored energy is released by injection saline water into the Jordanian zeolite (gap) through opening the valve (1) that separates the saline water from the zeolite, while valve (2) remains closed during evening. The released stored energy acts as internal source of thermal energy used to warm the saline water in sunless hours and in the night.

The k-type thermocouples were used to measure the basin water temperature, basin zeolite, and the inside air temperature. The highest temperature and solar radiation recorded in Tafila city were 36°C and 1,060 W/m^2 in June 2014, respectively. During one-day testing, the solar radiation, ambient temperature, glass cover temperatures, water basin temperature, and distillate output were measured. The measurements were recorded continuously every 30 min for 12-h period and started at 6:00 am. The solar still is tested for three days in a summer season (June 2014).

Two similar solar stills with basin of 0.95 m^2 and a pyramid glass cover have been designed and constructed by local materials. One of them was fed by saline water built in NJ zeolite about 3 cm in depth (modified), the second solar still manufactured without gap (conventional). It should be noted that in all experiments, the volumetric flow rate of air induced by the blower was constant. The thermal instantaneous efficiency (η) of the solar still is defined by the ratio of evaporation heat transfer to instantons solar radiation intensity that arrive in the solar still, which can be calculated as (Eq. (1)):

$$\eta = \frac{mL_{\mathrm{m}}}{GA_{\mathrm{g}}\Delta t} \tag{1}$$

where m is the mass condensate and collected in a time interval (kg), L_{m} is the water latent heat of evaporation (J/kg), G is hourly solar radiation flux (W/m^2), A_{g} is the glass area (m^2), and Δt is the time interval (s).

3. Results and discussion

3.1. Effect of solar incident radiation on the behavior of the solar still

The effect of using NJ zeolite as a thermal storage material on the pyramid-shaped solar still

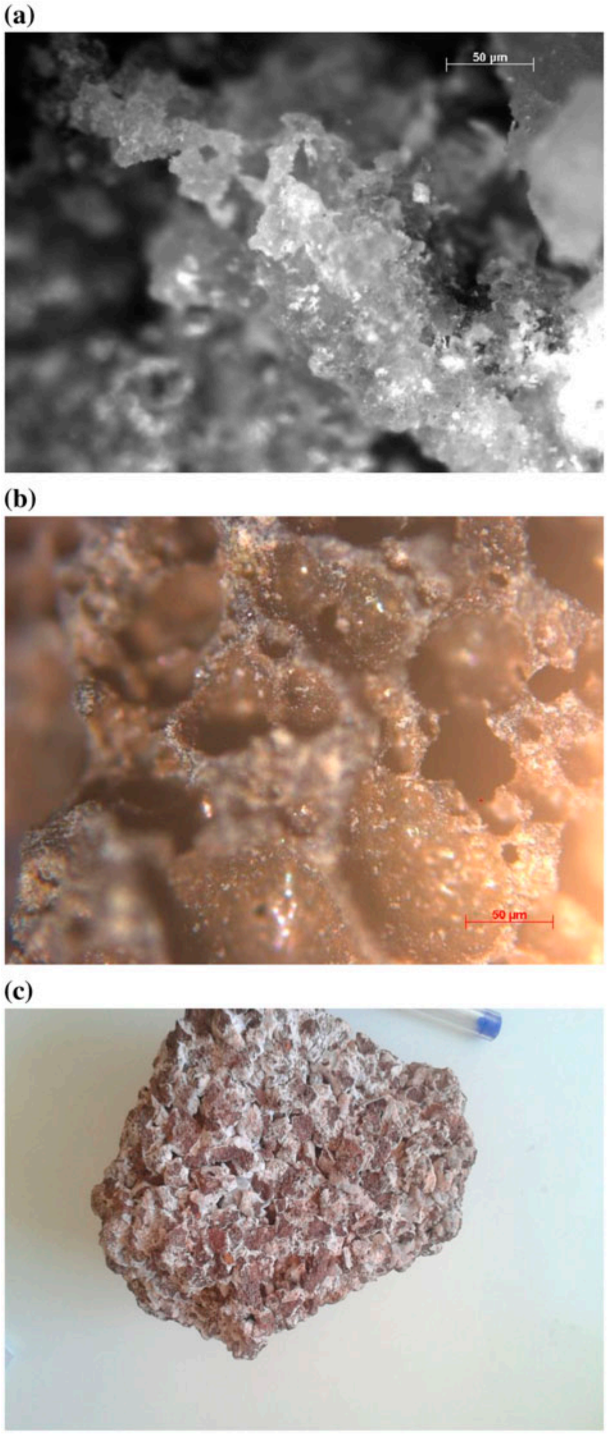

Fig. 3. (a) Crystallization, (b) pores shape of NJ zeolite used in experiment under microscope, and (c) natural Jordanian zeolite from the northeast of Jordan.

productivity is investigated experimentally. It has long been known that the performance of the solar still was mainly governed by the intensity of solar radiation absorbed by plate. Fig. 4 shows the variation of solar radiation during three days of testing. It is clear that the hourly solar radiation was high around midday and has the same tendency. For example, the maximum solar radiation is around midday, then decreases in the afternoon, and matches the variation of solar radiation incident. The hourly solar radiation values have insignificant fluctuations. Therefore, the solar still performance will not be affected during the three days of testing.

Fig. 5 shows the variation of basin water temperature, glass temperature, and the ambient temperature for the solar still with and without NJ zeolite during one-day testing. For solar still with zeolite, the maximum basin water temperature and the glass temperature are about 72 and 40˚C, respectively. On the other hand, for solar still without zeolite, the maximum basin water temperature and the glass temperature are about 60 and 38˚C, respectively. The basin water temperature of the solar still with zeolite is higher than that of solar still without zeolite by about 0–10˚C. This is mainly due to NJ zeolite that acts as a source of heat storage for the basin still in the period of low solar radiation incident as well as during night and some of the incident radiation penetrates the still to increase the temperature of zeolite itself and the basin still. The temperature of the measured points (water, glass, and the ambient temperature) is increased in the morning hours to reach it is maximum value around midday and decreased after that gradually.

3.2. Freshwater productivity

Comparisons between the hourly variations of freshwater production for conventional (without

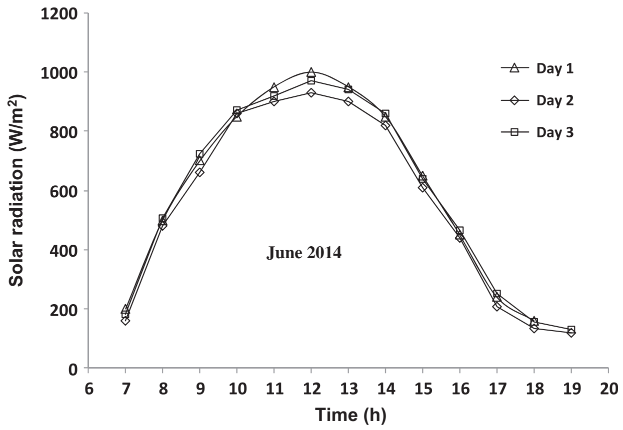

Fig. 4. The hourly solar radiation during the three days of testing in June 2014.

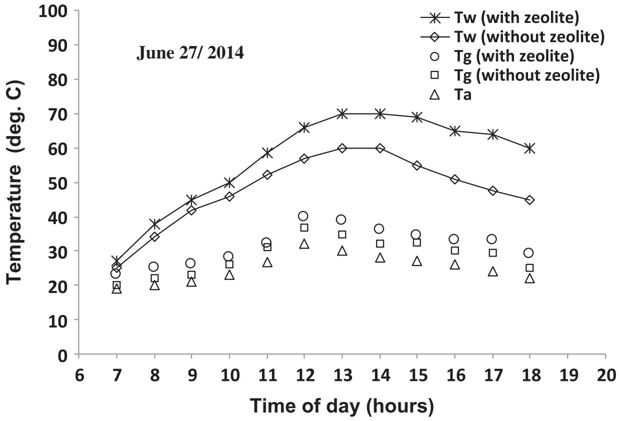

Fig. 5. The hourly temperature variation of basin water temperature (T_{w}), glass cover temperature (T_{g}), and ambient temperature (T_{a}) during day 1 for the modified and CSS at m_{z} = 1,500 g.

zeolite) and modified solar still (with zeolite) are depicted in Fig. 6. From the figure, it can be seen that the daily freshwater production increases gradually until it reaches the maximum value around midday at highest solar radiation, then decreases in the afternoon as the sun sets. Also, it can be observed that the hourly productivity increases from zero value in 6:00 am to the maximum values in 1:00 pm due to the increase in water evaporation and condensation rate. It is known that the rate of condensation depends on the difference in temperature between the outer glass cover and the basin water. The hourly productivity in the solar still with NJ zeolite is higher than that of the CSS, because of using the stored energy material (NJ zeolite) which acts as heat source during sunset. Furthermore, before sunset, the centrifugal fan used in experiments is operated to carry the warm air that holds high water vapor from the interior of the zeolite still to the main solar still chamber (through opening valve 2). This in turns increases the amount of vapor and thus the water productivity. After sunset, the centrifugal fan turned off and the dry zeolite bed represents as a source of stored thermal energy that is released by bringing water into contact with zeolite through opening the valve 1 and closing valve 2. The productivities of the two stills were around 0.0 at early morning, while their value recorded 0.5 and 0.38 L/h as a maximum freshwater productivity at 1:00 pm for the modified and CSS, respectively. The experimental results obtained from the modified and conventional sill are validated by comparing with corresponding theoretical results. In addition, it can be observed from Fig. 6 that the comparison between experimental and theoretical productivity for both solar still is in a reasonable agreement. The deviations between experimental and theoretical results were about 10% and reached up to 25% for conventional and modified solar stills, respectively.

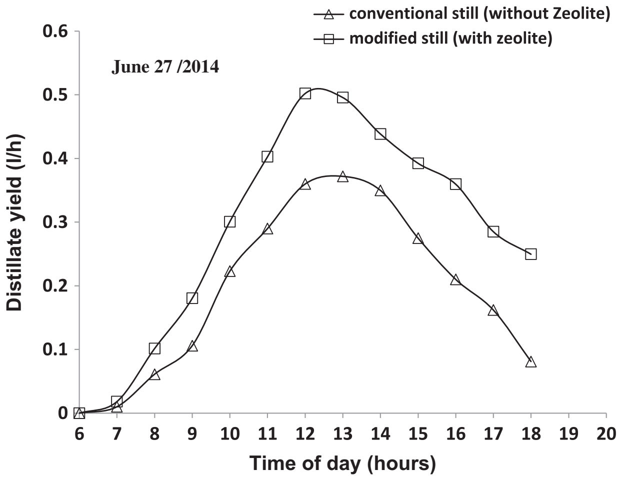

Fig. 6. The hourly variation of freshwater production for modified and CSS using NJ zeolite at m_{z} = 1,500 g.

3.3. Daily productivity

The comparative analysis of the accumulated distillate water for conventional and modified solar still during one-day test is shown in Fig. 7. Also, it is noticeable that the accumulated freshwater productivity for the modified solar still is higher than that of the CSS over the day. The accumulated freshwater production was around 3.6 L/d for modified solar still, whereas its value was 2.5 L/d for CSS. The increase in accumulated freshwater productivity for the modified solar still is 43% higher than that of the CSS. This is mainly due to the existence of the NJ zeolite that caused higher evaporation rate inside the still.

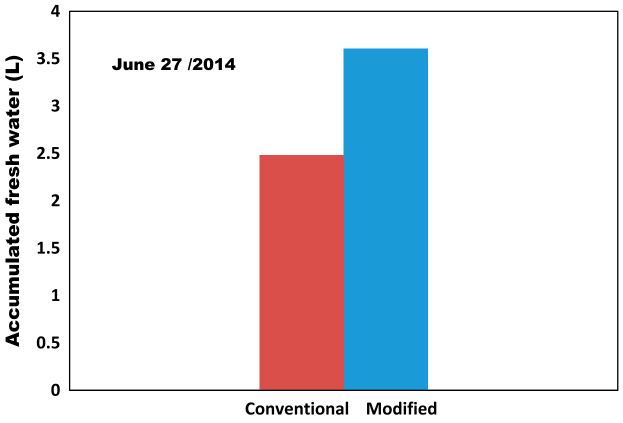

Fig. 7. The accumulated freshwater production for modified and CSS using NJ zeolite at m_{z} = 1,500 g.

3.4. Efficiency of the solar stills

The variations of thermal still efficiency for conventional and modified solar still along one day of testing are depicted in Fig. 8. The results showed that the solar still efficiency increases with time for both solar still. The maximum value of solar still efficiency achieved by CSS was approximately 36%, whereas the modified solar still produced 47%. It is clear from Fig. 8 that the hourly variation of the still efficiency after midday is significant for modified solar still compared with conventional solar because the freshwater production relative to incident radiation is increased. Therefore, the NJ zeolite has a considerable effect on the distillate yielding especially after sunset.

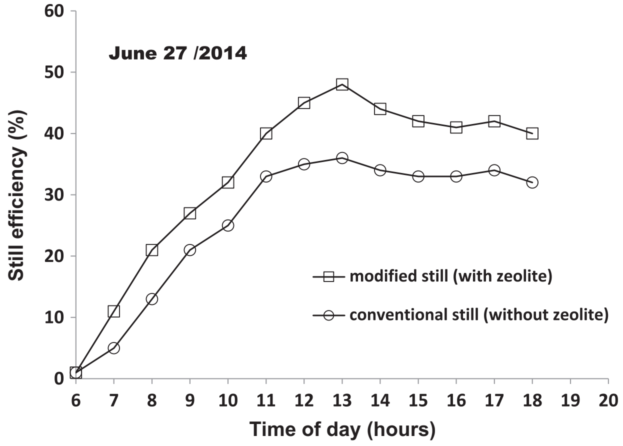

Fig. 8. Hourly variation of the modified and conventional still efficiency using NJ zeolite at $m_z = 1{,}500$ g.

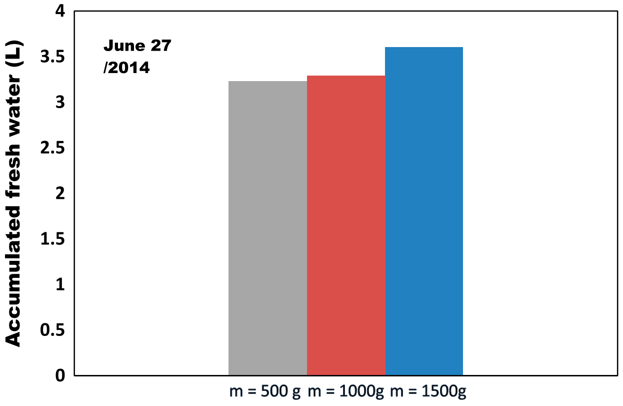

Fig. 9. Influence of NJ zeolite weight on the accumulated freshwater production for modified solar still.

Table 2
Uncertainty of instrument measurement

Instrument	Accuracy	Range	% error
Anemometer	±0.1 m/s	0–15 m/s	10
Thermocouples	±1°C	0–100°C	0.25
Solar meter	±1 W/m^2	0–5,000 W/m^2	0.25
Storage tank	±10 ml	0–1,000 ml	10

3.5. Effect of zeolite loaded

The comparative analyses of the productivity for modified solar still at different masses of zeolite are shown in Fig. 9. It is noticeable that the freshwater productivity of using 1.5 kg of zeolite produces a higher value of freshwater. The reason behind that is when the mass of zeolite increases, the amount of stored and released energy increases. This in turn enhances the evaporation and condensation rate.

3.6. Uncertainty (experimental errors)

The errors associated with measuring instrument are presented in Table 2. The errors were calculated for anemometer, thermocouples, solar meter, and storage tank. The minimum error associated with any instrument is calculated by dividing its least count over the minimum value of the output measured.

4. Conclusions

The performance of the modified and conventional pyramid-shaped solar still was experimentally investigated. Their performance was evaluated for Tafila city (south of Jordan) weather data. The results showed that the productivity of the solar still can be considerably improved through adding NJ zeolite beneath the water basin. It is found that the daily productivity of the solar still with NJ zeolite about 3.6 (l/d) compared with 2.5 (l/d) for the CSS, i.e. 43% increase in freshwater productivity.

Modified solar still provided slight increase in thermal performance over one day of testing. It is found that the freshwater productivity is affected by the amount of zeolite added.

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