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Research Paper

Experimental investigation of the impact of water depth, inlet water temperature, and fins on the productivity of a Pyramid Solar Still

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Abstract: This experimental study aimed to investigate the impact of water depth, inlet water temperature, and fins on the productivity of a pyramid solar still in producing distilled water. The experiment was conducted in three parts, where the first part explored the variation in water depth from 1 cm to 5 cm, the second part evaluated the effect of increasing inlet water temperature from 30°C to 50°C, and the third part added fins at the bottom of the still at a specific inlet water depth. Results showed that basin depth had a significant impact on the still's production, with a maximum variation of 40.6% observed when the water level was changed from 1 cm to 5 cm. The daily freshwater production from the pyramid solar still ranged from 3.41 kg/m^2 for a water depth of 1 cm to 2.02 kg/m^2 for a depth of 5 cm. Adding fins at the bottom of the pyramid solar still led to a 7.5% increase in productivity, while adjusting the inlet water temperature from 30°C to 40°C and 50°C resulted in a 15.3% and 21.2% increase, respectively. These findings highlighted the essential factors that can influence the productivity of pyramid solar stills and can be valuable in designing and operating efficient water desalination and purification technologies.

Keywords: Pyramid solar still; Basin depth; Freshwater; Efficiency; Desalination

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Introduction

Freshwater is one of the most essential elements for life on Earth. However, the production of freshwater remains significant challenge in many regions around the world, particularly in remote areas. In both unsophisticated and sophisticated regions, millions of people rely on water from unclear resources. Despite water covering about 70% of the Earth's surface, 97% of it is salty and unsuitable for consumption. Only about 3% of the total water on Earth is freshwater (Human Development Report, 2016). Additionally, the distribution of freshwater reservoirs around the globe is uneven.

Most research supports the effectiveness and affordability of solar energy-based desalination technology for producing fresh water (Kulandaivel and Karuppiah, 2014). A solar still is a device that uses solar energy to desalinate impure water, such as saline water, and convert it into fresh water (Taamneh and Allah, 2020; Khechekhouche et al. 2019). The principle behind the use of solar energy to convert the saline or brackish water to fresh water is simple. When water is exposed to the sun, it evaporates into the air. The solar still captures this water vapor by condensing it onto a cool surface. To capture and condense the water vapor, a transparent surface, such as glass, is required to allow sunlight to reach the water Pyramid solar stills offer several advantages over other distillation systems, including the following:

- Non-skilled operator required.
- The possibility of local manufacturing and maintenance.
- Low investment and can purify highly saline

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water, including seawater.

Moreover, solar still systems are categorized into two classes: Passive and active systems, depending on their source of energy supply passive solar still systems rely solely on solar energy as a thermal energy source, while active solar still systems use additional thermal energy sources, such as solar collectors (Badran, 2005) or waste thermal energy from a power plant (Aybar, 2007). The use of solar energy to desalinate seawater and brackish water has attracted the attention of many scientists. Too far, numerous practical and theoretical investigations have been conducted to enhance the solar still's output by modifying its design and employing various configurations (Rubio-Cerda, 2002). The output of solar still is dependent on several external and internal operational parameters, and the amount of water produced varies depending on the type of solar still used.

In a study by Ahmed (2012), the effect of adding a water heater device to the basin water of a double slope solar still was examined. Results showed that the performance of the still increased by about 370% when two water heaters, each with a capacity of 0.5 kW, was added. Kabeel et al. (2018) conducted a theoretical study that demonstrated the effect of using different types of organic and inorganic phase change materials (PCMs) on the performance of solar desalination. The study found that organic PCM A48 and inorganic PCM capric-palmatic resulted in higher productivity.

Badran et al. (2005) tested the effect of connected conventional flat-water heater collector with solar desalination system that used tap and saline water as feed. Experimental results showed that the proposed technique increased performance of the system by 231% compared to conventional stills in the case of using tap water and 52% in the case of using saline water. Voropoulos et al. (2001) designed a single slope solar still system that was coupled with a storage tank and flat plate collector. Experimental results showed that integrating a solar desalination system with a flat plate collector doubled the productivity compared to conventional stills. Furthermore, the performance of the still was enhanced at night due to an increase in temperature difference between the water and the glass cover of the still. Voropoulos et al. (2003) conducted an experiment to investigate the effect of integrated hot water storage tank with symmetric solar desalination system using a heat exchanger. The results showed that the productivity of still increased during the daylight as water temperature increased and shifted towards the night. Velmurugan et al. (2008) conducted an experiment to investigate the effect of adding fins with different types of materials such as black rubber, sand, pebble and sponge between the fins. The findings revealed that the daily efficacy of fin-type stills, fin-type stills with black rubber, fin-type stills with sand, and fin-type stills with pebbles were comparable. Fin type still with sponge and fin type still with sand sponge increased the productivity by 60.2%, 65.1%, 63.4%, 64.1%, 66.4% and 69.1%, respectively. Velmurugan et al. (2008) also studied the effect of integrated fins, wicks and sponges on the performance of solar still. The results indicated that the productivity of fins type, wick type and sponge type increased by 45.5%, 29.6% and 15.3%, respectively. Nayi and Modi (2018) pointed out that the inlet water temperature has a high effect on the performance of solar stills due to fact that the evaporative and convective heat transfer coefficient is increased. Jani et al. (2019) conducted an experiment to evaluate the effect of integrating circular and square cross-sectional hollow fins on the basin liner still at different water depth (10 mm, 20 mm and 30 mm). Results from the experiments employing a circular and square finned solar still at a water depth of 10 mm indicated the highest water productivity. Agrawal et al. (2017) conducted a theoretical and experimental study to find the performance of solar still at different basin water depths ranging from 0.02 m to 0.01 m. According to their experimental results, the daily distillate output decreased as the basin water depth increased. The theoretical daily efficiency values for the 2 cm and 10 cm basin water depths were approximately 52.83% and 41.75%, respectively. However, the experimental daily efficiency values were lower, at around 41.49% and 32.42%, respectively, for the same basin water depths. Arunkumar et al. (2012) assessed the performance of seven solar still designs such as spherical solar still, pyramid solar still, hemispherical solar still, double basin glass solar still, concentrator-coupled single slope solar still, tubular solar still and tubular solar still coupled with pyramid solar still. They evaluated the effect of these designs on basin water temperature and productivity. The results indicated that the compound parabolic concentrator-assisted tubular solar still achieved the highest water temperature and yield. In a study by Salah Abdallah et al. (2009), the effect of three types of absorbing materials, coated metallic wiry sponges, uncoated metallic wiry sponges, and black rocks, on the productivity of a solar still was examined. Results showed that the overall average gain of distilled water increased by approximately 28%, 43%, and 60% for coated metallic wiry sponges, uncoated metallic wiry sponges, and black rocks, respectively, compared to the conventional solar still. Muthu et al. (2019) conducted an experiment to investigate the performance of pyramid solar still at different water depth with and without insulation material. Experimental results revealed that the temperatures of distilled water without insulation were approximately 3.27 kg/m^2, 2.93 kg/m^2, 2.26 kg/m^2, and 1.59 kg/m^2 for water depths of 1 cm, 2 cm, 3 cm, and 3.5 cm, respectively. With insulated material, the temperatures were approximately 3.72 kg/m^2, 3.40 kg/m^2, 2.70 kg/m^2, and 2.08 kg/m^2 for the same water depths. In Kabeel et al. (2019), the effect of different water depths (0.5 cm, 1 cm, 2 cm, and 3 cm) on the performance of a tubular solar still (TSS) was investigated. The study founded that the productivity of still reached about 4.5 L/m^2 at a water depth of 0.5 cm, while at 3 cm, the daily productivity was 3 L/m^2. Rajamanickam et al. (2012) conducted an experimental setup to investigate the effect of different water depth (0.01 m, 0.025 m, 0.05 m and 0.075 m) on the performance of single basin double slope (DSSS) and single slope solar still (SSSS), each with the same area. Based on the findings, the highest possible water output was 3.07 L/m^2 /d at a water depth of 0.01 m in the DS solar still. In a study by Phadatare et al. (2007), the effect of water depth (varied from 0.02 m to 0.12 m) on the productivity of a single slope plastic solar still was investigated. The maximum water output measured 2.1 L/m^2/day at a water depth of 0.02 m.

It has been observed that few experiments have investigated the effect of varying inlet water temperature on the productivity of pyramid solar still. Additionally, most studies have focused on enhancing the performance of pyramid solar still by increasing water depth and incorporating basin liner fins in single and double slope solar still designs. Therefore, this research aims to investigate the behavior of pyramid solar still under Jordanian weather conditions with varying temperatures of inlet water (30°C, 40°C, and 50°C) in the first part. The inlet water has been heated by external source before starting experiment**.** Furthermore, the productivity of the still has been analyzed by increasing the water depth from 1 cm to 5 cm in the second part. The depth of water has been kept constant during the experiment. Finally, the performance of the solar still has been evaluated by integrating five vertical fins with a height, length, and thickness of 20 mm, 600 mm, and 2.5 mm, respectively, on the basin liner of the pyramid solar still at a specific water depth.

1 Experimental setup and procedure

The experiment was conducted at Jordan University of Science and Technology (JUST) in Irbid (32.48° N and 35.98° E) over a two-week period from the last week of August to the first week of September in 2018.

A pyramid-shaped solar still, referred to as the Pyramid Solar Still (PSS), was constructed and tested. Fig. 1 shows a three-dimensional model of the PSS, which comprises three layers of insulation placed between the glass cover, the internal galvanized iron sheet, and the external galvanized

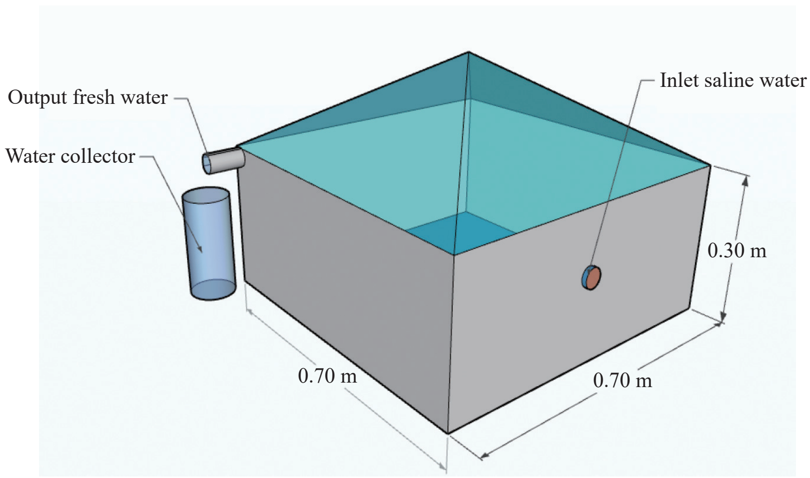

Fig. 1 Pyramid solar still used in the experiment

iron sheet. The glass plates have a depth of 6 mm, a width of 60 cm, a height of 25 cm, and a slope angle of 30 degrees. The enclosed box has a base area of 0.36 m^2 and a height of 30 cm, with galvanized iron sheets having an internal thickness of 1.25 mm. The exterior surface is made up of galvanized iron sheets with a base area of 0.49 m^2 and a height of 30 cm, separated by a polystyrene insulator that is 5 cm long. Additionally, as shown in Fig. 2, five fins, each with a height of 20 mm, length of 600 mm, and thickness of 2.5 mm, were used to reduce the preheating time required to evaporate water from the still basin.

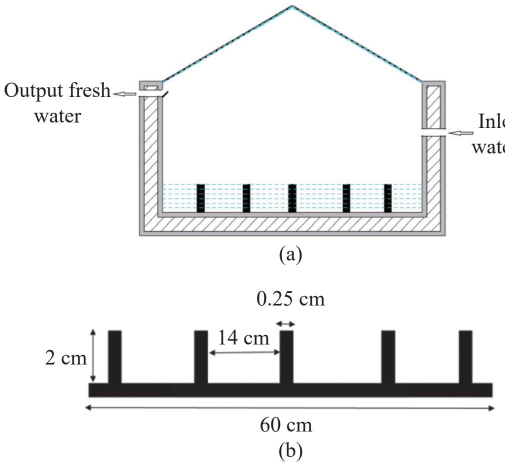

Fig. 2 (a) Schematic diagram of the pyramid solar still with fins in the basin; (b) Detailed dimension of the fins

The experiment consisted of three phases. In the first phase, the water level in the basin was varied. In the second phase, the effect of increasing the temperature of the incoming water (30°C, 40°C, and 50°C) on the efficiency of the PSS was investigated. In the third phase, the optimal water level was determined, and the influence of the fins on the operation of the PSS was analysed. The experiments were conducted from 8:00 am to 6:00 pm each day for ten days. The inlet water was obtained from the tap, and a small metal piece obstacle was attached to the condenser to collect the freshwater produced by the PSS at the inner surface of the condenser. The condensed water was collected into the measuring jar using a flexible hose pipe. Thermocouples were used to measure the temperatures of the basin, the water, and the glass. The ambient temperature was measured using a silver-colored Skytron temperature sensor with a range of 100 degrees Celsius and an accuracy of 0.5 degrees Celsius. To measure solar radiation, a Skytron radiation.

2 Results and discussions

The PSS was assembled and tested between in Irbid, Jordan from late June to early September. The study comprised of three phases. The first phase focused on the variation of water depth from 1 cm to 5 cm. The second phase investigated the effect of increasing the inlet water temperature from 30°C to 50°C. In the third phase of the experiment, fins were placed at the bottom of the still at a specified inlet water depth.

2.1 Solar radiation, water and ambient temperatures behaviors

Fig. 3 illustrates the hourly variation in solar radiation over the entire five-day test period of the pyramid solar still. The graph shows a consistent increase in solar radiation throughout the experiment, with negligible variation during the experimental days. For example, the maximum values of solar incoming radiation at midday for the five days were approximately 990 W/m^2, 970 W/m^2, 955 W/m^2, 940 W/m^2, and 930 W/m^2. Based on this observation, we hypothesize that the solar still efficiency would remain relatively constant for five days. As seen in Fig. 3, solar radiation increases over time, reaching a maximum between 1:00 pm and 2:00 pm, before decreasing in the afternoon. Fig. 4 displays the experimental results of hourly variation in ambient temperature during pyramid solar still testing on different days. As illustrated, the ambient temperature rises throughout the morning, peaks between 3:00 pm and 4:00 pm, and then starts to decline in the late afternoon (Yazan and Madhar, 2012).

Fig. 5 depicts the changes in the water tempe-

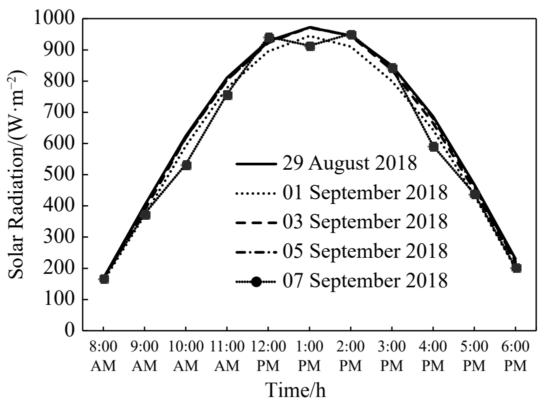

Fig. 3 Variation of solar radiation during experimental days

rature in a pyramid solar still basin with water depths ranging from 1 cm to 5 cm. The maximum basin water temperature of 72.3°C was recorded at 1:00 pm in the 1cm water depth basin, followed by a gradual decrease to 41.7°C at 6:00 pm. For the 2 cm water depth, the maximum water temperature of 67.3°C was attained at 2:00 pm, followed by a gradual decrease to 42.1°C at 6:00 pm. Increasing the water depth from 1 cm to 2 cm resulted in a maximum temperature reduction of up to 7% during the morning, and a maximum temperature rise of up to 1% during the evening due to the storage effect of the basin water. In contrast, the maximum temperature of the 5 cm water depth basin was recorded at 57.1°C at 2:00 pm. The basin water temperature increases significantly with a decrease in water depth between 8:00 am and 2:00 pm, followed by a decrease in temperature with an increase in water depth after 2:00 pm. This phenomenon can be attributed to the high thermal inertia of a larger mass of basin water, as reported in previous studies by Agrawal et al. (2017) and Phadatare et al. (2007).

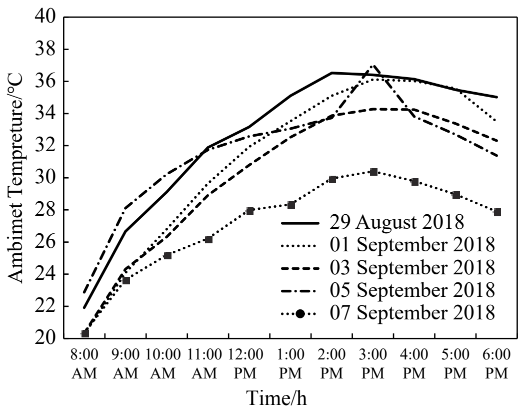

Fig. 4 Variation of ambient temperature during experimental days

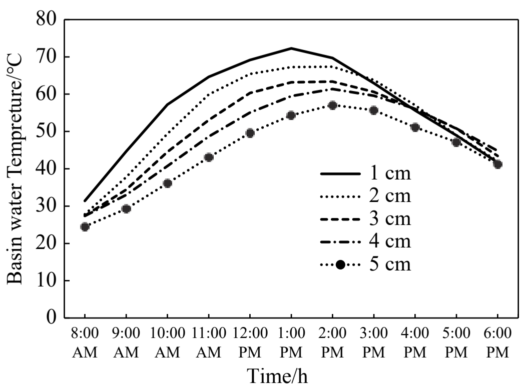

Fig. 5 Variation of basin water temperature during experimental hours for different water depths

2.2 Effect of changing water depth

Fig. 6 illustrates the hourly freshwater productivity variation of the pyramid solar still at different water depths, ranging from 1 cm to 5 cm with 1 cm increments. The daily freshwater production from the pyramid solar still varies with water depth, resulting in t 1.23 kg (3.41 kg/m^2), 1.04 kg (2.88 kg/m^2), 0.99 kg (2.75 kg/m^2), 0.9 kg (2.5 kg/m^2) and 0.73 kg (2.02 kg/m^2) for the water depths of 1 cm, 2 cm, 3 cm, 4 cm and 5 cm, respectively. The results indicate that the maximum freshwater production of 222 mL occurs at 1:00 pm with a water depth of 1 cm, t whereas at 3:00 pm, the maximum freshwater production of 128 mL occurs with a water depth of 5 cm. It is evident that the productivity of the pyramid solar still decreases with increasing water depth, as the heat stored during the sunshine hours in the higher depths results in higher production during the sunset hour than the lower depths.

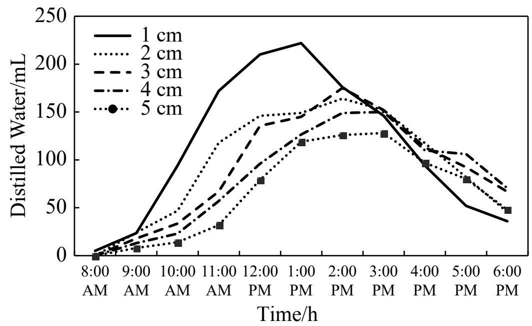

Fig. 6 Variation of hourly freshwater productivity for pyramid solar still with different water depths

Fig. 7 displays the total amount of freshwater produced by the pyramid solar still with different water depths. It is evident that the maximum production of freshwater was 1 230.5 mL occurs at

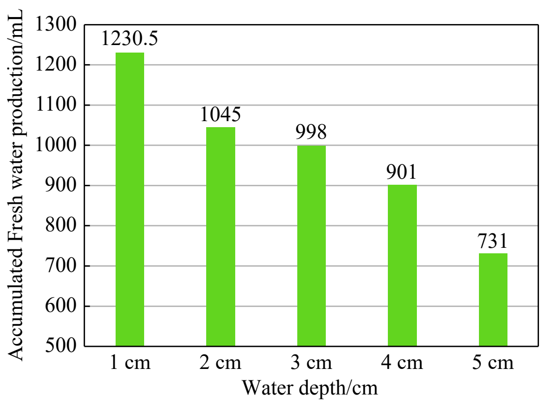

Fig. 7 Total amount of fresh water produced by the pyramid solar still with different water depths

a 1 cm water depth, followed by 1 045 mL for 2 cm, 870.5 mL for 3 cm, 798 mL for 4 cm, and 731 mL for 5 cm water depth.

As demonstrated in the previous figure, the total amount of freshwater production of the pyramid solar still increases when the water layer depth in the basin decreases. Specifically, the pyramid solar still enhances the daily freshwater production rate by up to 68.3%, 42.9%, 36.5%, and 23.2% for water depths of 1 cm, 2 cm, 3 cm, and 4 cm, respectively, compared to the 5 cm water depth.

2.3 Effect of changing inlet water temperature

Fig. 8 demonstrates the impact of varying inlet water temperature, from 30°C to 50°C, on the productivity of the solar still. The graph clearly illustrates that the productivity of the still increases as the inlet water temperature rises up to 2:00 PM. After 2:00 PM, the productivity of the still tends to stabilize. This behavior can be attributed to the water heat capacity, which increases with the inlet water temperature. Therefore, the productivity of the still also increases as the inlet water temperature rises. However, after 2:00 PM, the water temperature becomes equal for all inlet water temperatures, resulting in similar productivity values. The increase in the efficiency of the solar still can be attributed to the increase in the inlet water temperature.

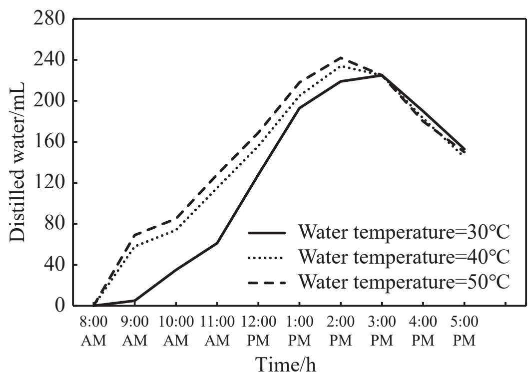

Fig. 8 The effect of changing inlet water temperature from 30°C to 50°C on solar still productivity

2.4 Effect of fins

The use of fins at the bottom of the solar still enhances its absorber plate's exposure area, allowing it to absorb more solar radiation. Consequently, the time required to preheat the basin water is reduced, resulting in increased productivity. This productivity increase can be observed in Fig. 9. Jani et al. (2019) and Agrawal et al. (2017) discovered that adding fins to the bottom of the pyramid solar still leads to a 7.5% increase in production.

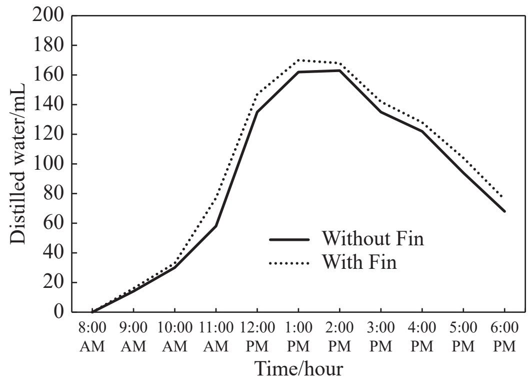

Fig. 9 Effect of fins on productivity in the pyramid solar still

3 Conclusions

(1) The pyramid solar still can be used to produce distilled water in Jordan's climatic conditions by adjusting the inflow water temperature and water depth. This study aimed to investigate the effect of fins on the yield of distilled water. Based on the results, the following conclusions can be drawn: A greater depth of water present can result in a reduction in the production of the pyramid solar still.

(2) The daily productivity of the pyramid solar still was measured at five different depths, and the results show that the maximum productivity was achieved at a depth of 1 cm, with a value of 1 230.5 mL, while the minimum productivity was achieved at a depth of 5 cm, with a value of 431 mL.

(3) The productivity of the still is affected by water depth, with a variation of up to 40.6% observed for depths ranging from 1 cm to 5 cm.

(4) Varying the inlet water temperature from 30°C to 40°C and from 30°C to 50°C resulted in a 15.3% and 21.2% increase in productivity, respectively.

(5) The use of fins in pyramid solar stills led to a 7.5% increase in daily production.

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