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Improving A Tubular Solar Still Performance Using A Thermoelectric Cooler Peltier And Internal Condenser.

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Abstract
This work aims to enhance the cumulative yield in a tubular solar still by using a copper packing, an internal condenser, and a thermoelectric cooler Peltier, as an instrument to improve the rate of evaporation and condensation. Also, study the effect of solar intensity and relative humidity inside the solar still on the yield.
The results showed that adding copper packing increased cumulative production by only 1.6%. The addition of the thermoelectric cooler showed high efficiency in increasing the cumulative yield by 34.37%. But the thermoelectric cooler results in a higher yield with the presence of the internal condenser and copper packing
This increase is attributed to the synergistic effects between the thermoelectric cooler and the packing in raising the water temperature, increasing heat transfer and vapor generation, and between the internal condenser with its high surface area and the cold side of the thermoelectric cooler in condensing this vapor. Also, it was observed that the solar intensity and relative humidity affect the performance of the solar still throughout the day.
High solar intensity increases the ambient temperature, which in turn increases the temperature of the saline water, leading to the formation of water vapor, while higher relative humidity reduces the hourly yield of the solar still and thus reduces the cumulative yield, and vice versa.
Keywords: *Thermoelectric cooler, Copper Packing, Internal Condenser, Solar Still, Tubular Solar Still.*

INTRODUCTION

There is an urgent need for clean water sources for residential, agricultural, potable, and sanitation purposes. Currently, water is limited in arid regions and remote locations. Research indicates that only 1% of the available water is freshwater, while an additional 20% is brackish. Approximately 79% of this water is saline [1]. This disparity has led to a substantial global crisis, as billions of individuals face challenges in accessing safe drinking water. Population expansion, pollution, climate change, and inadequate water management exacerbate the crisis, posing significant global challenges that impact health, economies, and ecosystems [2]. Climate change is a significant factor exacerbating the freshwater crisis. Increasing global temperatures modify precipitation patterns, resulting in extended droughts in certain areas and severe flooding in others [3]. Droughts result in the desiccation of rivers, lakes, and reservoirs, whereas floods inundate infrastructure and contaminate water sources with debris and waste. Melting glaciers, essential freshwater supplies for numerous countries, are diminishing at alarming rates, hence decreasing the long-term availability of potable water [4]. The alterations disturb the normal hydrological cycle and render freshwater sources progressively unreliable [5].
Desalination is a method that enables the generation of potable water from saline sources. Solar stills are employed to desalinate water in rural and remote areas with minimal traffic and low demand. Sunlight involves no transit and is readily accessible, plentiful, and consistently inexpensive. Distillation transpires spontaneously. Water is heated by solar radiation, then evaporates, condenses in clouds, and returns to the ground as precipitation. On a reduced scale, solar stills emulate this natural process. Desalination can be achieved either directly or indirectly by the utilization of sunshine. Indirect systems are those that integrate a conventional distillation process with a solar gathering system. Direct solar-powered stills utilize solar energy to produce distillate directly within the solar collector [6]. The water basin and its transparent cover constitute the two principal components of conventional solar stills, which can be easily constructed from locally available materials [7]. Solar stills can be categorized into two types:

- Passive solar stills

These systems integrate photovoltaic (PV) and thermal solar technology to optimize efficiency. Solar radiation, in both its direct and converted forms, supplies sufficient energy to heat water or other fluids within these systems. The efficacy of condensation is primarily contingent upon operational temperatures and vapor pressures. Reduced operational temperatures increase condensation rates by establishing conditions that enable the vapor in the system to effectively revert to liquid form, hence optimizing the overall efficiency of the solar-powered system [6].

- Active solar stills

To expedite the evaporation of water, this form of excessive heat energy is augmented by passive solar radiation. It may originate from excess thermal radiation of a manufacturing facility or via solar collectors. The majority of reviews concentrated on photovoltaic stills, specifically regarding wick type, configuration, construction, and enhancing model performance. Recent breakthroughs encompass the development of novel materials, such as phase transition and nanocomposite materials [6].

LITERATURE REVIEW

Hameed examine the potential to enhance the productivity of distilled water in single-slope, single-basin solar stills by developing an innovative absorbent base design with stainless steel geometry. The findings indicate that employing stainless steel geometry enhances the evaporation rate and optimizes still production. Cones generated the highest freshwater output, with an enhancement ratio of 38.2% and a 4.13 kg/m2 water yield **[8]**

An innovative heat storage system utilizing a solar air heater (SAH) and a single-slope solar still was assessed for its energy, exergy, and economic viability. The performance assessment of all sorts of solar stills was conducted to determine the most efficient model. Paraffin wax was utilized as a phase change material (PCM) at the base of the solar still to ensure sufficient heat storage **[9]**.

Aftiss identified three separate types of solar stills: the typical passive solar still (still-I), the solar still utilizing paraffin wax as a phase change material (PCM) (still-II), and the solar still employing PCM in conjunction with a storage tank (still-III). The research indicated that the PCM can store energy generated throughout the day for nighttime utilization [**10]**

Furthermore, the study by da Silva examines the feasibility of desalinating saltwater for human use. Numerical modeling and building were employed to predict the performance of the cost-effective solar still in the absence of experimental observations. The modeling results indicated enhanced efficiency with a reduced water content within the device and increased global radiation intensity **[11]**

Despite these improvements, solar energy remains less attractive in the market due to its limited efficiency. Researchers have attempted to improve the distillate yield of solar stills; however, none have yet explored the commercialization of solar stills as a product **[12].**

1. **Tubular Solar Still**

A tubular solar still is an advanced water purification system that utilizes solar energy to distill water, rendering it potable [13]. The apparatus comprises a transparent tubular chamber, usually constructed from glass or resilient plastic, serving as both the solar collector and evaporation chamber. Contaminated water is supplied at the base of the tube, where it is heated by sunlight, resulting in evaporation **[14].** The vapor ascends and condenses on the cooler inner surface of the tube, subsequently accumulating in a pristine reservoir. This technique efficiently removes pollutants such as salts, germs, and heavy metals **[15].** The tubular design maximizes sunlight absorption by increasing surface area and facilitating a greenhouse effect, improving evaporation rates. The cylindrical form facilitates effortless rotation, guaranteeing optimal sunlight exposure throughout the day. Tubular solar stills are compact, economical, and eco-friendly, rendering them suitable for rural or dry areas where potable water is limited [12]. Moreover, the efficiency of tubular solar stills can be augmented by applying improvement approaches while determining their thermal efficiency and distillation yield. One strategy involves the incorporation of thermal storage materials that may effectively retain heat during periods without sunlight and maintain the evaporation rate [16]. Reflectors can enhance energy concentration and heat absorption. Phase change materials can mitigate temperature variations by absorbing and releasing heat during phase transitions. It is also beneficial for heat retention [17]. This demonstrated to be an effective method for enhancing the efficiency of the tubular solar still. Moreover, new technological advancements, including the application of nanofluids, may enhance the thermal conductivity of water, hence augmenting heat energy absorption and evaporation rates [18].

2. The hybrid tubular solar still

The hybrid tubular solar still is a concept that integrates solar distillation with alternative energy systems, enhancing the system's versatility and efficiency. The hybrid system employs distinctive combinations of solar and supplementary energy sources, including geothermal and waste heat, which significantly enhance the performance of air and solar radiation on physical mechanisms, hence maintaining the system's functionality during periods of low solar insolation [13]. Integrating various energy sources into a singular hybrid still can substantially enhance water production. It is particularly pertinent in areas with challenging direct sunshine or nocturnal utilization. The incorporation of hybrid energy systems enhances thermal reliability while diminishing reliance on conventional energy sources. This signifies more promising hybrid ways for acquiring clean water [17]. This study seeks to optimize the performance of tubular stills in the context of Iraq. This is done by exploiting the Peltier effect, which no one has worked on in this field.

3. Experimental Setup

The tubular solar still (TSS) is an acrylic cylinder have dimensions of 14.5 cm in diameter and 86 cm in length, allowing the solar irradiance to penetrate from any direction. The basin (made of iron) has a half-cylindrical shape. Also, it is covered in black to enhance the absorptivity. The basin has dimensions of 4.5 cm in height and 85 cm in length. An iron frame was built to carry the TSS. The (TSS) shown in Figure 2 has been constructed from local materials. The selection of materials is generally based on the assessment cost of materials and ease of use in construction. A rubber tube is utilized to gather the condensate water from the lower section of the TSS to a container.

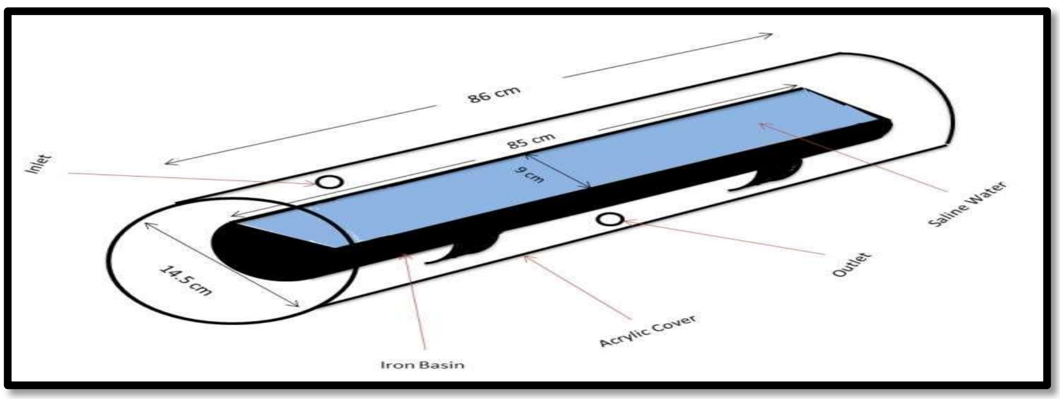

Figure 2. Schematic representation of a Tubular Solar Still.

To enhance the accumulative distilled water of the (TSS), the experimental study included four yield states, the first state: was a study of the accumulative distilled water production in a tubular solar still without any enhancement (convective tubular solar still) (CTSS) as a reference to recognize the improvement in the yield with other parameters. In the second state, test the productivity when exploiting the Peltier effect. The third state of the work studies the impact of an internal condenser on the water yield of the TSS, and the fourth state studies the effect of Peltier pieces with the presence of the internal condenser on distilled water production, and study the effect of copper packing on the yield for the above states. Also, discuss the factors that affect as operational variables, such as temperature distribution, internal humidity, and solar intensity, on the production of distilled water.

5.1 Peltier effect

The Peltier effect, discovered in 1834, refers to the thermal extraction or absorption at the junction of two metals when a direct current flows through them. The attempts to replicate the tests to validate this novel effect consistently had negative results, leading to its unrecognition by physicists until 1838, when E. H. Lentz successfully demonstrated the Peltier effect visually **[19].**

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The Peltier effect can be utilized to construct a tiny refrigerator (Figure 2) that operates without circulating fluid or moving components; these refrigerators are advantageous in scenarios where their benefits surpass the drawbacks of their low efficiency **[20].**

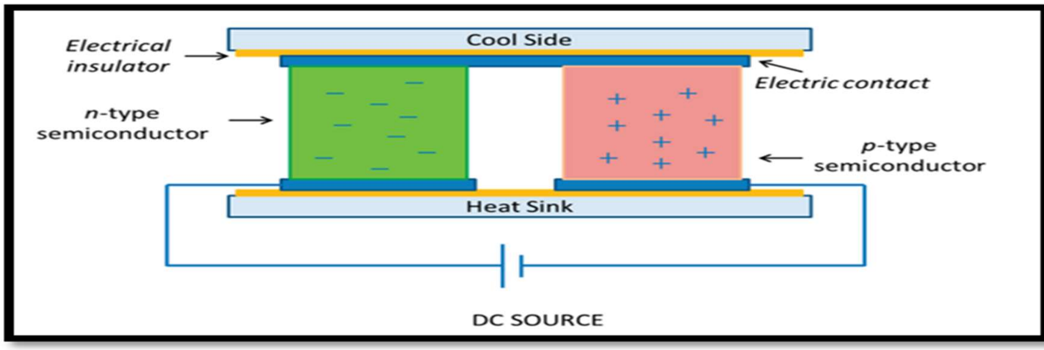

Fig. 2 Schematic of a Thermoelectric Couple[19].

In this work, the heat-emitting part was utilized to heat the saltwater in the basin, connected to a heat sink, to avoid damage during operation, and attached to the base of the basin from the outside. The cold part is also connected to a heat sink, acting as a coolant that helps increase the condensation rate. This allows the thermoelectric cooler to be used for increasing both evaporation and condensation rates at the same time (Figure 3). Five pieces of thermoelectric cooler Peltier were used, operating at 12 volts and a current of 6 amperes with a surface area of 4 cm * 4 cm. Table 1 shows the description of the thermoelectric cooler used, while Figures 4 and 5 show the arrangement of the thermoelectric cooler Peltier at the bottom of the basin, and their electrical connection, respectively. Solar panels supply them with electrical energy for economic feasibility purposes by charging the battery to ensure an electricity supply even at night (Figure 6). Each thermoelectric is operated for one minute every hour (to prevent damage), meaning that the total operation time for these pieces is five minutes every hour. The conversion between them is done manually. The features of using these thermoelectric are that they are characterized by:

- Providing thermal energy in a very short time.
- Making the evaporation and condensation process continue even when the sun is absent.
- Their small size.
- Availability in the markets.

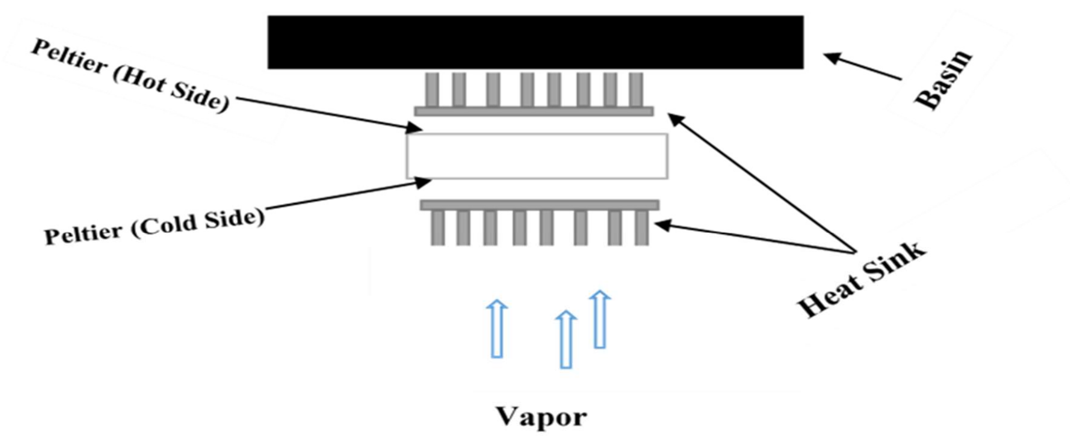

Fig. 3 Diagram for the installation of the thermoelectric cooler Peltier in TSS.

Table 1 The Description of Thermoelectric Cooler Peltier

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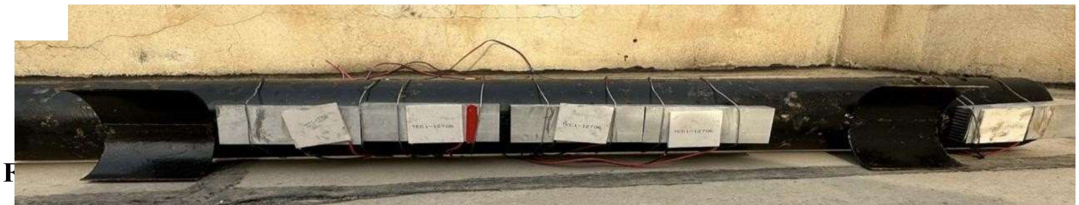
1	Operating Voltage	12 V
2	Maximum Voltage	15.4 V
3	Mximum Current	6 A
4	Maximum Power	92 W
5	Maximum Temperature	138 ℃
6	Power Cord	200 mm



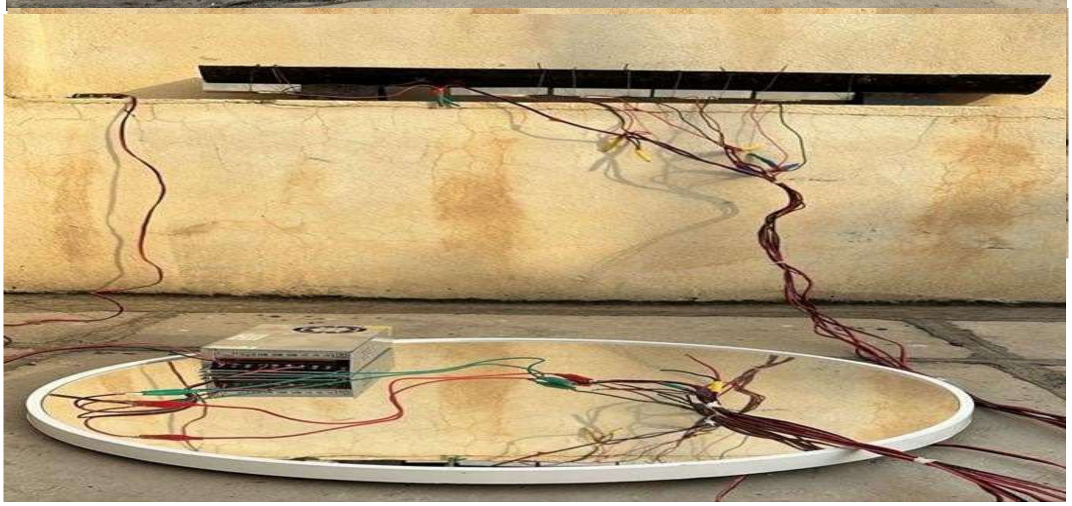


Fig.5 The Electric Connection of Thermoelectric Cooler Peltier.

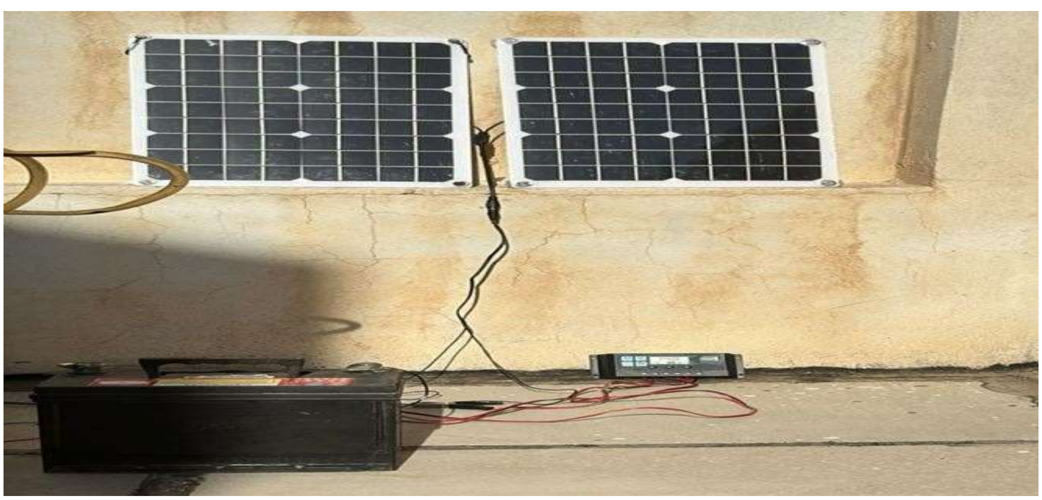


Fig. 6 The Solar Panels with Battery.

5.2 Internal Condenser

Internal condensers transform water vapor into liquid form, depending on materials that may support condensation, like fins, heat sinks, pins, and flat surfaces [21]. So, Peltier pieces and internal condenser (0.2 cm diameter and 570 cm effective length with 4 passes) made of copper is fixed inside the (TSS) to increase condensate and therefore enhance the water production**.**

5.3 Hollow Cylindrical Copper Packing

Copper cylindrical hollow pipes of 1 cm in diameter and an average of 2.5 cm in height were used as fins in the TSS basin. It used about 850 g of this packing. The fins in the basin were utilized to enhance heat transfer and enhance evaporation rate. In comparison to solid fins, hollow fins with a circular cross-section offer a higher surface area that enhances freshwater production [22].

4. Experimental Procedure

Experiments were carried out from 7:00 A.M. to 9:00 P.M. in August/ 2024, Baghdad City, Iraq. The solar intensity, inside relative humidity, basin temperature, ambient temperature, cover temperature, water temperature, vapor temperature, and distillate water production were measured every 1 hour. Saltwater (1L) is added to the basin before 7:00 A.M. The cooling water is pumped from a clay tank to the condenser and returned to that tank through rubber pipes. The pump turned on at 75% inside relative humidity and turned off at 55% by setting up the humidity controller. Figure 7 shows a photographic view of the TSS.

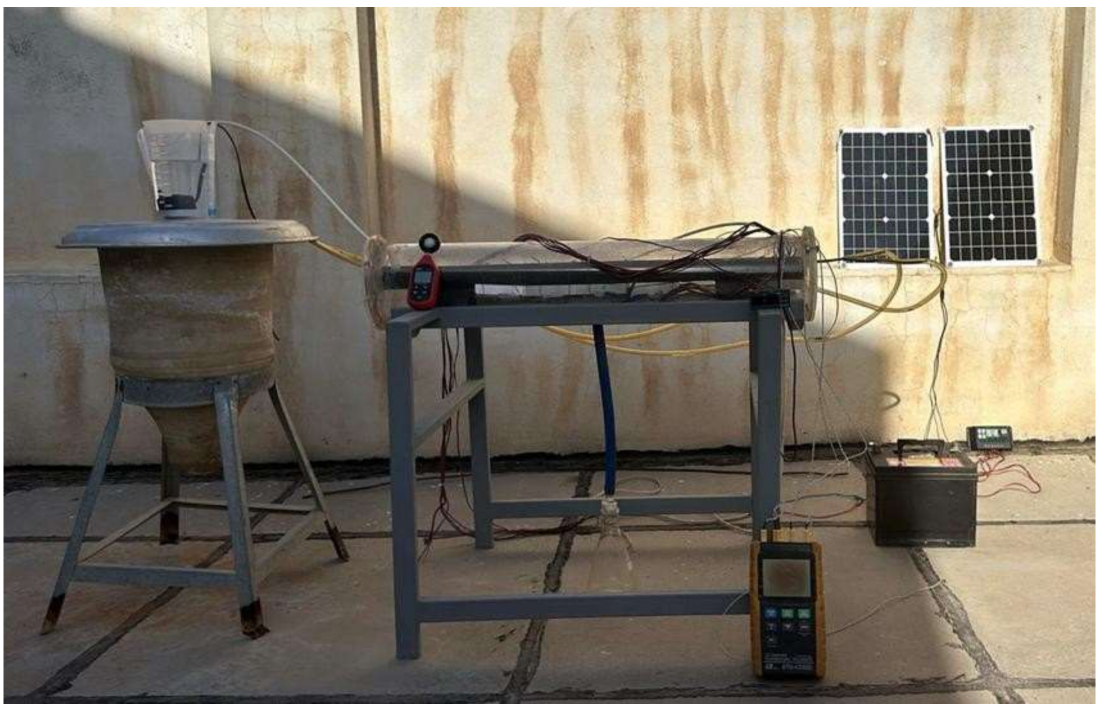


Fig. 7 The TSS During Operation with Thermoelectric Cooler Peltier and Internal Condenser.

5. Results and discussion

Figures 8 and 9 show the accumulated and hourly yields, respectively, with and without packing. The presence of packing increased the cumulative and hourly distilled yield of (TSS) in small quantities (due to the condensation-limited nature of the system). The increase in productivity is attributed to the expansion of the absorption area in the basin, which enhances the heat transmission rate due to high thermal conductivity for the copper packing of approximately 398 W/m·K compared to water (W/m·K), which contributes to the rapid distribution of absorbed solar energy throughout the saline water. Also, the surface area available for evaporation increased by the formation of a thin water film around the copper structure of the packing. This enhances water evaporation due to the reduced thermal resistance. This mechanism helps increase the evaporation rate in the solar still **[23], [24].**

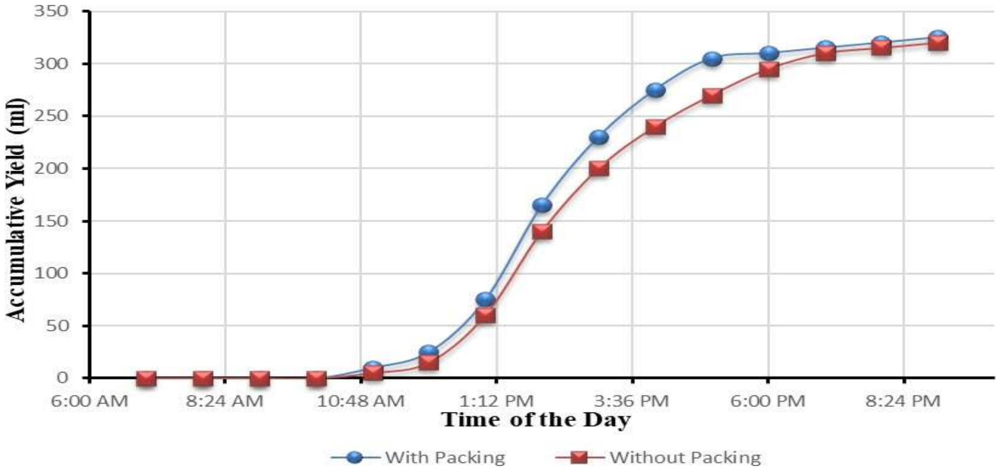


Fig. 8 The Accumulative Yield (ml) in TSS with and Without Packing (2/8/2024), (1/8/2024).

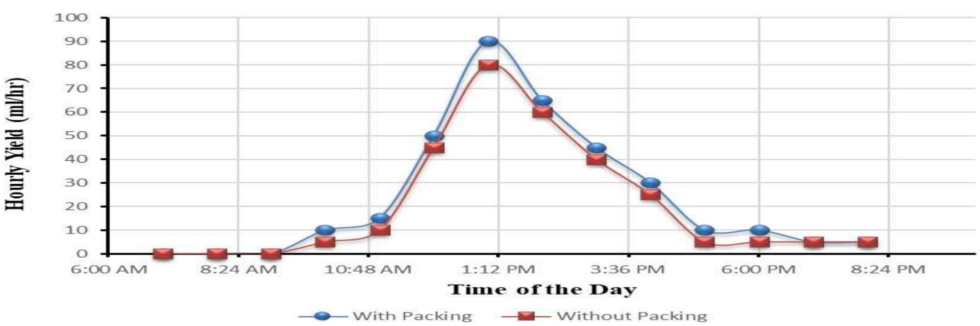


Fig. 9 The Hourly Yield (ml/hr) in TSS with and Without Packing (2/8/2024), (1/8/2024).

Figure 10 illustrates that adding a thermoelectric cooler beneath the basin of the solar still increased the cumulative yield of the solar still by 34.37%. This increase is attributed to the multiple heat inputs, which, in turn, raise the temperature of the saline water and, consequently, increase the evaporation rate. Also compensated for heat losses and maintained high temperatures during periods of low solar radiation (especially early in the morning), which means a higher rate of phase change during the experiment [25]. Additionally, the cold part has a positive effect on increasing the condensation rate inside the solar still. From Figure 11, it can be observed that production starts at 9:00 AM with the presence of the thermoelectric cooler (while the solar still recorded zero production at the same time without the thermoelectric cooler) and continues until 6:00 PM with sunset time, which supports the above statement. Figure 12 shows the solar intensity in the experiment with the thermoelectric cooler. It can be observed that there is little solar intensity at 9:00 AM and also a sharp decrease in light intensity at 6:00 PM.

Fig. 10 The Accumulative Yield (ml) in TSS with and Without Thermoelectric Cooler (25/8/2024), (1/8/2024).

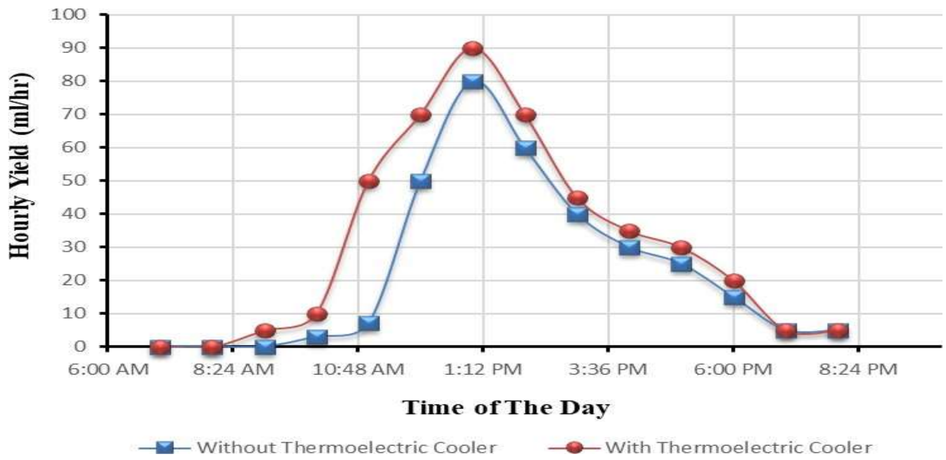


Fig. 11 The Hourly Yield (ml/hr) in TSS with and Without Thermoelectric Cooler (25/8/2024), (1/8/2024)

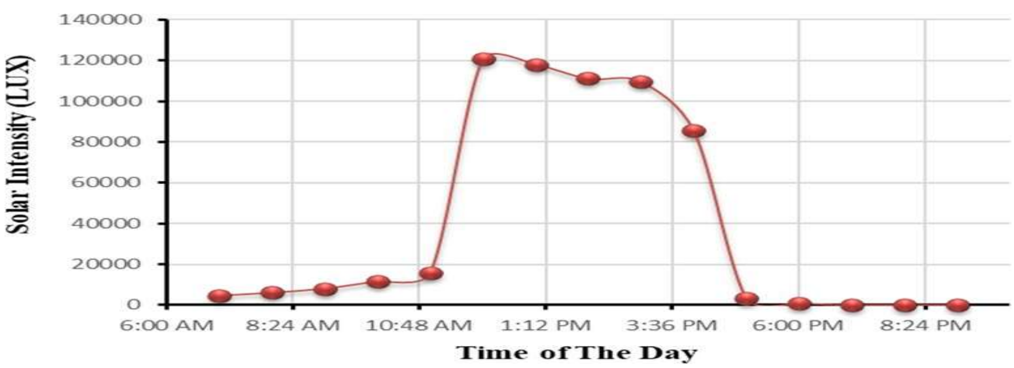


Fig. 12 The Solar Intensity (LUX) of Experiment with Thermoelectric Cooler (25/8/2024).

Figure 13 shows a significant decrease in cumulative production when packing is added.

From Figure 14, it can be seen an increase in relative humidity (from 10:00 AM to 5:00 PM), which is the peak production time. From both figures, it is clear that adding the packing saturates the inside air with water vapor, thus nearly halting evaporation and hindering condensation. Therefore, even with increased evaporation through the thermoelectric cooler and packing, production is limited [26].

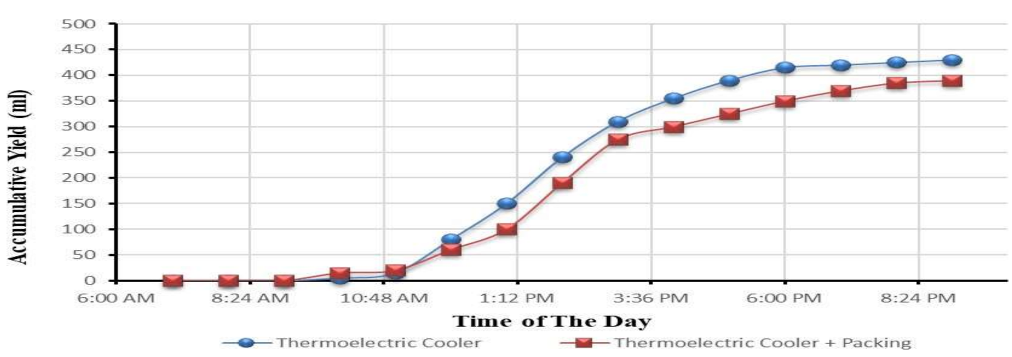


Fig. 13 The Accumulative (ml) Yield in TSS with Thermoelectric Cooler, and with Packing + Thermoelectric Cooler (25/8/2024), (22/8/2024).

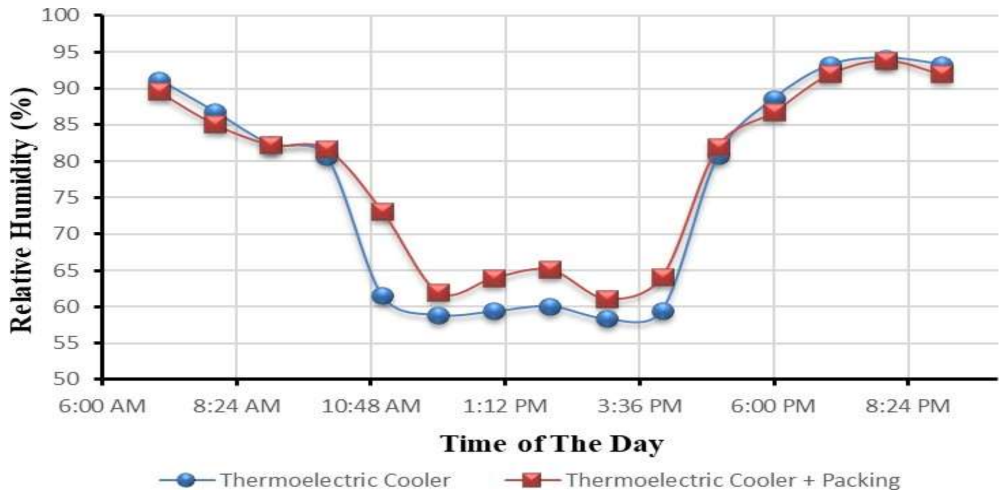


Fig. 14 The Relative Humidity (%) in TSS (with Thermoelectric Cooler), and (with Packing + Thermoelectric Cooler) (25/8/2024), (22/8/2024).

Therefore, it was expected that the internal condenser would work perfectly and efficiently under these conditions due to its large surface area, which might be equivalent to the amount of vapor production. Figure 15 shows that the solar still's productivity increased when the internal condenser was added, as expected. This is due to the increased evaporation rate with the thermoelectric cooler, making it necessary to have a condenser with a surface area that matched the increased evaporation, unlike in previous experiments without the thermoelectric cooler.

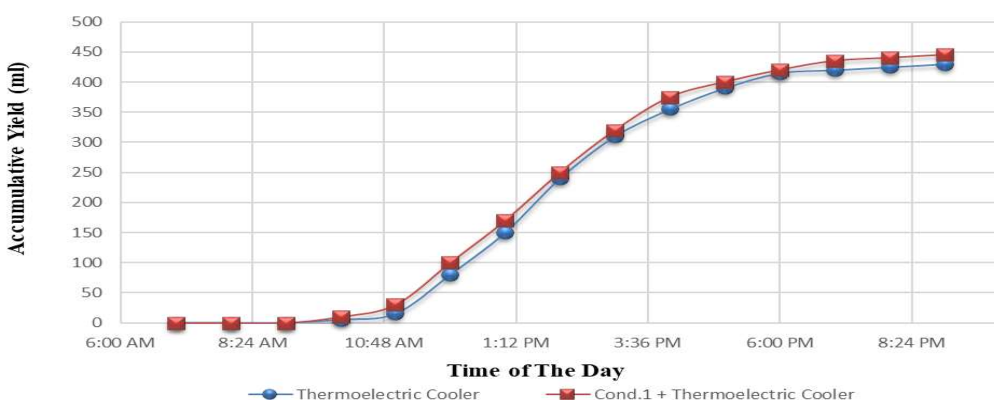


Fig. 15 The Accumulative Yield (ml) in TSS with (Thermoelectric Cooler), and (Internal Condenser + Thermoelectric Cooler) (25/8/2024), (27/8/2024).

Packing was added in the presence of the internal condenser, and a significant improvement in solar still yield was observed. This increase is attributed to the synergistic effects between the thermoelectric cooler and the packing in raising the water temperature, increasing heat transfer and vapor generation, and between the internal condenser with its high surface area and the cold side of the thermoelectric cooler in condensing this vapor. This experiment, under these conditions, yielded the highest cumulative yield in this work (455 ml). Figure 16.

By comparing the production under these conditions with the production in the experiment without any enhancement, it was found that the increase was about 42.18%.

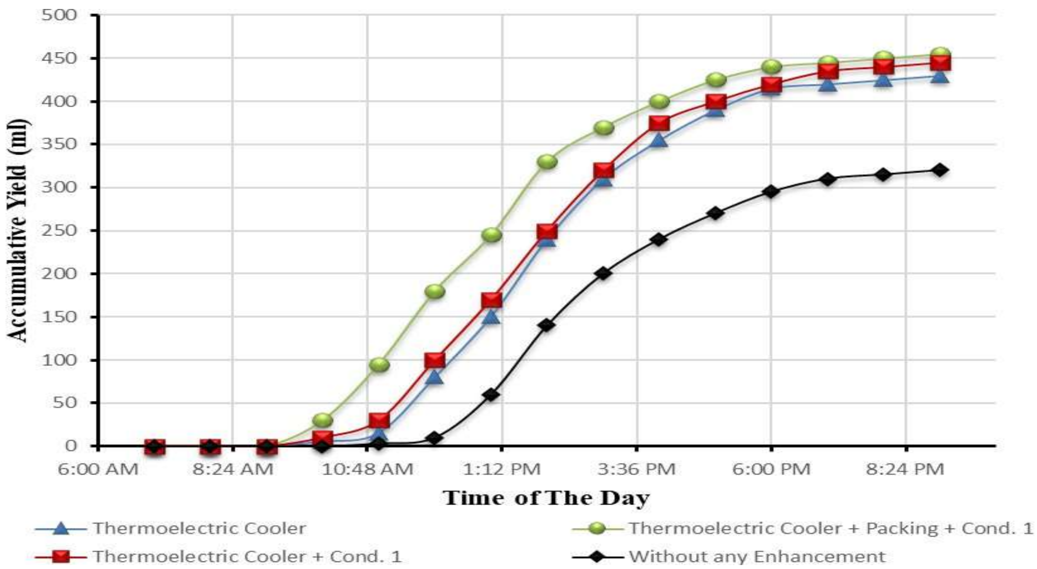


Fig. 16 The Accumulative Yield (ml) in TSS with (Internal Condenser Type 1, Packing, and Thermoelectric Cooler), (Internal Condenser and Thermoelectric Cooler), (Thermoelectric Cooler), and (Without any Enhancement) (29/8/2024), (27/8/2024), (25/8/2024), (1/8/2024).

The influence of solar radiation combined with ambient temperature on solar stills is a vital factor in their performance and efficiency. Solar radiation serves as the principal energy source for the distillation process in solar stills, although ambient temperature affects the total heat transfer dynamics inside the system [27].

Figure 17 illustrate the fluctuation in solar intensity during the experiment with conditions (thermoelectric cooler + internal condenser + packing). It peaked (128,000 LUX) at noon (the same time that the ambient temperature reached its peak) and thereafter declined to 0 LUX by 8:00 PM, marking the conclusion of the experiment.

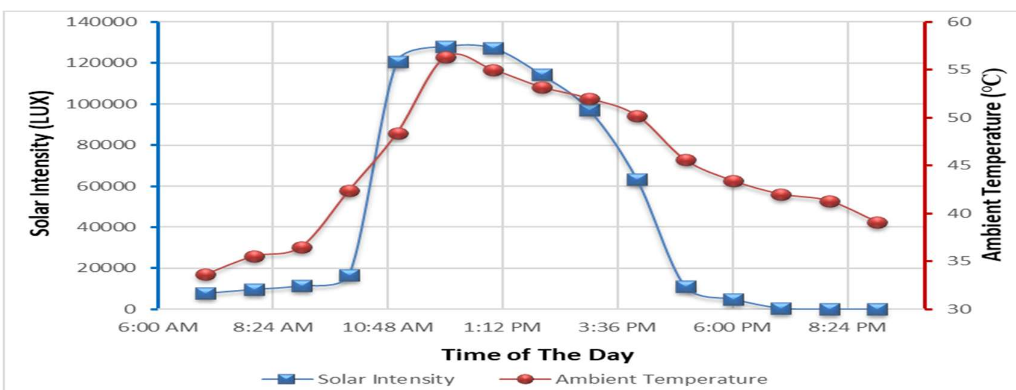


Fig. 17 The Solar Intensity (LUX) and Ambient Temperature (℃) for Experiment with Conditions (Thermoelectric Cooler, Internal Condenser, and Packing) (29/8/2024).

Figure 18 illustrates the hourly yield and solar intensity for the aforementioned experiment. From the Figure, it can be seen that the highest hourly production occurred at 1:00 PM, one hour after the highest solar intensity and ambient temperature were recorded. This is due to the time taken for heat transfer to the components of the solar still, including the saline water; therefore, the peak evaporation and condensation rates are delayed [28]. This illustrates the important role of solar intensity and ambient temperature on the productivity of a solar still.

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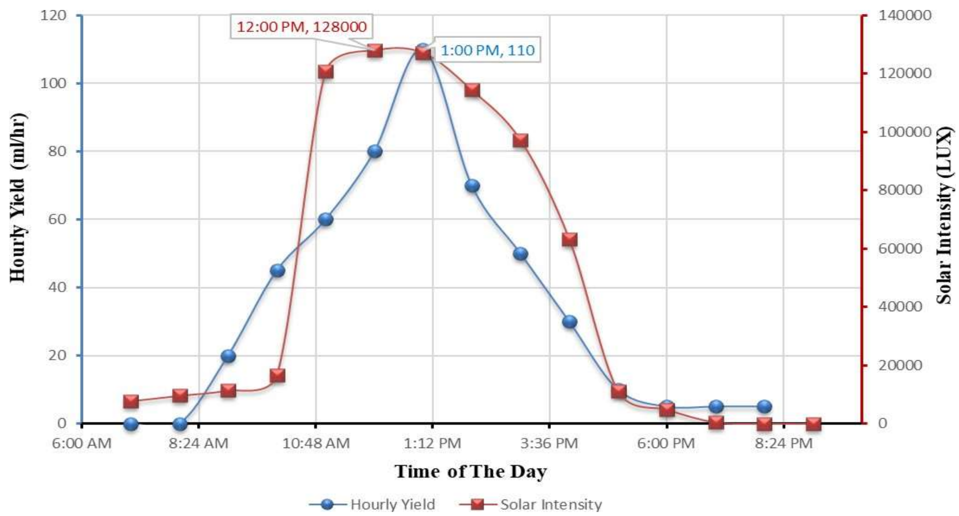

Fig. 18 The Hourly Yield (ml/hr) for Experiment with Conditions (Thermoelectric Cooler, Internal Condenser, and Packing) (29/8/2024).

The condensation process in a solar still relies on the temperature difference between the water vapor and the cover temperature. The greater the temperature difference, the greater the rate of latent heat removal, which, as mentioned above, improves the solar still's production.

Figure 19 shows the temperature variations of the day's saline water, vapor, and acrylic cover. It can be seen that the vapor temperature remains highest throughout the experiment, followed by the water temperature. This is a result of the dynamic heat transfer between the internal components of the solar still. Heat is transferred from the basin to the water and vapor. The cover temperature remains the lowest because it is directly exposed to the surrounding air and normally loses heat to the environment. Therefore, this temperature gradient is the primary driver of the condensation process [29].

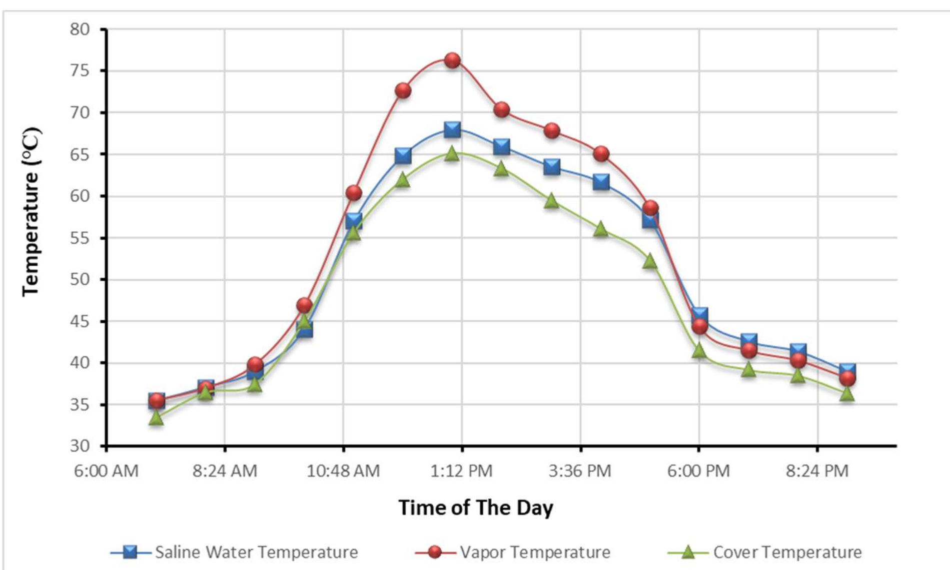

Fig. 19 The Temperatures (°C) of Saline Water, Vapor, and Cover for Experiment with Conditions (Thermoelectric Cooler, Internal Condenser, and Copper Packing) (29/8/2024).

Figure 20 shows the temperature difference curves between the vapor and the cover, with and without packing, and compares these temperature differences with the cumulative production under the same conditions. It can be seen that the increased temperature difference led to a higher cumulative production of the solar still under the same conditions, confirming the above statement. The comparison between the presence and absence of packing was used because in these two experiments, the condensation process relies solely on the temperature difference between the water vapor and the cover.

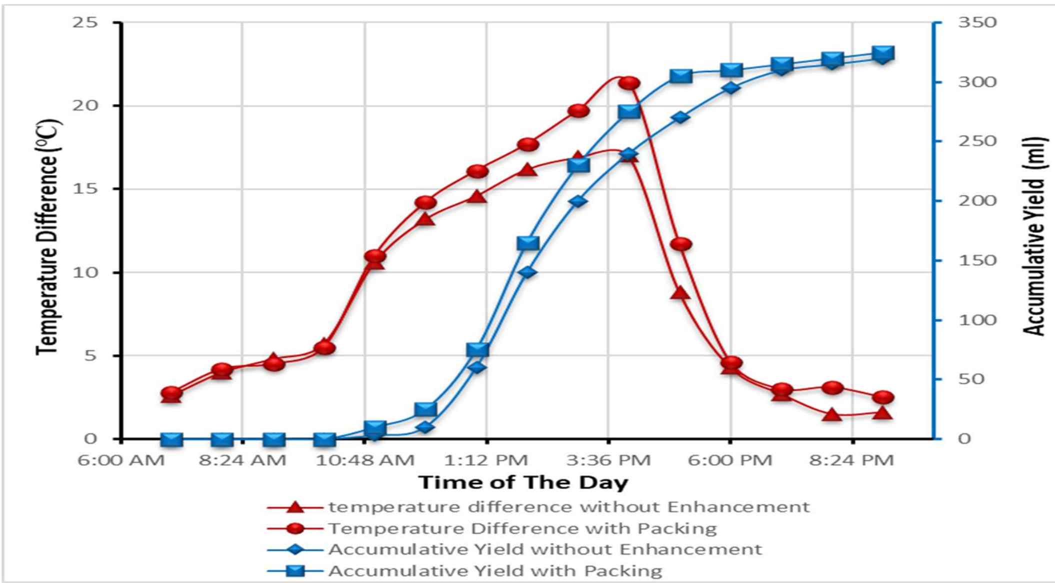

Fig. 20 The Temperature Difference (℃) and Accumulative Yield (ml) with and without Copper Packing (2/8/2024), (1/8/2024).

Solar intensity is the primary energy input to the Earth. As the amount of absorbed radiation increases, the ambient temperature rises. Conversely, humidity exhibits an inverse relationship with solar intensity (Figure 21) and ambient temperature (Figure 22). As temperature increases, the air's ability to retain moisture increases, leading to a decrease in relative humidity. This explains the thermodynamic behavior observed in the figures above, where relative humidity decreases during midday as the sun's intensity and ambient temperature increase [28]; [30]. Therefore, daily changes in these parameters are an important factor affecting the production of solar stills. The decrease in relative humidity combined with the increase in ambient temperature during peak solar hours helps increase the evaporation rate, while the condensation efficiency depends on the temperature gradient between the vapor and the cover.

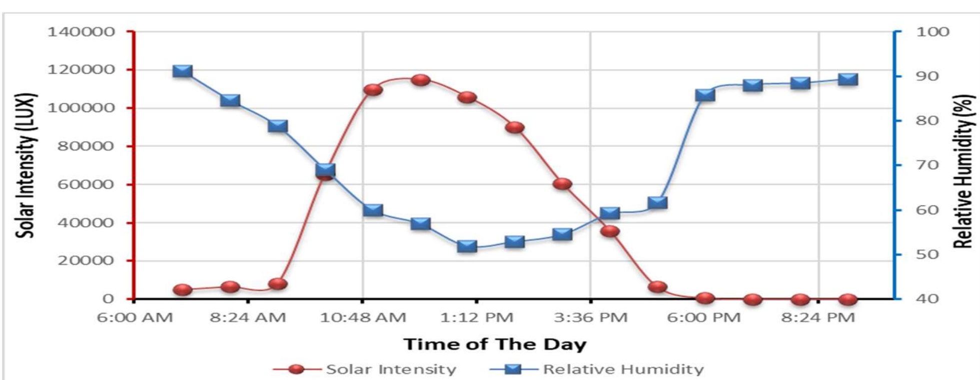

Fig. 21 The Solar Intensity (LUX) and Relative Humidity (%) in TSS with Conditions (Thermoelectric Cooler, Internal Condenser, and Copper Packing) (29/8/2024).

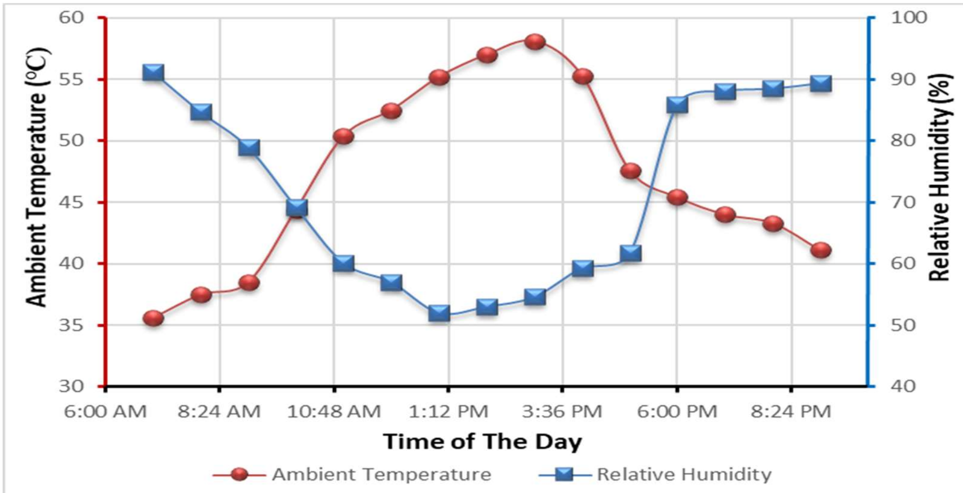

Fig. 22 The Ambient Temperature (℃) and Relative Humidity (%) in TSS with Conditions (Thermoelectric Cooler, Internal Condenser Type 1, and Copper Packing) (29/8/2024).

Therefore, the reasons for choosing an internal condenser to improve the productivity of a solar still can be identified, as it is directly related to relative humidity and so to production. lowering of the relative humidity means a higher production, and vice versa.

Figure 23 shows a comparison of hourly yields with and without an internal condenser and their correlation with the rise and fall of relative humidity. It can be seen that relative humidity is high in the early morning hours and then begins to decline around noon, coinciding with the rise in hourly yield. This illustrates the inverse relationship between yield and relative humidity inside the solar still. It then continues to decline with the rise in yield until around 6:00 PM, then begins to rise again from the low yield near the end of the experiment. This is also related to solar intensity and ambient temperature, as mentioned above.

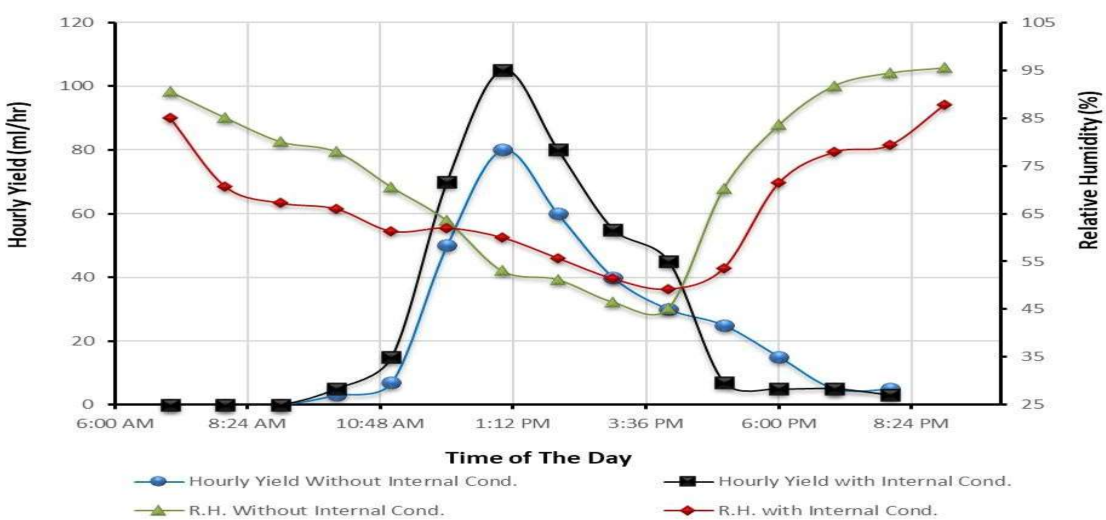

Fig. 23 The Hourly Yield (ml/hr) and Relative Humidity (%) in TSS for Experiments (with Internal Condenser and Copper Packing) and (without any Enhancement) (17/8/2024), (1/8/2024).

6. CONCLUSIONS

Experiments conducted on a tubular solar still in the hot climate of Iraq have shown that the addition of copper packing, internal condensers, and a thermoelectric cooler significantly impacts the performance of the solar still in terms of productivity and heat distribution inside the still. It can be summarized as follows:

1. The addition of copper packing in the basin increased the surface area for evaporation, but the presence of packing alone resulted in a slight increase in productivity of up to 1.6% only. This is due to the condensation-limited nature of the system, as the condensing surface (the acrylic cover) was unable to accommodate the additional vapor generated by the addition of packing.
2. The use of the thermoelectric cooler resulted in a significant increase in production of up to 34.37%, as it increased the evaporation rate of the saline water, meanwhile as in the condensation rate, thus positively impacting the performance of the solar still.
3. Adding copper packing with the thermoelectric cooler and the internal condenser results in the highest production in this work, as the percentage of potable water production increased to 42.18% of what it was without any enhancement on the solar still. This increase is attributed to the synergistic effects between the thermoelectric cooler and the packing in raising the water temperature, increasing heat transfer and vapor generation, and between the internal condenser with its high surface area and the cold side of the thermoelectric cooler in condensing this vapor.
4. The solar intensity affects the performance of the solar still throughout the day. High solar intensity increases the ambient temperature, which in turn increases the temperature of the saline water, leading to the formation of water vapor.
5. Relative humidity is inversely proportional to the hourly yield of the solar still. Higher relative humidity reduces the hourly yield of the solar still and thus reduces the cumulative yield, and vice versa.

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