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Comparative Evaluation of a Conventional and Photovoltaic/Thermal-Integrated Solar Distiller under Iraqi Climatic Conditions

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ABSTRACT

The integration of photovoltaic/thermal (PV/T) collectors with solar distillation processes is explored in this investigation, which seeks to augment the efficiency of solar distillers. Development and experimental assessment of a novel solar system, employing a PV/T collector for performance enhancement of a solar distiller, were carried out in Kirkuk City, Iraq, located at 35.46˚N latitude and 44.38˚E longitude. Two experimental models were constructed: a conventional double-slope solar distiller served as the baseline, whereas the second model was a double-slope solar distiller integrated with a PV/T collector. Four water depths (3, 4, 7, and 10 cm) were investigated to ascertain their effects on the system's output and efficiency. It was observed that the integration of the solar distiller with the PV/T collector resulted in a significant enhancement in system efficiency, achieving 18.81%, compared to a 5.15% efficiency demonstrated by the conventional distiller. The study further confirmed the substantial influence of water depth in the basin on the performance of both the hybrid and traditional solar distillation systems. Optimal results were achieved with a water depth of 3 cm, yielding productivity of 1.55 and 0.447 litre/day, and efficiency of 18.81% and 5.15%, for the integrated and conventional systems, respectively. When the water depth was increased to 5 cm, the respective productivity decreased to 1.252 and 0.243 litre/day, with corresponding efficiency of 16.87% and 3.22%.

1. INTRODUCTION

Currently, humanity is confronted with a significant energy crisis, a peril of paramount importance. The global population, having reached an estimated 8 billion in 2022, is projected to escalate to 9.7 billion by 2050 [1]. Over the last three decades, a substantial increase in fuel consumption has been witnessed, culminating in heightened fuel prices and exacerbated environmental pollution issues, alongside the looming risk of conventional fuel depletion. In response, the scientific community has been propelled to seek alternative, sustainable energy sources, among which solar energy has garnered substantial attention. Solar energy, renowned for its ubiquity, low technical requirements, and ease of maintenance, has found diverse applications, ranging from solar collectors and cells to solar stills, ponds, and chimneys.

With the surge in population density, a concomitant increase in freshwater demand is inevitable [2]. A mere 0.01% of the world's accessible water, found in lakes, swamps, and rivers, is immediately utilizable. Predominantly, the earth's surface water is saline, necessitating desalination for human consumption. Numerous nations are currently grappling with freshwater scarcity, despite possessing ample saline water resources, whether from seas or groundwater [3]. The desalination of saline water, albeit a solution, is often economically prohibitive, prompting governments to pivot towards renewable energy sources [4]. Solar distillation, utilizing sunlight for water purification, emerges as a cost-effective solution, with a rich historical precedent [5].

The solar distiller, employed for the distillation of water using solar energy, is identified as a simplistic, environmentally sustainable, and economical solution, with additional benefits of low maintenance requirements. Recognized as an attractive and facile alternative for the acquisition of potable water, this apparatus necessitates only sunlight and minimal human labor for operation. Its suitability for addressing the water scarcity issue in Iraq is underscored. Constructed from water-resistant soft materials, the solar distiller comprises a thermally insulated basin, enclosed on all sides and surmounted by a clear glass cover [6]. The design ensures that condensed vapor is directed into a side channel for collection of pure water, facilitated by the inclination of the glass cover, as depicted in Figure 1 [7].

Emphasis is placed on the necessity for thermal insulation of the basin's base and sides, aimed at minimizing heat transfer from the water within to the external environment, thus enhancing the distiller's efficiency. A black or other suitable paint is applied to the basin's base, serving to augment sunlight absorption. Further design enhancements include the application of radiation-reflective coatings on the interior vertical surfaces of the basin, resulting in the redirection of incident rays into the water. Sealing of the basin's sides is deemed essential, serving the dual purpose of mitigating steam leakage and reducing heat loss through air leakage holes [8]. The prevalent application of solar panels in electricity generation from solar energy is acknowledged, despite challenges associated with low electrical efficiency stemming from high panel temperatures [9]. This has necessitated innovations such as the photovoltaic/thermal (PV/T) collector, which integrates the PV panel in place of the traditional black solar absorber [10, 11]. The ongoing pursuit of enhanced solar distiller efficiency is highlighted, with numerous designs and proposals under investigation [12, 13]. Among these, the integration of the solar distiller with a PV/T solar collector is explored as a means of performance optimization [14], as illustrated in Figure 2. This approach represents a noteworthy stride towards the advancement of solar distillation technology.

In recent years, the coupling of solar stills with photovoltaic/thermal (PV/T) collectors has been extensively investigated, as evidenced by a plethora of scholarly articles and studies. Kumar and Tiwari [15] undertook the development and evaluation of two distinct solar still configurations: a single-slope passive solar still and its counterpart, a single-slope PV/T active solar still, the latter of which incorporated a DC water pump for water circulation. Experimental evaluations were conducted across varying water depths of 0.05, 0.10, and 0.15 m. The findings revealed that at a water depth of 0.05 m, the daily production of the passive and active hybrid solar stills reached maximum values of 2.26 kg and 7.22 kg, respectively. Furthermore, it was deduced that the hybrid active solar still design exhibits an approximate 20% enhancement in total electrical and thermal efficiency in comparison to the passive solar variant. Gaur and Tiwari [16] embarked on a research endeavor aiming to optimize the quantity of collectors utilized in PV/Thermal distillers. The study's results substantiated that for a water mass of 50 kg, a configuration of four collectors (N=4) yielded the most favorable results in terms of exergy efficiency. In a different vein, Mazraeh et al. [17] introduced an innovative solar distiller, integrating PV panels, phase-change materials, and evacuated tube collectors. The study identified the number of tubes as a critical parameter, influencing not only the distilled water output positively but also imparting a negative effect on energy and efficiency metrics. Additionally, it was confirmed that while the integration of Phase Change Materials (PCMs) enhances energy efficiency, its impact remains marginal. Rajaseenivasan et al. [18] delved into the implications of varying the gap between the saltwater surface and the cover glass, ranging from 0.45 m to 0.15 m. The study employed numerous thermal models to scrutinize the effects of this elevation modification, with validation from experimental data. The results unequivocally indicated an inverse relationship between the distance of the water surface to the glass cover and the rate of freshwater production from solar energy. These findings collectively underscores the paramount importance of optimizing design parameters in solar distillation systems, particularly when augmented with PV/T collectors, to achieve heightened efficiency and output.

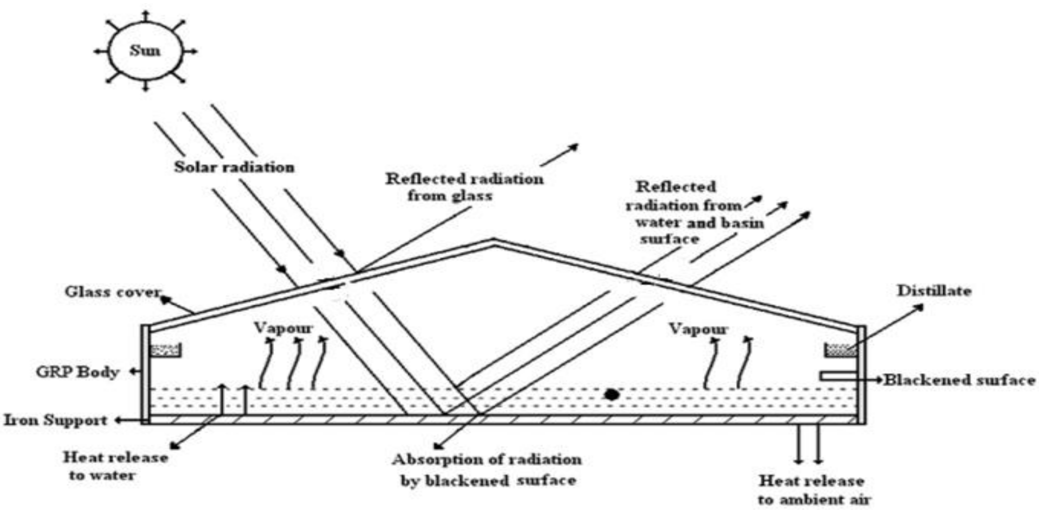


Figure 1. Mechanism of the operation for a double-slope solar distiller [7]

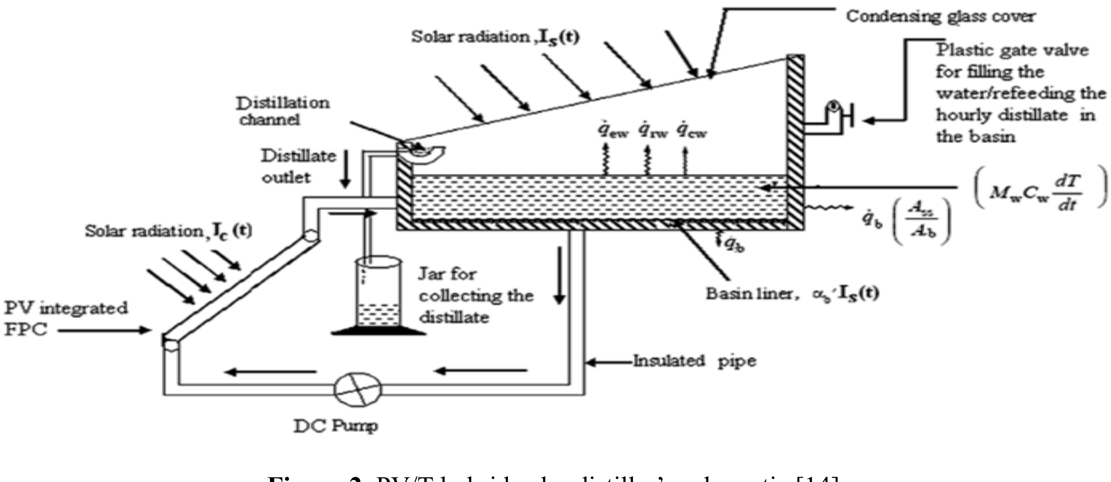


Figure 2. PV/T hybrid solar distiller's schematic [14]

The influences of water flow rate on the performance of an inclined PV/solar distiller were investigated by Muthu Manokar et al. [19], with three distinct flow rates (4.68, 7.56, and 10.08 kg per hour) under scrutiny. The results elucidated that an increase in flow rate corresponded with a decrease in distillate output, whilst concurrently engendering an increase in power output. In a study by Al-Nimr and Dahdolan [20], a concentrated PV/T system, newly developed, was explored for its ability to distill salty water utilising the thermal energy rejected by the PV cell. The impacts of various parameters, such as solar intensity, wind speed, ambient temperature, and condenser temperature on the proposed system were elucidated through a mathematical model. An assessment of the efficiency of a solar-integrated PV panel in conducting a desalination process whilst simultaneously supplying power was presented by Manokar et al. [21]. It was revealed that an inclined solar distiller, endowed with insulation at both the bottom and sidewalls, yielded the highest amount of distillate at 7.3 kg. Hansen et al. [22] provided both theoretical and experimental evaluations aimed at enhancing the efficiency of inclined-type solar stills through the integration of PV panels. The introduction of black cotton cloths was found to significantly influence diffusion, culminating in a maximum water output of 3.61 L/day. Xiao et al. [23] embarked on an assessment of a desalination system's productivity, supplementing theoretical analyses with experimental validations. The focus was placed on elucidating the impact of the bottom channel's structure on the solar distiller's efficiency. It was found that a 1cm depth of the bottom channel resulted in a 3% increase in average thermal efficiency and a 51.7% increase in daily freshwater output. The performance of a double-slope distiller, integrated with a PV/T collector and phase change materials, was scrutinised by Hedayati-Mehdiabadi et al. [24]. It was discovered that an increase in the mass flow rate from 0.001 to 0.01 kg per second resulted in a 10.6% increase in freshwater productivity and a 27% and 2% increase in exergy efficiency on July 6 and December 23, respectively. A hybrid active solar still, incorporating a solar photovoltaic (PV)-powered heater made of nickel-chrome (NiCr), was proposed by Praveen Kumar et al. [25]. This system utilised salty water for cooling the solar PV module, thereby enhancing both the efficiency of the solar energy system (PV) and the quantity of distillate water produced. An augmentation of the performance of a PV/solar still using a Peltier device was introduced by Pounraj et al. [26]. The proposed hybrid solar PV/T distiller demonstrated an efficiency approximately 30% higher than the conventional passive distiller and 38% greater than the actual solar PV system. In a study by Saeedi et al. [27], a mathematical model was proposed to enhance a PV/T solar still. The findings indicated that an increase in wind speed and a decrease in basin area led to an increase in the PV/T active solar's energy efficiency, while an increase in ambient temperature and basin water volume resulted in a decrease. Over the past three decades, Iraq's hydrological environment has undergone significant transformations, attributed to escalating demands on water resources and a concomitant decline in their availability. The resultant decrease in surface water levels and precipitation has been mirrored by perilously low water reserves in reservoirs, lakes, and rivers, with the Tigris and Euphrates rivers' levels plummeting to less than a third of their natural capacities. Concurrently, the government has reported alarming rates of depletion in water reserves, coupled with a severe drinking water deficit affecting millions. The alarming rate of water pollution has rendered the drinking water in Iraq unfit for human consumption. In response, the state has explored the utilization of solar energy for distilling salty water to produce fresh water. A review of extant literature reveals a paucity of studies comparing the performance of integrated solar distillers with PV/T solar collectors in hot climates, with Iraq serving as a case study for such climates [28]. Thus, the research aims to elucidate the performance of a solar distiller integrated with a PV/Thermal solar collector under Iraqi climatic conditions, with the potential to provide electricity and potable water, particularly in remote areas. The system is posited as a viable solution for supplying electricity, hot water, and fresh water, especially in areas distant from population centers.

2. METHODOLOGY

The optimization of the solar distiller's efficiency to maximize distilled water productivity has been identified as a crucial objective. Concurrently, efforts have been directed towards the reduction of the operational temperatures of solar panels, with the goal of maximizing their electrical output. In this context, the heat emitted by the solar panels has been harnessed to enhance the solar still's efficiency, thereby augmenting the yield of distilled water. This strategy aligns with the utilization of Iraq's abundant solar irradiance, addressing the prevalent issue of water scarcity. The integration of photovoltaic/thermal (PV/T) solar collector technology with solar distillation processes has yet to be explored within the Iraqi context, thus establishing the focus of the present investigation. The hybrid system, encompassing both PV/T solar collectors and solar distillers, is subjected to a comprehensive performance analysis under the specific climatic conditions of Iraq. The structure of the article has been meticulously organized as follows: details pertaining to the practical aspects of the study, as well as the equipment utilized, are delineated in the subsequent section. This is followed by a section dedicated to the computation of performance metrics and efficiency evaluations of the proposed systems. The penultimate section presents and critically discusses the findings obtained, culminating in the final section, which articulates the main conclusions drawn from the study. In order to maintain the rigour and precision required by top-tier academic journals such as Nature and Science, the methodology section has been refined to ensure clarity and coherence. This includes the adoption of the passive voice, ensuring consistency in the utilization of professional terminology, and aligning the structure and logic of the content with the high standards of academic discourse. Furthermore, the content has been expanded upon, ensuring originality and adherence to best practices in academic writing. Any discrepancies or errors within the professional domain of the study have been meticulously addressed and rectified, ensuring the integrity and reliability of the presented work.

3. EXPERIMENTAL SET-UP

In the pursuit of assessing the performance of the integrated system, a comparative analysis was conducted using two fabricated solar distillers of identical dimensions. The first distiller, serving as the control, was a conventional solar distiller, while the second was augmented with a photovoltaic/thermal (PV/T) collector, connected via heat exchangers located both behind the PV panel and within the distiller basin. The distiller basin, constructed from 3 mm thick galvanized iron sheets, and the double-sloped glass lid, measuring 100 cm in length, 90 cm in width, and 20 cm in height, constitute the fundamental components of the solar distiller. The inner surface of the basin was treated with a black coating to enhance solar radiation absorption, and the basin was thermally insulated on the sides and the bottom to minimize thermal losses. The basin featured two openings: one for water ingress, regulated by a specialized valve, and another for the egress of distilled water, which was collected in a graduated cylinder for hourly production measurements. The glass lid was inclined at an angle of 35° and had a thickness of 4 mm. A copper tube, fashioned into a serpentine heat exchanger with a diameter of 12.5 mm and a length of 15 m, was situated at the base of the basin to dissipate heat extracted from the solar panel (Figure 3). This heat exchanger was connected on one end to a second heat exchanger mounted behind the solar panel, and on the other end to a storage tank via a smooth hose. The inlet of the heat exchanger behind the solar panel was linked to a water supply source, maintaining a constant water temperature.

The heat exchanger affixed to the solar panel was crafted from an iron tube with a square cross-section, dimensions of 1.5×1.5 cm, and was securely attached to the panel's rear (Figure 4). The PV/T collector was encased in a wooden box, isolated from the sides and back with glass wool, possessing a thermal conductivity of 0.038 W/m·K [29]. A galvanized iron plate was affixed to the rear of the solar panel post-installation within the box. The solar panel's emissivity was determined to be 0.95 [30], and its specifications are detailed in Table 1. To optimize solar radiation capture and mitigate thermal losses from the solar panel's front face, a 4 mm thick glass layer was positioned 2 cm from the panel. The periphery of the glass layer was sealed with plastic material to prevent the escape of hot air, and the glass itself had an emissivity of 0.88 [8]. This experimental setup was meticulously designed and constructed to facilitate a comprehensive evaluation of the proposed system's performance, ensuring that all components were appropriately integrated and calibrated for accurate data acquisition and analysis.

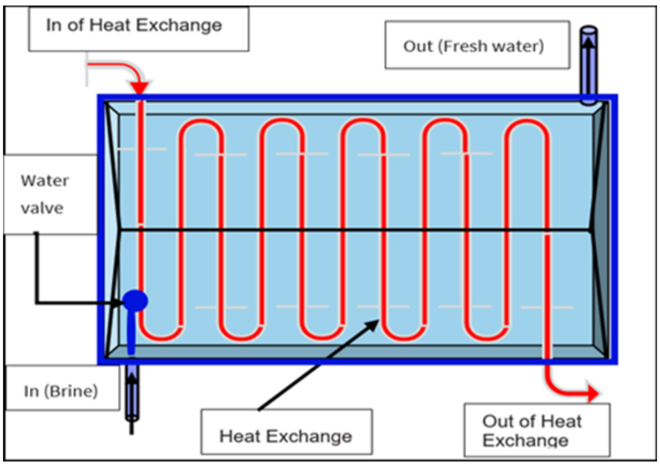


Figure 3. The heat exchanger for the distiller basin

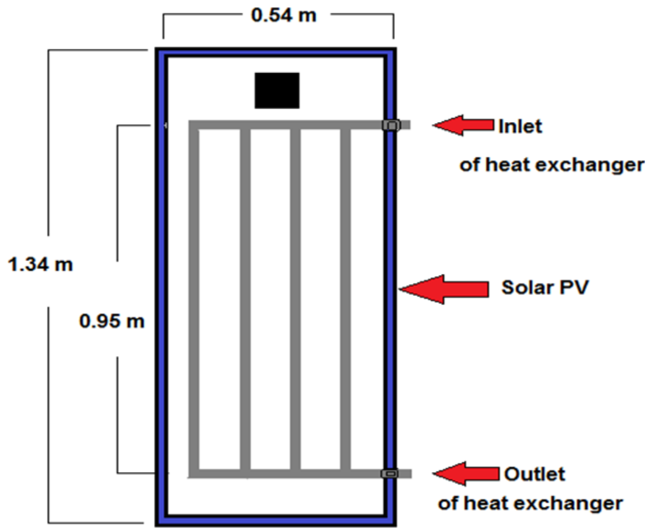


Figure 4. Sketch of the heat exchanger fixed at the rear of the PV panel

Table 1. Specifications of the PV panel

Variable	Unit	Variable	Unit
Operating temperature	25°C	Maximum power	100 W
The maximum difference in the electric current	5.71 A	Short circuit current	6.14 A
Maximum voltage difference	17.5 V	Dimensions	(35×540×1340) mm
Frame material	Aluminum	PV panel type	Polycrystalline

In the study of the solar collector's performance, the pivotal role of temperature variations was meticulously examined, particularly their impact on efficiency and electrical capacity. A total of thirteen K-type thermocouples were strategically deployed throughout the system to precisely measure temperature variations, adhering to the following distribution: two sensors were placed above and below the solar panel to monitor its temperature; two additional sensors were situated at the inlet and outlet behind the PV panel, adjacent to the exchanger; three sensors were allocated to the inlet, outlet, and midpoint of the exchanger inside the distillation basin; four sensors were distributed across different levels within the basin itself; one sensor was dedicated to gauging the temperature of the wet steam within the still; and finally, a probe was positioned on the surface of the glass cover to measure its temperature. Solar radiation levels were quantitatively assessed using a solar radiation meter, specifically the SP216 type. The electrical load for the system was established using four 25-watt bulbs, with the electrical connection process illustrated in Figure 5. Additionally, Figure 6 provides a detailed visualization of the system's main components. This arrangement of temperature sensors and measurement devices was implemented with precision, ensuring comprehensive coverage for accurate temperature profiling within the system. The data gathered from these instruments is integral for evaluating the system's performance under various operating conditions, ultimately contributing to a thorough understanding of the temperature-dependent behavior of the solar collector.

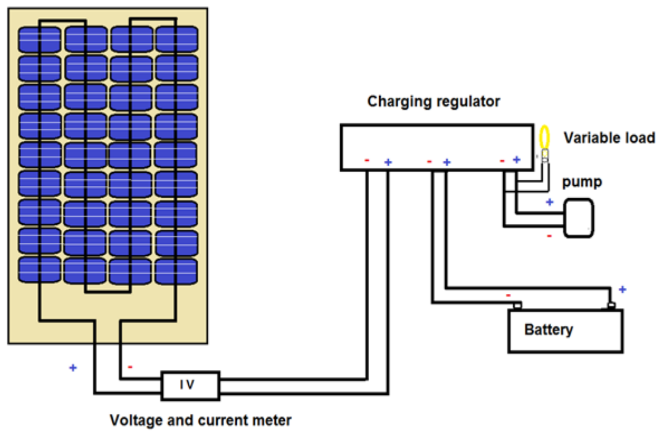


Figure 5. Electrical connection of the experimental-setup

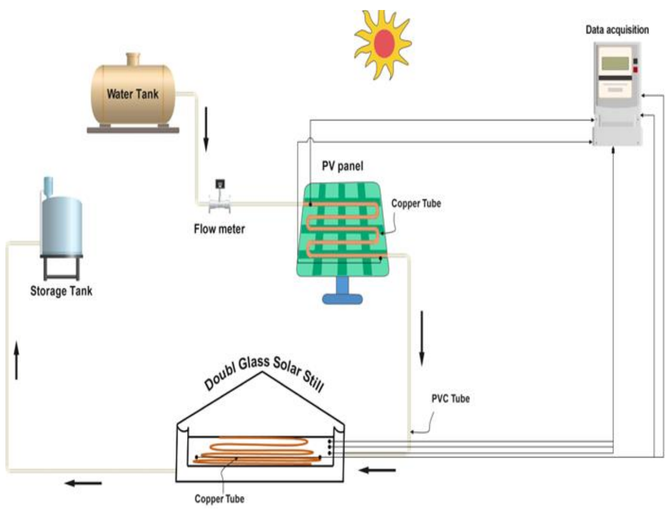


Figure 6. The main parts of the system

4. CALCULATION EQUATIONS

The governing variables of the basic components of the current practical system have been classified according to the following details:

4.1 Solar still

The productivity, efficiency and useful heat in the heat exchanger of the solar still were calculated using these equations, these laws have been used as used by previous researchers [31];

The productivity of the solar still per second can be computed by the productivity produced per hour during the test is divided by the second, using the equation:

$$\dot{m}_{ew} = \frac{Prod.(LPh)}{3600s} \quad (1)$$

The efficiency of a simple solar distiller can be calculated from the product of productivity and enthalpy divided by the product of solar radiation and the area of the solar distillation basin. written from the following equation:

$$\eta_{ss} = \frac{\dot{m}_{ev_{ss}} \times h_{fg}}{G \times A_{ss}} \quad (2)$$

where,

$\dot{m}_{ev_{ss}}$ is the productivity of solar still ($\frac{kg}{s}$) and can be calculated from Eq. (1).

h_{fg}: Enthalpy of evaporation ($\frac{J}{kg}$) and can be calculated from the steam table [15].

G: The amount of solar radiation (W/m^2).

A_{ss}: The area of the solar still (m^2).

4.2 Useful heat in the heat exchanger

The useful heat collected by the heat exchanger of the still basin ($q_{hx_{ss}}$) was obtained as:

$$q_{hx_{ss}} = \dot{m}.C_p.(T_o - T_i) \quad (3)$$

where, $\dot{m}$, the mass flow rate of flowing water inside the heat exchanger and measured using a rotameter.

C_p, the specific heat of the water and calculate from the following:

$$C_p=4.1855*10^3.[0.966185+0.0002874\,((T-173)/100)^{5.26}] \quad (4)$$

T_O , T_i , the heat exchanger's exit and inlet water temperatures, respectively.

4.3 Photovoltaic panels

Electricity produced by the PV solar panel was calculated as:

$$P_{pv} = V \times I \quad (5)$$

V: PV panel voltage, I: Solar panel current.

The electrical efficiency of the solar panel is calculated using the following relationship

$$\eta_{pv} = \frac{output}{input} = \frac{V \times I}{G \times A_{pv}} \quad (6)$$

where, A_{pv} represents the PV panel area.

The useful heat collected by the PV panel's heat exchanger ($q_{hx_{pv}}$) was obtained as

$$q_{hx_{pv}} = \dot{m}.C_p.(T_{PVo} - T_{PVi}) \quad (7)$$

T_{PVo}, T_{PVi}, the heat exchanger's output and inlet water temperatures for the PV panel, respectively.

The total efficiency of the solar distiller integrated with the PV/Thermal collector can be estimated as:

$$\eta_{total} = \eta_{pv} + \eta_{ss} \quad (8)$$

The uncertainty analysis is required to assess the error associated with the measurement equipment. the error percentage for all measuring equipment as listed in Table 2. The uncertainty was calculated as [32]:

$$U_R = \left(\left(\frac{\partial R}{\partial x1} \times w_1\right)^2 + \left(\frac{\partial R}{\partial x2} \times w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial xn} \times w_n\right)^2\right)^{1/2} \quad (9)$$

WR. (ω_1, ω_2, …., ω_n) are the uncertainties in the independent variables, while R is a known function of (x_1, x_2,…., x_n). The uncertainty of this experiment is 4.36%, indicating acceptable results.

Table 2. Information about the instruments

Equipment	Measurement	Error
Multi-meter	DC current	±(0.8%)
Multi-meter	DC voltage	±(0.5%)
Digital thermometer	Temperature	±(0.5°C)
Rotameter	The mass flow rate of water	±(3%)
Solar Power Meter	Solar radiation	±(10 W/m^2)

A model for calculating uncertainty
For example, the temperature of water=25°C
Digital thermometer error=0.5%°C

$$\frac{W_T}{T} = \pm\sqrt{(\frac{W_T}{T})^2 \times 100}$$

$$\frac{W_T}{T} = \pm\sqrt{(\frac{0.005}{25})^2 \times 100} = 0.02$$

5. RESULTS AND DISCUSSIONS

The investigation was conducted in the province of Kirkuk (35.5No, 44.33Eo), located in the northern region of Iraq, during the month of April. Preparatory steps, including the removal of dust from the solar cell and the cleansing of the distiller's glass cover, were diligently performed prior to data acquisition. Additionally, the thermal sensors' readings were meticulously verified. Data recording was systematically carried out from 9 a.m. to 5 p.m.

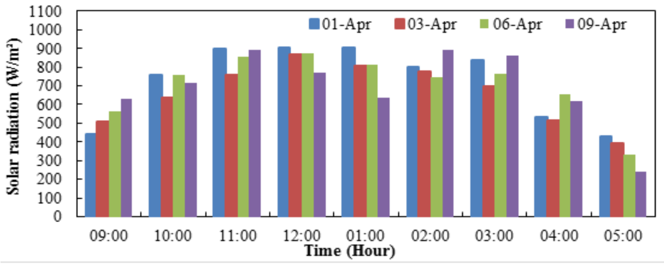


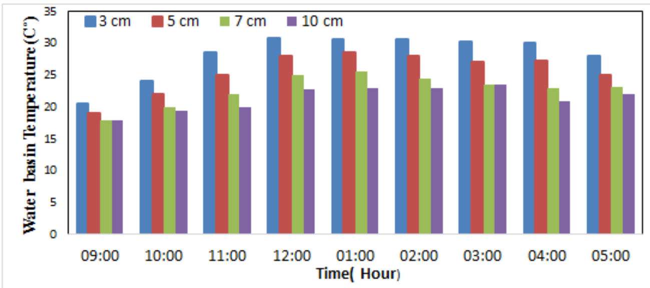
Figure 7. Displays the solar radiation intensity over time for still images

Water basin temperatures were rigorously calculated at four distinct depths (3, 5, 7, and 10 cm), spanning a period of three days for each specified level. The installation of thermocouples was methodically executed at critical points: (1) at the inlet and outlet of the solar cell exchanger, (2) at the entrance, exit, and midpoint of the exchanger located inside the distillation basin, (3) on both the inner and outer surfaces of the glass, and (4) at four different levels within the basin for each water depth.

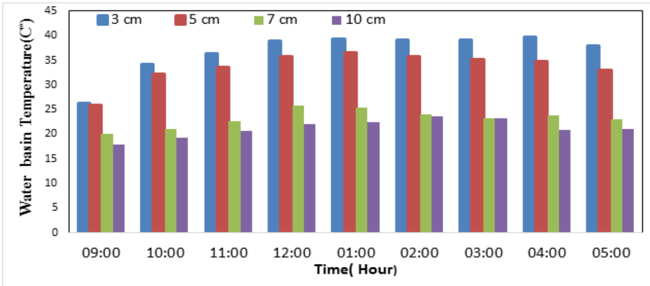
Figure 7 provides an illustrative depiction of the average solar radiation recorded on the initial day of each experimental run, corresponding to each water level. The recorded solar radiation levels were found to be within acceptable ranges, demonstrating the suitability of the study area for solar thermal system applications.

5.1 Temperatures of the system

Temperature stands out as a pivotal variable governing the efficiency of solar thermal systems, with thermal efficiency being directly contingent upon the temperature levels within any solar apparatus. Figure 8 delineates the temperature variations of the water basin across four different depths (3, 4, 7, and 10 cm), highlighting the thermal behavior for both solar distiller configurations. Within the basin, a diurnal temperature increase was observed, culminating in a peak at 3 p.m., congruent with the ascension in solar radiation measurements—a phenomenon commonly witnessed in solar thermal energy systems. This escalation in basin temperatures is attributed to the amplification in solar radiation values. Post 3 p.m., a diminution in water temperature values was recorded, a trend ascribed to the concurrent decline in solar radiation values and augmented heat losses. Integration of the conventional solar distiller with the PV/T solar collector was found to induce a noticeable augmentation in the basin's water temperature. Additionally, a reduction in water depth within the basin, applicable to both solar still designs, was correlated with an increase in water temperature, subsequently enhancing the efficiency of the solar still—a finding corroborated by existing research [12, 33]. A pinnacle water temperature of 39.4°C was recorded at 1 p.m., with the basin water depth at 3 cm. It was discerned that variations in the depth of the traditional distilled water exerted a negligible influence on the basin water's temperature. In contrast, the presence of an exchanger within the basin of the enhanced distiller, fed with warm water from the exchanger situated behind the solar cell, played a significant role. This exchanger siphons heat from the solar cell, facilitating its cooling, thereby bolstering both thermal and electrical efficiency. The heat is then transferred to the fluid (water) circulating through the exchanger, eventually reaching the exchanger within the enhanced distillation basin, culminating in an elevated brine temperature and, subsequently, a higher evaporation rate. This phenomenon underscores a marked improvement in productivity relative to the conventional distiller. The data elucidates that a shallower water depth is conducive to more efficient heating processes, with the water entering the heat exchanger exhibiting a higher temperature than the saline water. This paradigm underscores the success of the heating process, with shallower depths accruing greater heat quantities, thereby elevating the water temperature within the basin. This, in turn, augments the kinetic energy of the fluid molecules, culminating in an increased evaporation rate. Within the scope of this experiment, the 3 cm level was identified as the optimum depth, followed closely by the 5 cm level. This comprehensive analysis elucidates the intricate interplay between various system components and environmental variables, shedding light on the optimal operating conditions for enhanced solar distillation efficiency.



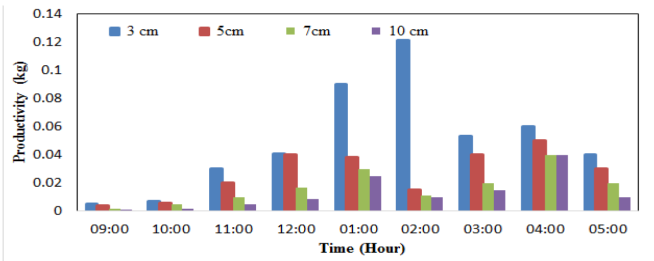
(a) Conventional distiller system



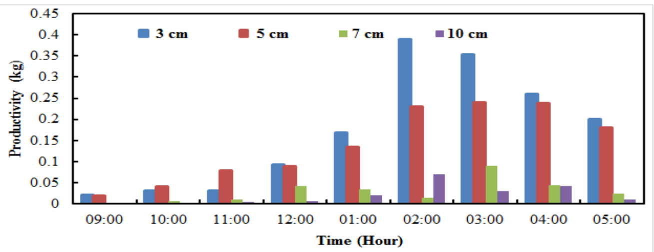
(b) Enhanced distiller system

Figure 8. Water temperatures for each level with time for a system

5.2 Productivity of the systems



(a) Conventional distiller system



(b) Enhanced distiller system

Figure 9. Productivity (in kg) for each level with time for a system

Figure 9 illustrates the fresh water output of the system, quantified in kilograms. A noteworthy observation is made, highlighting a pronounced increase in distilled water production from the system integrated with the PV/T collector, in comparison to the traditional distillation system. This enhancement is attributed to the heat extraction from the solar panel and its subsequent addition to the basin water via heat exchangers. Furthermore, the depth of water in the distiller system's basin is identified as a crucial factor, significantly influencing the system's freshwater productivity. The optimal productivity is achieved at a water depth of 3 cm in the distillation basin, recording a yield of 0.39 kg at 2 p.m. This finding is consistent with previous research outcomes, as documented in studies [34, 35], which assert that a reduction in water depth enhances water productivity, attributing this to the lower heat capacity of shallower depths in comparison to their deeper counterparts. For the solar still connected to the PV/T solar collector, the productivity at water depths of 7 and 10 cm is observed to be inferior relative to other depths. It is also discerned from Figure 8 that the quantity of distilled water escalates throughout the day, mirroring the increase in solar radiation values. Post 2 p.m., a decline in production is noted, concomitant with a decrease in solar radiation values and an escalation in heat losses.

A comparative analysis between the improved and traditional distillers yields the following observations:

(1) The water temperature in the basin of the improved still is found to be higher than that of the traditional one.

(2) A superior practical efficiency is exhibited by the improved distiller in comparison to the traditional variant.

(3) The freshwater productivity of the improved still surpasses that of the traditional one.

5.3 Electrical power

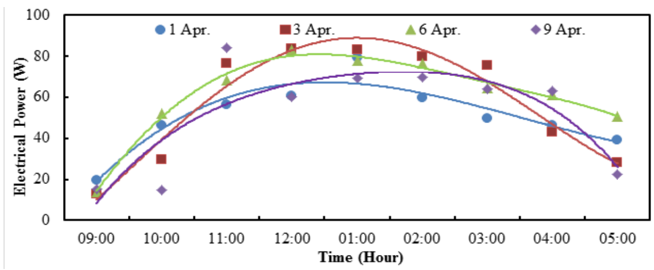


Figure 10. The electrical power of the system for different days

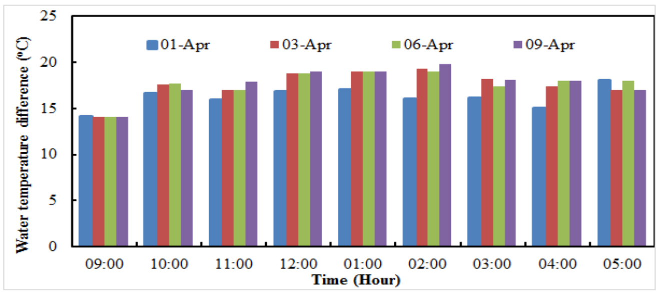


Figure 11. Temperature difference between the two ends of the heat exchanger installed behind the PV panel

The optimization of the efficiency of photovoltaic (PV) panels stands as a primary objective within PV/Thermal systems, which is achieved through the cooling of PV panels and the subsequent utilization of this heat across diverse applications. As depicted in Figure 10, the electrical output generated by the solar panel is presented, revealing a production that is proximal to the design capacity of the solar cell, set at 100 watts. It is observed that the generated electrical power experiences an augmentation throughout the course of the day, in concordance with the increase in solar radiation, culminating in its maximum values around 1 p.m. Figure 11 holds significant relevance for thermal systems, elucidating the temperature gradient across the two terminals of the heat exchanger mounted behind the solar panel. The recorded temperature differentials span a range of 10–20°C, providing an indication of the quantum of heat extracted from the PV panel. This extraction process plays a pivotal role in the amplification of the electrical power output.

5.4 Efficiency of the system

The efficiencies of solar thermal systems stand as pivotal determinants of their performance quality. In Table 3, the efficiencies of both traditional and enhanced solar distillers across various depths are delineated, calculated utilizing Eqs. (2), (6), and (8). A noteworthy observation is made for the enhanced still at a water depth of 3 cm, revealing an efficiency of 18.81%, a stark contrast to the mere 5.15% efficiency exhibited by the conventional distiller at the same depth. This substantial disparity underscores the significant impact of the heat exchanger's presence within the still, which receives warm water from the exchanger positioned behind the solar cell. The dependency of efficiency on both the water depth within the distillation basin and the solar distiller's engineering design is further illuminated by these results. Moreover, Table 3 presents the efficiencies at water depths of 7 and 10 cm, wherein no discernible difference is noted between the enhanced and traditional distillers. Intriguingly, the traditional distiller demonstrates a slight superiority over its enhanced counterpart at these greater depths. This phenomenon is attributed to the lower temperature of water entering the basin exchanger compared to the saline water within the basin, compounded by the substantial water volume relative to the temperature within the exchanger.

Table 3. Efficiency of enhanced and conventional solar still at (3, 5, 7, and 10) cm

Time	Enhanced (3 cm)	Conventional (3 cm)	Enhanced (5 cm)	Conventional (5 cm)	Enhanced (7 cm)	Conventional (7 cm)	Enhanced (10 cm)	Conventional (10 cm)
9	3.76	0.86	2.93	0.59	0.33	0.26	0.11	0.11
10	3.05	0.69	4.93	0.71	0.60	0.50	0.10	0.18
11	2.65	2.50	7.69	1.98	0.97	0.88	0.33	0.38
12	7.64	3.39	7.57	3.46	3.61	1.46	0.58	0.88
13	13.86	7.48	12.48	3.54	3.25	2.78	2.37	2.96
14	36.18	11.34	22.04	1.44	1.51	1.11	5.93	0.68
15	31.28	4.70	25.57	4.29	8.89	1.97	2.62	1.31
16	36.14	8.42	34.59	7.28	5.17	4.59	5.14	4.89
17	34.77	7.02	34.07	5.72	5.73	4.59	3.15	3.14
Average value	**18.81**	**5.15**	**16.87**	**3.22**	**3.34**	**2.01**	**2.25**	**1.61**

6. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

In the context of the present investigation, a comprehensive empirical analysis has been conducted to evaluate the performance of solar distillers integrated with PV/T collectors under the climatic conditions prevalent in Iraq. Derived from the results elucidated in preceding sections, the following conclusions have been drawn:

(1) Integration of a solar distiller with a PV/T solar collector has been demonstrated to enhance the performance of the hybrid system.

(2) The depth of the basin water has been identified as a critical factor, significantly influencing the productivity and efficiency of both the hybrid and traditional solar distillation systems.

(3) Optimal performance in both systems was achieved at a water depth of 3 cm in the basin, beyond which no notable disparity was observed between the traditional and improved distillers at depths of 7 cm and 10 cm.

(4) The efficiency of the hybrid system was calculated to be 18.81% at a depth of 3 cm, markedly higher than the 5.15% efficiency recorded for the conventional distiller.

(5) A direct proportionality was observed between the productivity of the distiller and the temperature of the water in the still basin.

(6) An increase in solar radiation intensity was correlated with an augmentation in distillery productivity.

(7) It is imperative to note that the applicability of this test is confined to moderate and cool seasons, as the elevated air temperatures in summer lead to a rise in the temperature of the saline water, surpassing that of the water emanating from the solar cell exchanger, and consequently reversing the process.

Among the future recommendations derived from the results are:

(1) Extending the length of the heat exchanger situated within the solar still basin is proposed, with the intention of prolonging the residence time of hot water. This modification aims to elevate the temperature of the brine, thereby enhancing the system's efficiency.

(2) A closed-circuit system is recommended, wherein the hot water exiting the distillation basin exchanger is cooled before being rerouted to the exchanger located behind the solar cell. This approach not only facilitates the cooling of the cell but also enables the re-extraction of heat, optimizing the energy utilization.

(3) To extend the operational feasibility of the system to the summer months, a cooling mechanism for the glass of the solar still is suggested. This adaptation is anticipated to mitigate the challenges posed by elevated air temperatures and maintain the system's performance.

(4) The application of the system for water purification is highlighted, particularly in contexts involving the removal of dyes and pollutants from water in industrial and laboratory settings. This expands the utility of the system, showcasing its versatility and potential for broader implementation.

(5) An alternative configuration of the system is introduced, wherein distilled water produced from solar distillation beds is employed to cool the solar cell. This reverse operation not only contributes to the cooling of the cell but also exemplifies the system's adaptability and efficiency in resource utilization.

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