

Performance Enhancement of Hybrid Solar Pv Module By A Novel Configurations

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Abstract: In common, energy input to PV panels is the incident radiation which is converted to electrical energy to external load as energy output. Percentage of 4–17% of the incident solar radiation only converts to electric power by PV module. So, more than 50% of the solar energy converts into heat inside panels and this increased the temperature of PV module. Decrement of electricity efficiency and power with a continuous structural deterioration of modules is due to long thermal stress period as a result from increasing PV module temperature. In order to get better efficiency of PV module and to reduce its thermal degradation rate, there is an effective method of reducing its temperature of operating through utilizing of PV module cooling technique. In the present study, experimental system was designed in an effective and simple way in construction. Outdoor testing conditions were carried for produce distilled water from cooling PV module by using a wetted porous cotton wick structure. The proposed module is assumed to represent an integration of solar still with a PV(PV/T). Total efficiency and productivity of proposed module was enhanced as seen from results. Results of experimentations showed that the maximum instantaneous PV electrical efficiency acquire the highest value of about (14.4%) through desalination with back wick (PVWDWBW) compare to 13.9% for (PVWD) that indicate an improvement of about (2%) as compare to PV module without system of cooling(PV only). The daily (PVWDWBW) thermal efficiency (η_d) is about (21.4 %) as compared to (18.4%) for(PVWD). For productivity, temperatures, and different terms, results were presented. For productivity, temperatures, and different terms, results were presented.

Key word: Evaporating cooling, water distillation, porous wick, hybrid system

1. Introduction

The most important sources in present days are renewable energies that become more and more popular because of permanence and non-pollution of their sources of energy. With increment of the human inhabitation and after fossil evanescence, a query appears what are the fuels of the alternative energy sources that can be dependable? one of the most plentiful sources are solar energy that presented as direct solar radiation, or indirect wind and biomass energies. Considering the energy transformation efficiency, two different energy types can be generated: thermal and electrical energies. Electricity energy is particularly more worthy than thermal energy, due to its capability easy transformation into work. The most efficacious method to acquire electrical energy by direct fallen solar irradiance are photovoltaic cells (PV cell)[1,2]. Progressive technologies were acquired in the former days by utilizing of solar energy as an input energy. The solar energy had functionally participated in generality of the new applications, in addition, it is renewable and sustainable. The most appropriate technology that made a quickly advancement in the field of transform sunlight to electrical energy is the Photovoltaic (PV) technology.

Anextra development in studies introduced a system compiles the solar thermal and electrical power simultaneously which is called as photovoltaic thermal (PV/T) system. The PV-T system may be distributed in the field of the glazed and unglazed cover and air and water depending on the used working fluid. Hybrid thermal system of photovoltaic (PV/T) means combination of solar collector or solar still and PV module. Output energy (thermal yield and electrical per unit surface area) can be supplied by PV-T systems higher than the standard PV modules, and the systems can be considered as effective cost systems in case of low extra costs of the thermal units [3,4]. PV cells don't convert all the fallen solar radiation into electrical power and generally of radiation amount rises the cell temperature and decreases its electric efficiency. The literature reported that when the PV temperature increases 1°C, that causes a 0.5% decrement fits efficiency[2]. A suitable system can be used to partially remove this unwanted effect through heat extraction with natural or forced mode circulation of the fluid. In PV-T solar systems, a beneficial fluid heating can be acquired by the reducing the temperature of PV module. So that, hybrid PV-T systems can synchronously provide thermal and electrical energies, so, posteriorly acquire a larger rate of energy diversion from absorption of solar radiation. The main primacy in the PV-T system applications is the electricity production, thus, in order to keep the electrical efficiency of the solar cell at an acceptable level, it is necessary to make the PV modules operation at low temperatures [5,6]. The cooling method is therefore beneficial to keep the panel at the operation temperature and must be with a uniform

distribution, it holds the average panel temperature at its lower value. PV module cooling techniques classified in two general method; PV active cooling improve the transfer of heat between the PV module and the cold source by using external power. Active systems regulation always use (i) jet impingement cooling, (ii) channels or ducts for air or water passing and (iii) water spraying on the panel top surface. Passive methods are the other type of cooling systems regulation which are not needed external source of energy and also no power additional consumption, which involve (i) using dielectric medium and immersion of PV module inside it (ii) cooling by using submerged water (iii) evaporative cooling technique (iv) cotton wick cooling (v) expansion of stored gas to spray water (vi) dissipaters of heat / sink of heat (vii) phase change materials (PCM) (viii) air flow induced by buoyancy and (ix) wind driven roof top turbine ventilator [3,6,7].

The water is the fundamental human need. Everyone on world needs 20 to 50 liter of pure safe water per day for cooking, cleaning themselves and drinking. There are several areas of low abundance of health pure water, despite the efforts of developed states. More than 700 million people sustain difficult acquirement of enhanced sources of healthy water, approximately 50% of them lives in sub-Saharan Africa. This is the cause of many connected diseases to the unhealthy water. Unhealthy and dirty water sources are available around us, which can be purified and treated to turn into healthy water [8]. Distillation is one of the most effective methods of getting pure water. The distillation process utilizes a source of heat to convert water into vapor. This method have advantage of turning the contaminated, seawater, and brackish water into healthy pure drinking water. In comparison to other distillation devices, the solar still is the most basic and traditional solar desalination device. Solar stills, in general, employ salt water and operates on the evaporation–condensation principle. The saline water in the solar still's basin is evaporated by solar energy in the humid air area and condenses on the solar still's walls. The vapor condenses on the solar still walls and is deposited as freshwater. Solar stills can be divided into two categories: passive and active solar stills. The incident solar radiation on the solar still is the only parameter that causes the evaporation process in a passive solar still. Evaporation is generated in active solar stills in addition to incident solar radiation by using a supplementary device such as a fan, pump, solar collectors, sun tracking system, or any other device. So, process of distillation sometimes considered as a pure drinking water acquiring process. [9,10,11,12].

Haidar et al. [13] used evaporative cooling method to enhance performance of PV panels theoretically. Air is blown through adduct by using fan and a process of heat and mass transfer occurs between air and a layer of water which is flowing inside same duct. Effect of transferred heat between air and back surface of PV panel is also studied. Temperature of PV panel is predicted to be decreased to 6 °C approximately. Lucas et al. [2] utilized an evaporation chimney for enhancement of a PV panel performance thermally and electrically by using experimental investigation. It made a temperature reduction to about 8 °C and enhancement of electrical efficiency. In Electrical efficiency improvement is obtained from results through a range of 4.9-7.9%. The average temperature of ambient was taken below 30 °C. A cooling system with combination of cotton wick structures and heat spreader of aluminum was presented by Chandrasekaret al. [14]. This system is used to overcome the trouble of increasing temperature of heat dissipaters in conditions of high ambient temperature. They accomplished their experimental investigations for a PV module with 25Wp at Tiruchirappalli in India. Results showed a lowering in maximum PV module temperature from 49.2 °C to about 43.3 °C with a reduction of about 12% in module temperature. This improving was achieved because of evaporative cooling and fin effect which fixed at a back side of the PV module surface. The evaporative cooling effect of solar photovoltaic (PV) panels was studied experimentally by Haidare et al. [15]. PV module temperature was decreased because latent heat of evaporation which has been used for absorption of heat generated by the PV module surface and to decrease the surface temperature subsequently. The experiential system was effective and simple, and it was designed, constructed and examined at outside environment. The posterior PV panel surface has been moistening and its open to ambient. Water is fed by gravity from tank to the PV module rear surface. Several experiments were conducted and analyzed under actual conditions in the city of Riyadh to show the activity of this method. There was more than 20 °C reduction in PV temperature and about 14% increment in electrical efficiency were achieved with comparison of a reference PV panel. A novel study consist of solar still integrated with a PV (semi-transparent) and collector of evacuated tubes was presented by Yari et al [8]. Different types of PV module have been chosen (Six types) as a well as diverse depths of trough water and some tubes was tested. It is shown by results that the productivity of health water not effected by PV type. For a depth of trough of about 0.07m and a typical number of tubes was 30, a maximum yield of pure water (4.77 kg/m².day) was obtained. Elbaret al. [16] integrating PV panel with a solar still single slope and testing experimentally. The new integrating technique is due to coupling of the PV over the glass condenser cover of the still, since the output energy of PV panel is immediately converted for the brackish water by using electric resistance placed in the trough of still. A basin is equipped with fibers of black steel wool (BSWF) is studied for forced and natural air convection cooling (FAC). The results indicate that integrating conventional solar still (CSS) and the CSS plus the BSWF with PV panel can enhances the still output with 9% and 23%, respectively. Still output increases with 3.2% by utilizing a PV consider as a reverser with minimization of the cost of the present system as

compared to others. The cost of freshwater producing by utilizing of PV BSWF FAC with CSS is the same as CSS approximately, but it increases its efficiency and daily production by 35% and 30% respectively.

Agrawal et al.[17]enhanced heat absorption and so, experimentally increases the productivity of a traditional solar still by using a multiple floating wicks(V-shaped). The testing is carried out during winter and summer seasons in India. These floating wicks are made of cloth of black jute covered with V-shaped thermocol pieces. Because of their V-shaped profile, there is increment of about 26% in the surface area exposed to evaporating of modified solar still, higher than that of traditional solar still. In winter the maximum daily productivity is found to be about 3.23 kg/m² and in summer and one of the clear days was 6.20 kg/m²and the daily efficiencies are47.75% and 56.62%, respectively. Omara et.al.[18]introduced experimental investigation for the performance parameters of the traditional solar still (CSS) and corrugated solar still (CrSS). Corrugated basin was used instead of liner and using double layer of wick material and reflectors. Comparison of results between corrugated still and the traditional still. It is indicated by their results that the using of the proposed design can increase the productivity and the efficiency. They also tested the influence of depth of brackish water (1, 2, and 3 cm) on the performance of CrSS. Enhancement in the results was obtained for CrSS. From testing, it is found the productivity of CrSS with wick, reflectors and a brackish depth of 1 cm are higher to about 145.5% than the CSS, and the daily efficiency of CSS and CrSS are about 33% and 59%, respectively.

There are several regions suffering a difficulty in obtaining of both electrical power and healthy water, the present experiment research study the thermal behavior of a photovoltaic module by introducing an innovated evaporative cooling with wetted wick of pored cotton positioned at the PV module back surface that may be assumed as a coupled of solar still with a PV in order to produce simultaneously electrical energy and fresh water. There is no similar research in the literature as far as the best of our knowledge. Another enhancement is introduced by covering the PV frame by a back glass cover (commercial glass) and consider as condenser surface. The following advantages are the major objectives of this research: effectiveness in lowering the PV panel temperature and acquiring distilled water, simplicity in setup and construction, zero energy needed for cooling components, environmental friendship, and finally cheapness of components and cost. The experiments were carried out in real ambient status of Najaf / Iraq. The PV module performance was studied during several days from two months. Productivity and temperature of PV module has been recorded and monitored periodically every 5 minute during the experiments that were continual for various hours.

2. Description of the Proposed System

(Figure 1) shows the schematic view of cross sectional for the proposed PV modules with a heat transfer types which including:

(i) –Reference PV without addition (**PV only**)(Figure 1a), (ii) –Desalination with PV (**PVWD**)(Figure 1b):containing wick of porous cotton on the PV back surface to obtain desalinated water. At the suction pipe, the material of porous is fully moisten with the water by the capillary action of porous wick .Wick insure the increment of the evaporating rate and more surfaces for convective and radioactive heat transfer.(iii) – (**PVWDWBW**) consist of a Back wick for PVWD(Figure 1c):similar design as case (ii)(desalination with PV), but extra wick is added on the rear surface of the back glass cover(surface of condenser),for enhancement of the PV thermal performance and reduction of its PV temperature. The PV layers transmit the solar radiation which falling on the module and heated it, then, a part of this heat is absorbed by the wetted wick to generate a temperature difference between the concentration of the vapor in the surrounding moist air and the vapor at the water–air interface (saturation layer). This difference generates the water evaporation process. The water vapor density of the humid air increases due to the occurred evaporation at the water surface, and then the water vapor starts the condensation process at the back glass cover inner surface, and emits its evaporation latent heat. At last, the condensed water is dripped in a natural manner by gravity to the bottom of back cover to be stored in a collector represented by a slot in pipe that has been maintained at the back glass cover bottom end. In the present study, the cases (ii and iii) are assumed to represent a combination of solar still with PV. That's because the solar still principle work is the same as that of proposed PV modules here, except the construction.

3. Theoretical Consideration

In this section, a description is presented for the internal heat transferred by four heat transfer modes through the several module surfaces: conduction, convection, radiation and evaporation. In the present modules, the controller is the processes of the internal heat transfer. By using the following assumptions, the energy balance equation is accomplished for each module component:

- 1.The nodal approach is adopted for the module (spatially the assumed constant temperature for each layer in the module).
2. Constant thermo-physical parameters are taken of each solid layer of the module.
- 3.PV module has been prevented from any vapor leakage.
4. Dependent heat transfer coefficients on temperature.
5. Neglecting of the heat loss from module sides.

The various components of the proposed modules can be expressed by the following energy balance equations (Figure1):

Case (i) - Photovoltaic module only (PV only)

Case (i) consists of PV panel which consist of following layers: front cover of glass(fg), solar cells(sc), and tedlar(t). The equation of heat balance for the PV only module components is expressed below (Figure1a)[19]:

Front glass cover

$$M_{fg}C_{fg}\frac{dT_{fg}}{dt} = A [R_{fg} + Q_{rfg-s} + Q_{camb-fg} - Q_{cofg-sc}] \dots (1)$$

The R_{fg} represent the solar radiation amount absorbed by PV front glass layer and T_s is the sky temperature.

$$R_{fg} = \alpha_{fg} I \dots (2)$$

$$T_s = 0.552 T_{amb}^{1.5} \dots (3)$$

The following equation represent an expression for the coefficient of radiation heat transferred between the PV module front glass layer and the sky [19]:

$$h_{rfg-s} = \sigma \epsilon_{fg} \frac{(T_{fg}^2 - T_s^2) - (T_{fg}^2 + T_s^2)}{(T_{fg} - T_s)} \dots (4)$$

The following relationship expresses the coefficient of conducted heat transferred between neighboring components of the module (i and j)[19]:

$$h_{coi-j} = \frac{1}{\left(\frac{l_i}{k_i} + \frac{l_j}{k_j}\right)} \dots (5)$$

The following equation can give the coefficient of convection heat transfer cause by wind from (i) layer and can be given as[14]:

$$h_{ci-amb} = 5.7 + 3.8 V_{wind} \dots (6)$$

For the solar Photovoltaic cell

$$M_{sc}C_{sc}\frac{dT_{sc}}{dt} = (R_{sc} - Q_{cosc-fg} - Q_{cosc-t})A - Q_{ele} \dots (7)$$

R_{sc} represent the solar radiation amount absorbed by PV solar cell layer. The generated electric energy is Q_{ele} .

$$R_{sc} = \tau_{fg} \alpha_{sc} I \beta \dots (8)$$

$$Q_{ele} = IA \zeta_{ref} [1 - \beta (T_{sc} - T_{sc,ref})] \dots (9)$$

For the Tedlar layer

$$M_t C_t \frac{dT_t}{dt} = [R_b + Q_{cosc-t} - Q_{ct-amb}]A \dots (10)$$

R_t represent the solar radiation amount absorbed by PV tedlar layer.

$$R_b = \tau_{fg}^2 \alpha_t I (1 - \beta) \dots (11)$$

Case (ii) Photovoltaic module with desalination (PVWD)

This module contains a wick used for desalination and consist of: PV panel ,a wet porous wick layer(w), and additional back cover of glass(bg)in the PV module back surface with enclosed air space. PV panel are the same heat balance equations used in above of case (i), but the tedlar layer change heat balance equation. Start the model from tedlar layer, wetted wick, and back glass cover ,the following equations can express the heat balance equations for PVWD (Figure1b):

For the tedlar layer

$$M_t C_t \frac{dT_t}{dt} = [\alpha_t \tau_{fg} I (1 - \beta) + Q_{cosc-t} - Q_{ct-w}]A \dots (12)$$

For the wetted wick

$$M_w C_w \frac{dT_w}{dt} = [Q_{ct-w} - Q_{cw-bg} - Q_{rw-bg}]A - Q_{evw-bg} - Q_{thw} \dots (13)$$

The convective heat transfer coefficients between the wetted wick and back glass cover is h_{cw-bg} . The heat of evaporation of water in wick is Q_{evw-bg} where was expressed as in following:

$$Q_{evw-bg} = \dot{m}_{ew-bg} H_{vap} \dots (14)$$

Where: $\dot{m}_{ew-bg}$ is the mass flow rate of evaporation, and H_{vap} is heat of vaporization of water equal to 2454[kJ/kg]. Q_{ouw} that represent the amount of heat carried by water coming out of the module where it write as below :

$$Q_{ouw} = c p_w (\dot{m}_{ouw} T_{ou,w} - \dot{m}_{inw} T_{in,w}) \dots (15)$$

Where: $\dot{m}_{ou}$ is the mass flow rate of water that out from wick, $\dot{m}_{in,w}$ is the mass flow rate of water that inlet to wick, $c p_w$ is the specific heat capacity of water at constant pressure, $T_{ou,w}$ is the out water temperature from the wick, and $T_{in,w}$ is inlet water temperature to wick .The rate of outflow from wick can be express as:

$$\dot{m}_{ouw} = \dot{m}_{inw} - \dot{m}_{ew-bg} \dots (16)$$

For Back glass cover

$$M_{bg} C_{bg} \frac{dT_{bg}}{dt} = [Q_{cw-bg} - Q_{cbg-amb} + Q_{rw-bg}]A + Q_{evw-bg} \dots (17)$$

Case (iii) Photovoltaic module with desalination with back wick (PVWDBW)

Similar mentioned components of setup above of case (ii) is used for the present case but there is a difference is the back wet wick (bw) made of similar material of previously used wick is supplied to the back glass cover. The heat balance of all components is same to case (ii), but back glass cover is change. And an additional equation for back wetted wick is added to the equations of energy balance for PVWDBW (Figure 1c) which is as:

Back glass cover

$$M_{bg}C_{bg}\frac{dT_{bg}}{dt} = [Q_{cw-bg} - Q_{cbg-bw} + Q_{rw-bg}]A + Q_{evw-bg} \dots (18)$$

The convective heat transfer coefficients between back glass and back wick is h_{cbg-bw} .

For the back wetted wick

$$M_{bw}C_{bw}\frac{dT_{bw}}{dt} = [Q_{cbg-bw} - Q_{cbw-amb}]A - Q_{evbw-amb} - Q_{oubw} \dots (19)$$

$$Q_{oubw} = cp_w(m_{oubw}T_{ou,bw} - m_{inbw}T_{in,bw}) \dots (20)$$

Detailed of the all above mentioned equations was found in [20].

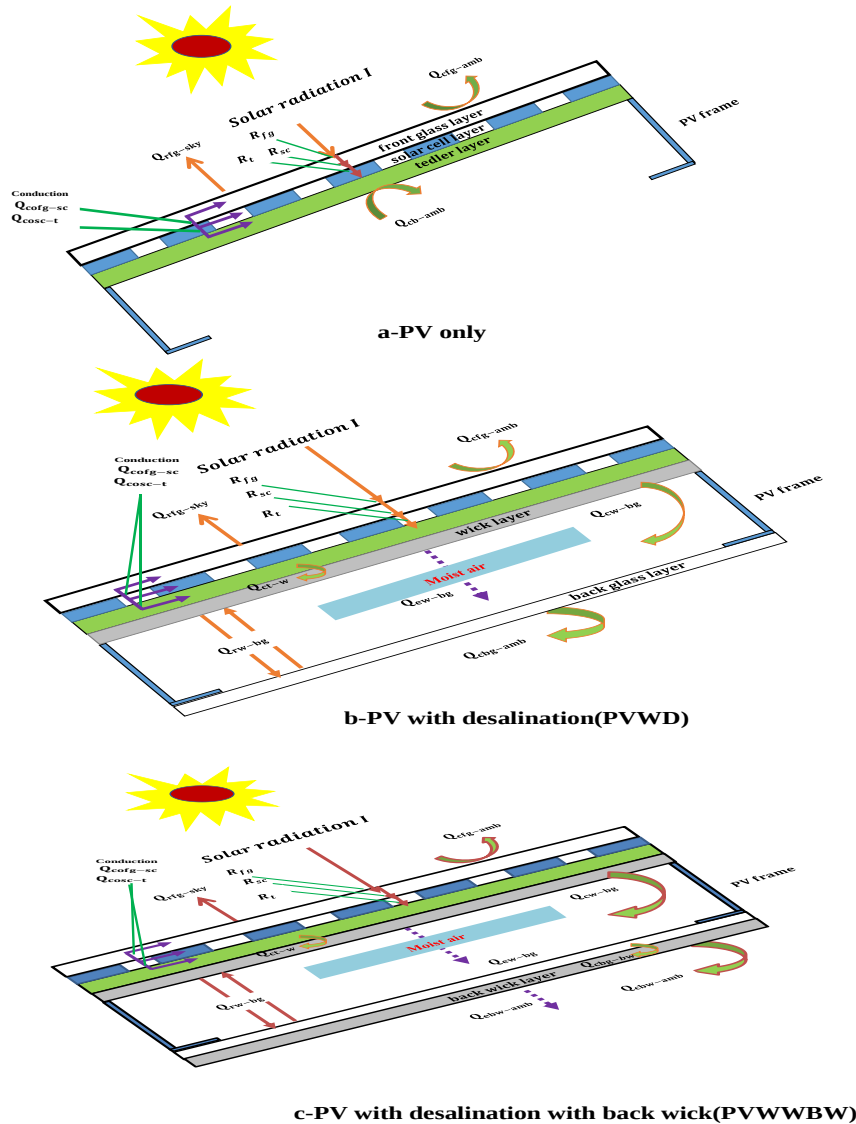


Figure1. Schematic view of cross sectional for PV proposed modules

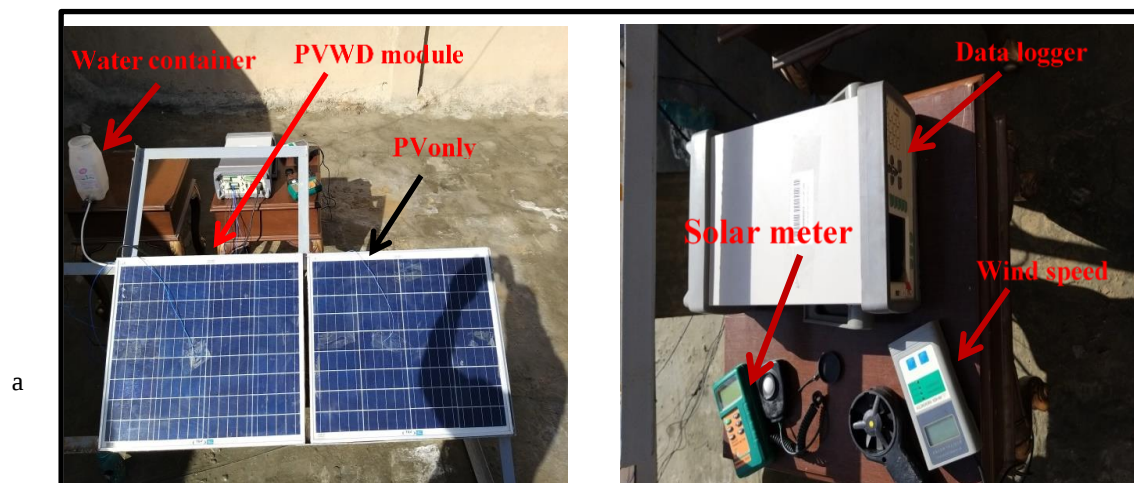
4. Set-up of Experimental Work

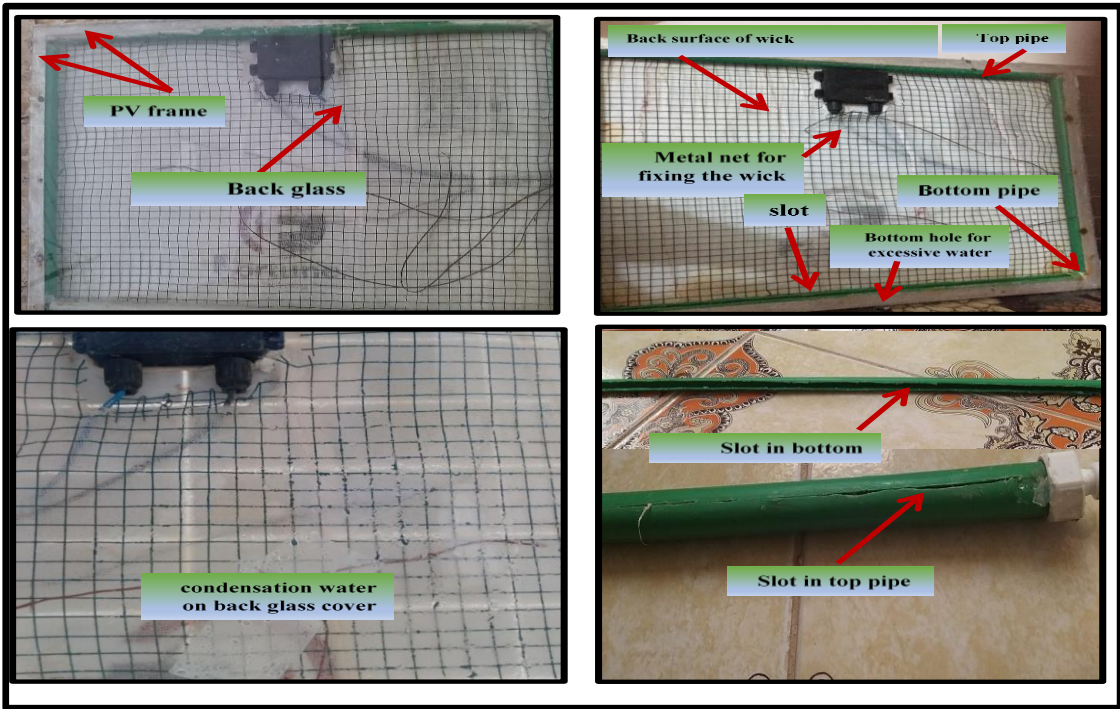
Two PV modules with the same peak power are used in the experimental setup. The first test PV module (PV only) serves as a reference module, while the other PV test modules are equipped with a distillation cooling system. The experimental rig (shown in Figure 2a) is built in Najaf, Iraq, with a PV modules with a 30° slope and a latitude angle of 32. The (table 1) summarizes the specifications and dimensions of PV. The two PV modules tested are parallel aligned toward the south direction for a large solar radiation rate. The rig is prepared

for measurement of distilled water amount, ambient air, humid air inside the enclosure space, surface of pored wick, glass cover, and temperatures of PV back surface. Some thermocouples are attached at three different locations on the panel back side, two are fixed to the wick back surface, and another one is allocated to the back glass cover on its inner surface and for humid air to calculate the modules components temperature. The ambient temperature is measured using a different thermocouple. The temperature is recorded using a data logger that is programmed and connected to a computer every 5 minute time periods. On an incline surface near the test module, a solar power meter (Type SR 11) with a 5 W/m^2 accuracy is used to calculate total solar radiation. The condensate water is measured and collected in a graduated 500 ml capacity vessel which manual recording over a one-hour period. A piece of wick with 0.01 mm thickness of porous cotton was directly attach to the (PV only module) back surface to make the PVWD module. This type of wick is used usually for health objects. Two 15mm plastic pipes are inserted into two bores drilled on the same sidewall of the PV frame. The distilled water is collected using the bottom (15mm diameter) tubing. This pipe contains a slot of rectangular shape (approximately 5mm) that crosses the length of the pipe to collect the condensate water. Brackish water is supplied via the other top (15mm diameter) tubing. A slot of about 0.75 mm was cut longitudinally on the surface of this pipe to insert the wick ends and allow water to flow from a controlled small container to the cotton wick through a valve. To discharge the excess water, a hole of around (0.5cm) diameter is drilled in the bottom wall of the PV frame (Figure 2b). The wick make tight contact to the back surface of the module, then, when the wick is wet, an attempt was done for prevention of space formation between a wick layer and PV back surface (tedler layer). The panel is covered with a layer of commercial back glass sheet (6 mm thick) inclined at approximately 30° to the horizontal and pasted (using silicon) to the PV module frame without exceeding it. A layer of silicone is used to fill all the openings and gaps between the frame of the panel and the edges of the back glass cover to prevent leakage of vapor. To prepare the PVWDWBW module, another porous back wick is mounted on the back glass cover outer surface. The wick's top ends are inserted into a pipe attached to the top of the back glass cover, which has the same size slot as the top pipe slot of PVWD module (Figure 2c). The wicks are wetted by capillary wick action from water which is flowing from another container by gravity. The solar PV module are fixed by a stand made from iron as explained by (Figure 2a). It must be observed that size and location of various cooling system components are selected according to two items, the first item is ensure of uniform distribution for water and the second item is the possibility of contact among PV panel and cotton wick and insure plastic pipes insertion between the aluminum frame of the PV panel and the panel itself. The main objectives was to confirm the reasonable technique to acquire healthy water from brackish water by using inexpensive and simple module, and to study the performance variation of the cooling for a comparatively long time in actual ambient. Proposed modules schematic diagram was display in (Figure 2d).

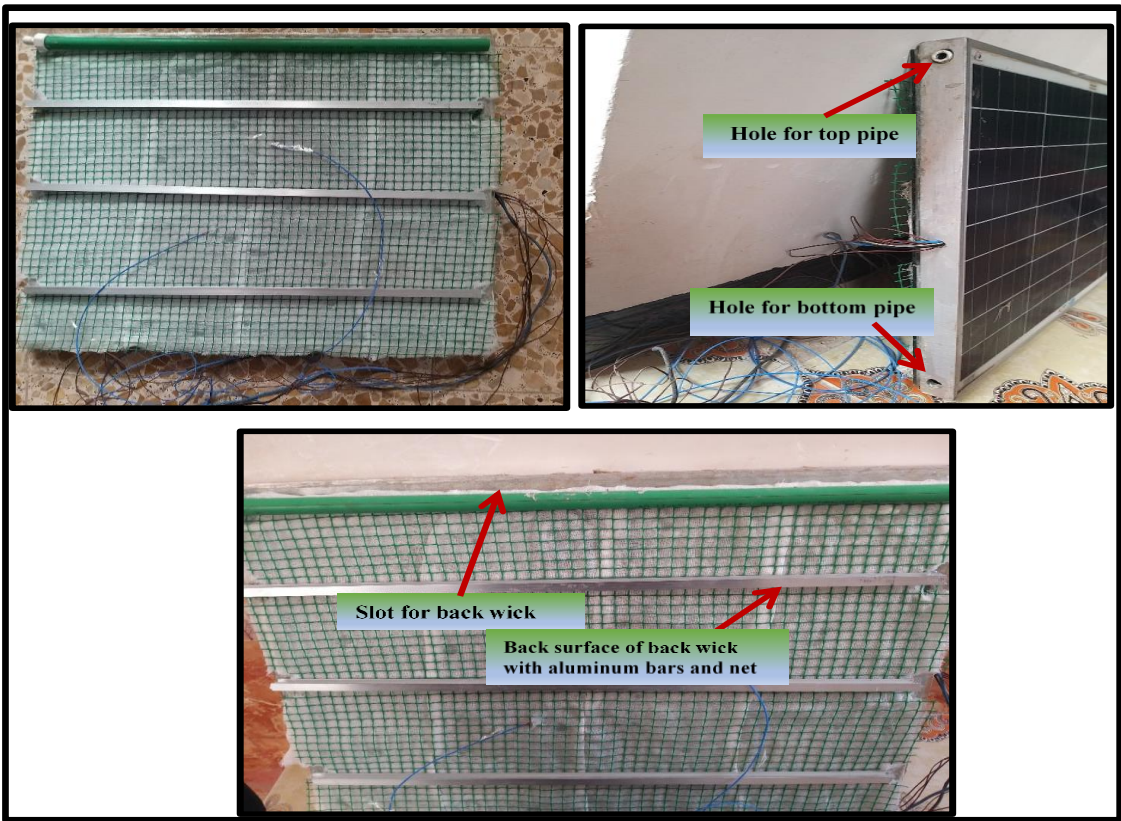
Table 1. Specifications of used solar PV module at STC.

Electrical parameters	Specifications
Power maximum (P _{max})	52.4886 W
Voltage at P _{max} (V _{mpp})	18.3544 V
Current at P _{max} (I _{mpp})	2.8597 A
Short circuit current (I _{sc})	3.168 A
Open circuit voltage (V _{oc})	21.88 V
Efficiency of module (η_{ref})	15.59%
Fill factor (FF)	0.7569
Model area (A)	3589.74 cm ²

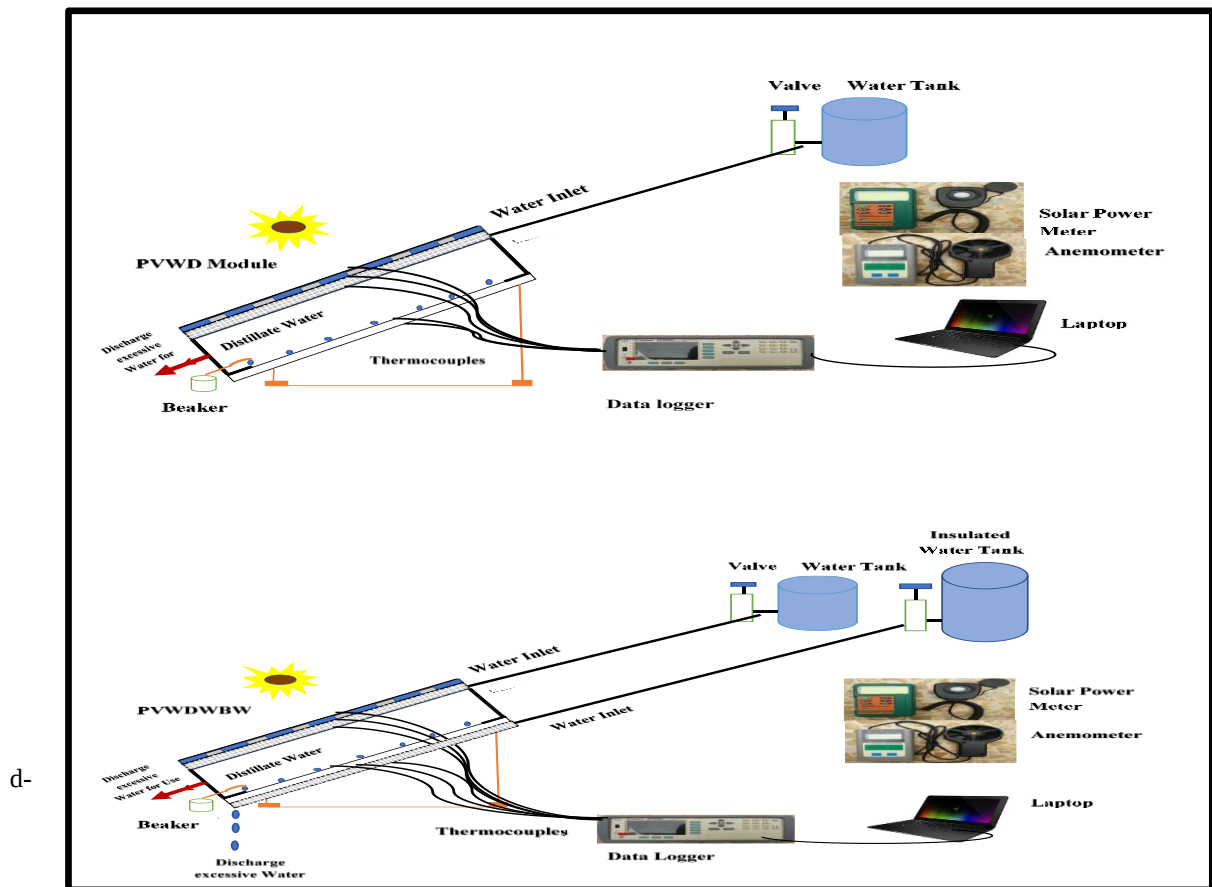




PVWD module



c-PVWDWBW module



Schematic diagram of proposed modules
Figure 2. Set up of Experiment and modules

5. Procedure of experimental work

The experiment tests are performed in the outdoor environment during November and December through twenty seven days. Each experiment was carried out through one day. All measured data are recorded and collected beginning by 9 a.m. into 4 p.m every 5 min. Different measurements has been achieved during this experimental work. The irradiation data were measured on the tilted surface of the module by solar power meter. Separate thermocouple has been sighted in a ventilated and shaded space at approximated high of 0.25 m to the ground surface was used to measure the ambient temperature. Temperatures of the ambient, back glass cover (condenser surface), humid air region, brackish water and back surface of PV are measured and recorded for each module. A bottom slot pipe is used to collect the pure water condensed on the wall of the back glass cover. The total accumulated pure water amount is weighted and recorded every hour. Additionally, the measured data recorded by thermocouples has been calibrated, hence a calibration process is considered for all the measured data results in this work. The output results represent the averages of measured values.

6. Analysis of uncertainty

During each experiment, error occurs in the measurement instruments, and it can be described as a difference between the real and calculated values. In general, errors in experiments are caused by calibration, human error, experiment conditions, uncontrollable variables, atmospheric conditions, measuring instruments, and other factors. As a result, there are two forms of uncertainty: systemic and random errors. Systematic errors may be measured by looking at the manufacturer's datasheet or data from the calibration of measurement instruments. Statistical processes may be used to quantify the random errors. Statistical processes may be used to quantify the random errors. Random error causes are undefined and can occur due to a variety of factors such as human error or environmental circumstances, and they are often uncountable. In other words, for the experiment of unchangeable circumstances, systemic errors are not varied, but random errors are. Since it is assumed that all measurement instruments are uniformly distributed, the second type of uncertainty is considered in this analysis. The basic uncertainty equation can be written as [21]:

$$u = \frac{a}{\sqrt{3}} \dots (21)$$

Where u is the standard uncertainty value and a_n is the measuring system accuracy. Table(2) records the levels of uncertainty associated with experiments.

Table 2. Instrument ranges, standard uncertainty, and accuracy.

Range Instruments	Ranges	Accuracy	standard uncertainty of Instruments	Parameter Measured
Thermocouple	0–100 °C	1°C	0.6°C	Temperature
Solar power meter TES1333R	0-1999 W/m ²	5 W/m ²	2.8 W/m ²	Global Solar Radiation

7. Results and discussions

The production of pure water and the enhancement the PV performance through lowering its operation temperature are the main goals of the proposed modules. The rate of the produced healthy water is related to the brackish water evaporation rate and rate of its vapor condensation. The rate of the evaporation could be increased by increase brackish water temperature or by increasing the difference of temperature between the brackish water and moist air in PV enclosed space. Also, if the condensation rate increased, the module operation temperature can be decreased. Condensation rate could be increased by increasing the outside air velocity, the difference in temperature between the back glass and ambient air, and a temperature difference between the back glass cover and the water in wick. Therefore, to understand the performance of PV, it is necessary to analysis and study the temperatures and other parameters for the all modules.

7.1. Temperatures of the PV modules

Experiment tests were performed in conditions of outdoor air at province of Najaf in November and December 2019. Figures 3 & 4 explain the weather parameters variation (ambient temperature and solar radiation) on several days from 9:00 to 16:00 of these months. Figure 3. shows that the curves approximately appear the same behavior excepting some days that have some curve deformation due to the occasional clouds moving quickly. Experimentation on the successive days was carried out and its solar radiation intensity was measured, it was found different but, it appear to be rather stable after 13 noon. The day that has the highest occurred radiation is 10 of November and was about 930 W/m². The temperature of ambient air for the same successive days are shown in Figure 4. The highest value of ambient temperature in November, it surpasses 33°C and at middle hours on some days in December it was about 23 °C. For two modules (PV only, PVWD), Figure 5. shows the instant temperature of the PV panel back surface (tedler layer) for a period for time start at 9:00 to 16:00 on the several days. The blue line of curve explains back surface temperature for PVWD module, and the red line of curve explains the back surface temperature for PV only module. That two temperatures were almost equal at the beginning of the experiments, but when the wick start wet, the desalination module (PVWD) temperature quickly increases due to effect of the evaporation. The rapid increment in the temperature of PV module indicates the start of pure water producing. It can be concluded by the two indicated curves that its trend and fluctuation are approximately identical. The temperature of the PVWD module behaves in the same trend of the instant temperature of reference PV module as its value make increment or decrement. In general, difference between the two temperatures remains approximately stable. Fluctuation in the curves is caused by weather conditions variation like the solar radiation intensity variation (due to presence of clouds). The temperatures of the wick back surface can be seen to have identical tendency as PVWD temperatures, but it is less at all times. Fresh water producing as results from evaporating of wetted porous wick can be obtained from PVWD module.

Figure 6. illustrates temperature instantaneous variation for the cooling module equipped with a back cotton wick (PVWDWBW module). As seen from Figure the cooling start at (10:45) to see influence of back wick. The distribution profile of the temperatures of back surface (tedler layer) for the PVWDWBW module is nearly identical for different experiment days, and this detects the PV module reliable functioning under different conditions of operation. Temperature of back surface for (PV only) module without cooling is observed to be greater than temperature of ambient throughout a day, with about 60 °C maximum temperature at 11.48 AM while PVWDWBW module back surface temperature is decreased (at the same time of around 11.48 AM) to about 52 °C. This decreasing in back surface temperature because of good cooling that was available from a back wet wick and simultaneously, a fresh water was obtained by this module. As a result approximately to 12% dropping in back surface temperature for PVWDWBW was obtained. PVWDWBW module produces fresh water and at the same time enhance the thermal performance of the module by reducing the temperature of back surface of PV panel. The temperature of the wick back surface is also was presented in Figure 6. and it indicates identical behavior with a PV back surface temperature, with it is low temperature as compared to temperature of the PV panel back surface.

The temperatures of surface for different items (water-in to the wick, water-out from wick, humid or moist air, back glass cover) was presented in Figure 7. on 10/11/2019 and 16/11/2019. It could be cleared that the temperature of the humid air for cases (ii) and (iii) were greater than temperatures of cover of back glass

(condenser surface), water entering and exiting out of the two modules. The water out temperature and condenser surface temperature for PVWD and PVWDWBW follow the temperature of humid or moist air where increases when temperature of humid region increases because of the evaporating start and vice versa. Outlet water temperatures was observed for PVWD is higher than PVWDWBW with a maximum of around 53°C. For PVWDWBW the temperature of water out increase until 10:45 AM (start cooling) then the temperature gradually decrease due to back wick cooling. The outlet water from PVWD could be employ for domestic using. Distilled produced water is enhanced by PVWDWBW because the difference of temperature between back glass and wick increases. Due to increment of the solar radiation, the inlet temperature for a brackish water increases.

7.2 Productivity of Distilled

Figure 8. presents the time variation of distillate produce for proposed PV modules (PVWD and PVWDWBW) at a rate water of flow in wicks ($m_{inw} = 10 \text{ ml/min}$, $m_{inbw} = 66.6 \text{ ml/min}$) and for different days. Many different measured parameters influence significantly on the productivity of distilled water such as solar radiation. Additionally, notes indicate that the distilled water for the two modules is little at morning interval because water fed to PV module has a low temperature and has not been heated yet. Whereas max. Distilled water yield is acquired at around (12PM-13PM), and after that it started to decline. This was due to high rate of solar radiation and increase in the ambient temperature through this period of the days. From figure it can be observed PVWDWBW module produce higher yielding in compare with PVWD module due to cooling of back wick which provide increase in temperature difference between wick and back glass cover and as a result increase the condensation rate.

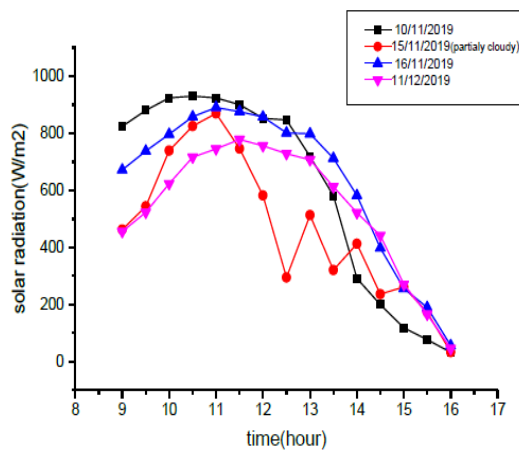


Figure 3. Intensity variation of solar radiation with time

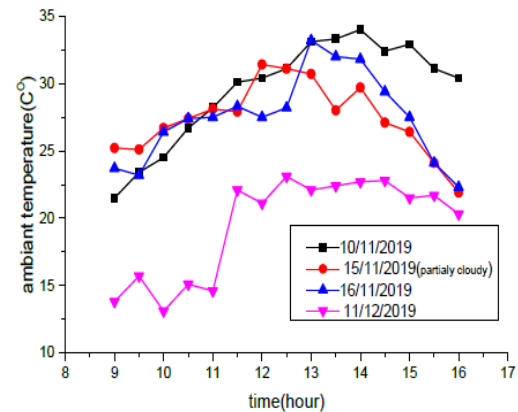


Figure 4. Ambient temperature variation with time

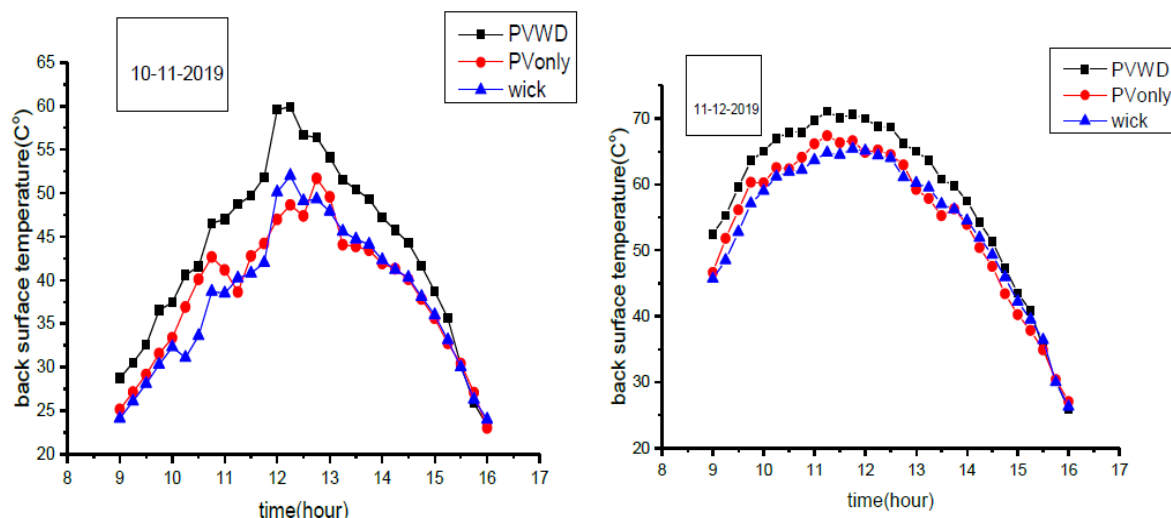


Figure 5. Temperature variation at back surface with time for the PVWD and PV only

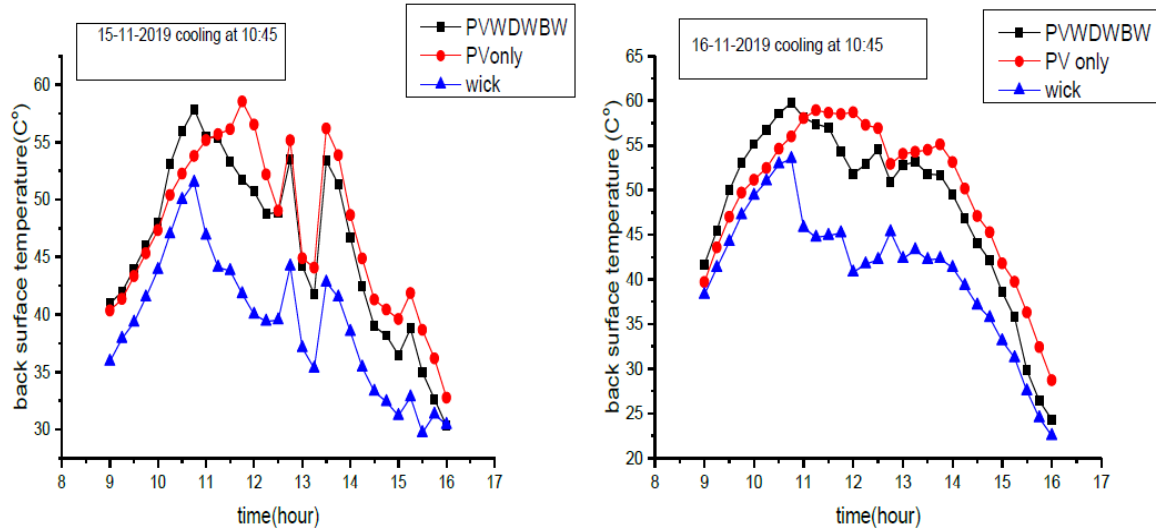


Figure 6. Temperature variation of back surface with time for PVWDDBW and PV only

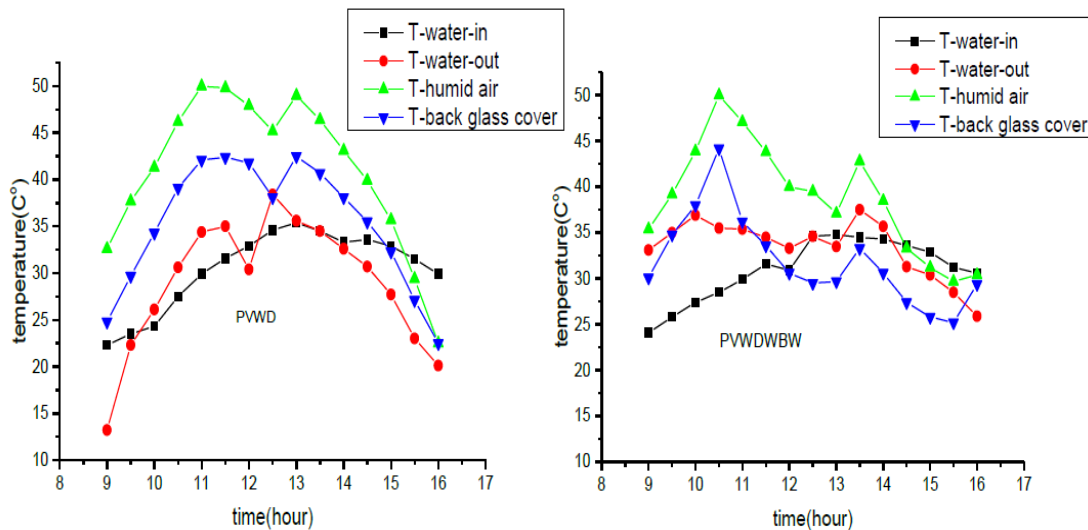


Figure 7. Temperature variation with time for PVWD at 10/11 and PVWDDBW at 16/11

7.3 Daily output

Variation of cumulative water output is represented in (Figure 9) starting by 9 a.m. up to 4 p.m. through different days for the testing modules (PVWD and PVWDDBW). It is found as explained in (Figure 8), that the maximum cumulated distillate amount for PVWDDBW was about (442 ml/day) with an average solar radiation of $753.5W/m^2$ while maximum yielding for PVWD was 357 ml/day with an average radiation of $824.8W/m^2$. This improvement in the rate of freshwater production for PVWDDBW due to the condensation and evaporation rates increasing due to back wick existing.

8. Mass flow rate effect

The effect of mass flow rate ($m_{inw} = 10, 20, 30 \text{ ml/min}$, $m_{inbw} = 33.3, 50, 66.6 \text{ ml/min}$) on the fresh water output and PV tedler layer temperature is shown in (Figure 10). The experiments were carried in successive days in order to obtain a small variation in conditions of weather. Production of water and tedler temperature for PVWD module increases because of higher evaporation rates when the rate of mass flow decrease in wick. This is due to a large period of contacting between water in wick and tedler layer causes more heat absorbing from PV panel and consequently increase in rate of evaporation and increase the temperature of tedler. For PVWDDBW module the readings are taken with a constant flow rate in wick ($m_{inw} = 10$) and variable mass flow rate in back wick ($m_{inbw} = 33.3, 50, 66.6 \text{ ml/min}$). The water yielding increase with mass flow rate increase in back wick because the difference in temperature between wick layer and back glass cover is improving with a mass flow in back wick increasing while for temperature of teller layer it decreasing with back wick mass flow rate increase as can be observed from (Figure 10).

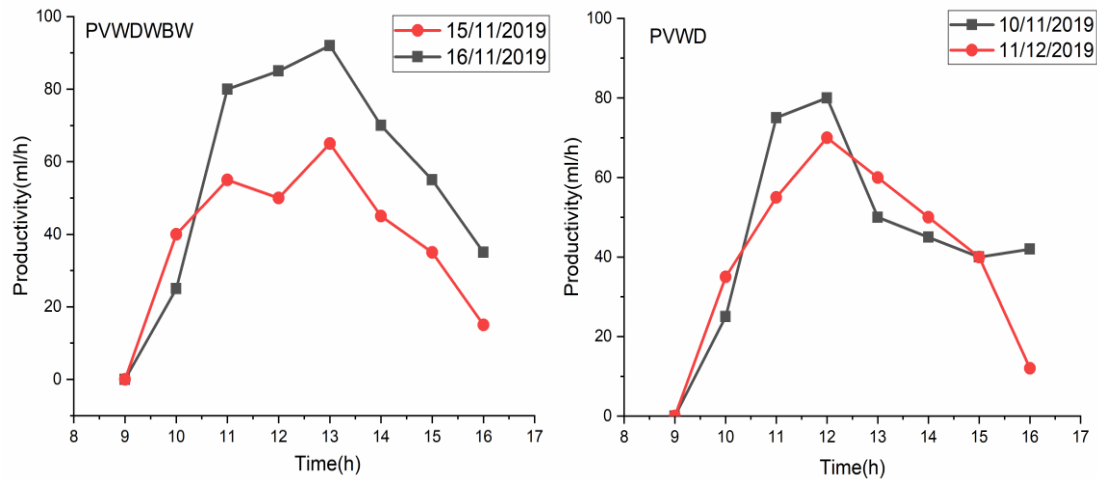


Figure 8. Hourly variation of solar radiation and production rate with time for PVWD and PVWDDBW

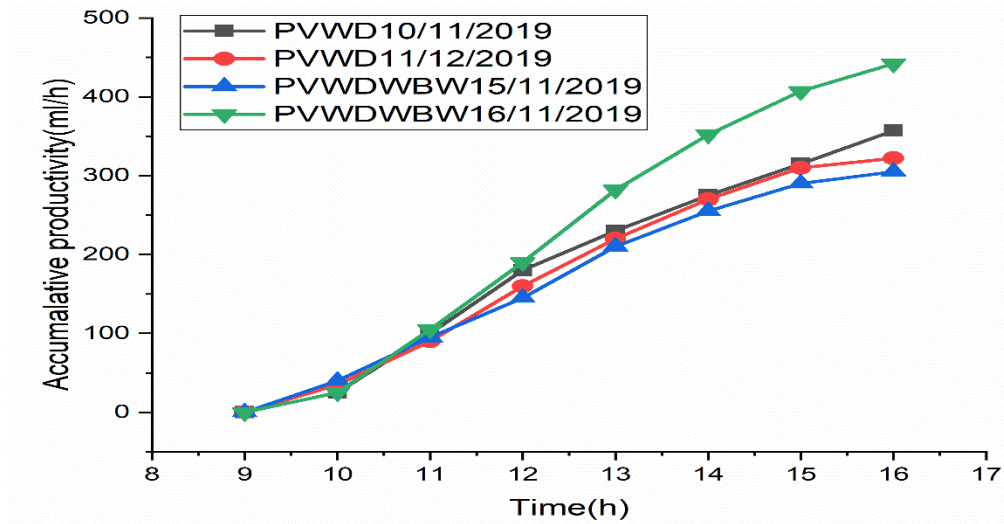


Figure 9. Variation of water cumulative productivity with time for PVWD and PVWDDBW

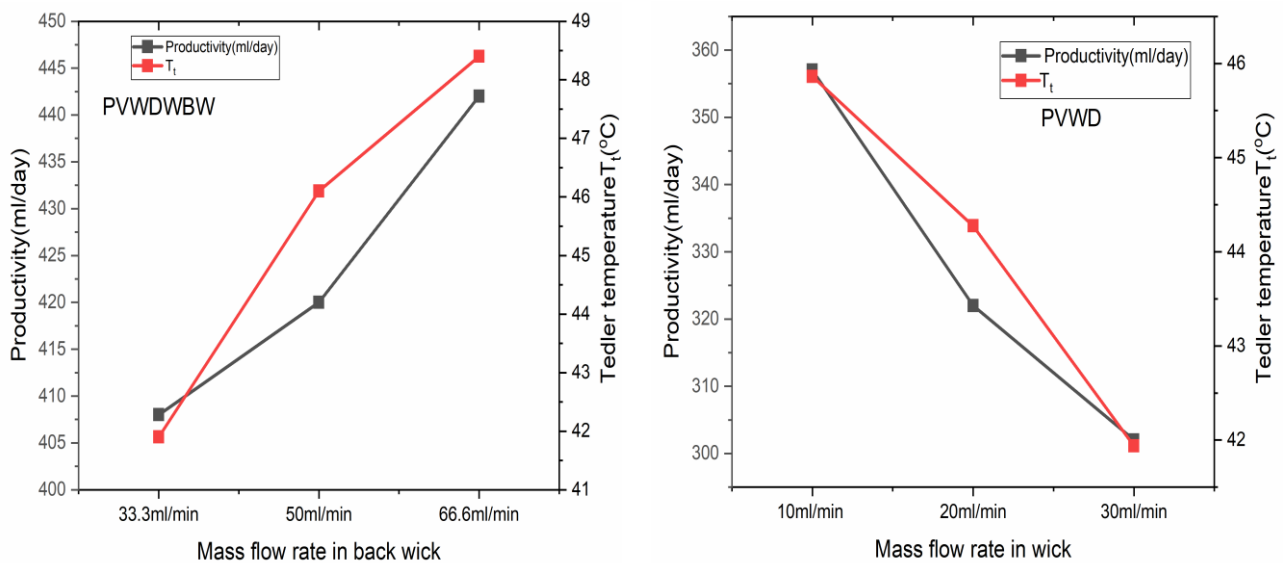


Figure 10. Mass flow rate effect on PVWD and PVWDDBW

9. PV module efficiency

The proposed module is assumed to introduce an integration of the solar still with PV module. Because its behavior is identical to solar still, therefore, the PVWD daily thermal efficiency (ζ_d) is obtained by the collection of the hourly condensate water m_{ew} multiplied by latent heat H_{vap} , then the product is divided by the daily averages collection of solar radiation and the total device area A [16]:

$$\zeta_d = \frac{\sum m_{ew} \times H_{vap}}{\sum A \times I} \quad (22)$$

The maximum daily thermal efficiency for PVWD and PVWDWBW modules was around 18.11% and 21.4% as shown by results. This indicates the present module is effective in obtaining desalination water at reasonable rate as compared with conventional solar still. The PV panel efficiency can be used to measure the improvement caused by reduction in the PVWDWBW temperature module. The following formula is used to find the efficiency of the PV panel [19]:

$$\eta = \eta_{ref} [1 - \beta(T_{sc} - T_{ref})] \quad (23)$$

η_{ref} is efficiency at 25 °C that is represented by the term T_{ref} (the reference temperature), β is efficiency temperature coefficient and T_{sc} is actual temperature. (β) value is considered as 0.45% [22]. Here the results were displayed for PVWDWBW module only because this module provides a reduction in temperature of PV panel as compared with PV only. (Figure 11) indicate effect of the cooling on PV module electrical efficiency from 11 AM to 14 PM because cooling in back wick start at 10:45 AM. As can be seen from Figure, the PVWDWBW efficiency is larger than the PV only module, mostly at the noon period. In addition, the efficiency variation for the PVWDWBW is smaller than efficiency variation for the PV only as indicated by comparison between time 11:00 and 13:00 and between two curves. Consequently, production of PVWDWBW electricity is more steady and dependable, and this augments the PV module performance in terms of power dependability and availability. The improvement percentage of electrical efficiency relative to evaporative cooling is shown in (Figure 12). Percentage of improvement can be found by using following equation [15]:

$$\text{Improvement\%} = \frac{\eta_{PVWDWBW} - \eta_{PVonly}}{\eta_{PVonly}} \times 100 \dots (24)$$

(Figure 12) shows the leaped improvement at the start of cooling operation. From this figure, the efficiency of employed setup in the present study is clear to lower panel temperature. The maximum profit of electric efficiency is 2% approximately on almost all period of experiments.

10. Evaluation of Cost of Productivity

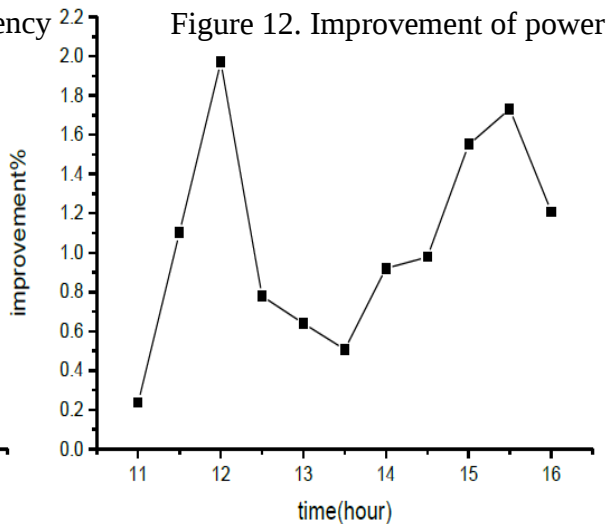
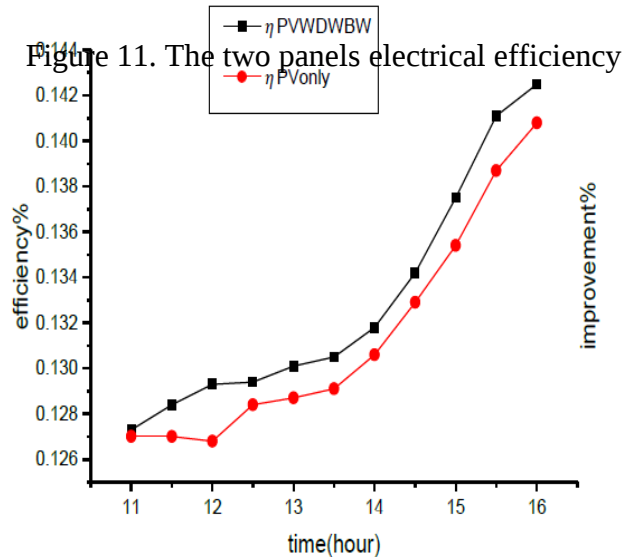
The primary source of energy used to operate the solar still is solar energy. Its energy input cost is zero is the most important value it provides (solar energy). Installation, maintenance and operation costs are primarily involved in the overall cost of solar stills. The economic analysis is described as follows [23]. The fixed cost of the conventional solar still CSS (1 m²) is around F=103 \$. Assume the variable costs V equal to 0.3 F per year and the total costs is C, where C = F + V and 10 years for the expected still life, then C = 103 + 0.3 × 103 × 10 = 412 \$ where the minimum average daily productivity can be calculated from the study of different experimental data, and it is estimated that 2.5 l/day. The sun rises along the year in Iraq therefore it is assuming that the still operates 340 days in the year. The total yielding during the still life is = 2.5 × 10 × 340 = 8500 l. The distilled litter costing from the conventional still is = 412 / 8500 = 0.048 \$ [23]. It is assumed that PVWD and PVWDWBW operating as a simple solar still therefore the same procedures were applied for PVWD and PVWDWBW modules to calculate the cost of proposed modules. For PVWD module the total fixed cost includes the cost of the PV panel, porous piece, plastic pipes, glass cover and some simple parts and can be evaluated to be approximately 67 USD (table 3). Assume the minimum average daily yielding as 0.302 l/day and a fixed cost is about F=67 \$ and for area of (1 m²) for the same expected life and operating days in year. Then the cost of distilled litter from PVWD module is = 0.261 \$ as shown in (table 4).

Table 3. Cost of components of PVWD module

Type of component	Cost (\$)
PV panel	52
Back glass cover	1.5
wick	1.5
Axillaries parts	12

Table 4. Type and the total cost

Type of Module	Area (m ²)	Productivity(l)	Total Costs(\$)	Cost of Distilled Litter(\$)
Conventional Solar Still CSS[23]	1	2.5	412	0.048
Present module PVWD	1	0.302	268	0.261



11. Conclusion

Hybrid photovoltaic thermal system is a one integrated system which can provide thermal and electrical energies. A hybrid PV modules was constructed and studied in this work by developing and adding a simple passive system evaporating cooling includes structures of cotton wick, this investigation is performed under factual environment conditions of Najaf city at Iraq middle area. The main study objectives are (i) obtaining distilled water from simple and very cheapness method as compared with conventional solar still (ii) lower the module temperatures (iii) to enhance output power from modules i.e, production of electricity and increasing efficiency. The conclusions below are drawn by this work:

- 1- The temperature of PV module back surface without cooling is greater than the ambient temperature during the day with a max. temperature of 60 °C. The power generation is negatively affected by higher panel temperature.
- 2- Modified PV modules produce both pure water , electrical energy and hot water for domestic using at the same time PV cooling will produce.
- 3- Supplying back cotton wick cooling reduces the PV back surface panel temperature from 60 °C to about 52 °C. This is equivalent to approximately 12% panel temperature reduction due to the prevalent moist condition at the module back side because of cotton wick wetness as a result from capillary action of wick structure.
- 4- Utilizing of a back wick structure caused a maximum module daily yield of 442 ml/day for PVWDWBW while maximum yielding for PVWD was 357 ml/day.
- 5- The PV module performance is fundamentally dependent to the availability of solar radiation.
- 6- A significant effectiveness in productivity and reduction in PV panel temperature appeared with a mass flow rate of $m_{inw} = 10 \text{ ml/min}$, $m_{inbw} = 66.6 \text{ ml/min}$.

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Nomenclature

Aarea, (m²)

a accuracy of the measuring tools

I solar radiation on inclined surface, (W/m²)

m_{ew-bg} mass flow rate of evaporated water from wick, (kg/s).

m_{inw} mass flow rate of inlet water to wick, (kg/s).

m_{inbw} mass flow rate of inlet water to back wick, (kg/s).

m_{ouw} mass flow rate of water out from wick, (kg/s).

m_{oubw} mass flow rate of water out from back wick, (kg/s).

t time(s)

H_{vap} vaporization of latent heat of, (KJ/kg).

$h_{cfg-amb}$ coefficient of convection heat transfer between front glass layer and ambient, (W/m².K).

h_{cw-bg} coefficient of convection heat transfer between wick and back glass cover, (W/m².K).

$h_{cbw-amb}$ coefficient of convection heat transfer between back wick layer and ambient, (W/m².K).

$h_{cbg-amb}$ coefficient of convection heat transfer between back glass cover and ambient, (W/m². K)
 $h_{cofg-sc}$ coefficient of conduction heat transfer between front glass and solar cell layer, (W/m². K).
 h_{rw-bg} coefficient of radiation heat transfer between wick layer and back glass cover, (W/m². K).
 h_{rfg-s} coefficient of radiation heat transfer between front glass layer and sky, (W/m². K).
 C_i specific heat capacity of i component, (J/kg· K)
 Q_e useful electric power, (W)
 Q_{evw-bg} heat of evaporation of water between wick and back glass cover, (W)
 $Q_{evbw-amb}$ heat of evaporation of water between back wick and ambient, (W)
 $Q_{cfg-amb}$ heat of convection between front glass layer and ambient (= $h_{cfg-amb}(T_{fg} - T_{amb})$) (W)
 Q_{cw-bg} heat of convection between wick layer and back glass cover (= $h_{cw-bg}(T_w - T_{bg})$) (W)
 $Q_{cbw-amb}$ heat of convection between back wick layer and ambient (= $h_{cbw-amb}(T_{bw} - T_{amb})$) (W)
 $Q_{cbg-amb}$ heat of convection between back glass cover and ambient (= $h_{cbg-amb}(T_{bg} - T_{amb})$) (W)
 $Q_{cofg-sc}$ heat of conduction between front glass layer and solar cell layer (= $h_{cofg-sc}(T_{fg} - T_{sc})$) (W)
 Q_{csc-t} heat of conduction between solar cell layer and tedlar layer (= $h_{csc-t}(T_{sc} - T_t)$) (W)
 Q_{rfg-s} heat of radiation between front glass layer and sky (= $h_{cfg-s}(T_{fg} - T_s)$) (W)
 Q_{rw-bg} heat of radiation between wick layer and back glass cover (= $h_{cw-bg}(T_w - T_{bg})$) (W).
 Q_{ouw} heat carried by water coming out of the wick, (W).
 Q_{oubw} heat carried by water coming out of the back wick, (W).
 T temperature of a component i (°C)
 m_i mass of i component (kg)
 L length of flow channel (m)
 K thermal conductivity (W m⁻¹ K⁻¹)
 u standard uncertainty

Subscripts

PVWD photo Voltic with desalination model
 PVWDWBW photo Voltic with desalination with back wick model
 CrSS corrugated solar still
 CSS conventional solar still
 BSWF black steel wool fibers
 FAC forced convection air cooling
 PV-T photovoltaic/thermal
 PV photovoltaic
 sc solar cell
 fg PV front glass cover
 bg back glass cover
 in, w inlet of water to the wick
 in, bw inlet of water to the back wick
 ou, bw outlet of water from the back wick
 ou, w outlet of water from the wick
 t tedlar
 c convection
 co conduction
 r radiative
 ev evaporation
 w wick, water
 s sky
 amb ambient

Greek Symbols

η electrical efficiency
 ζd daily thermal efficiency
 τ transmissivity
 α absorptivity
 ε emissivity
 β packing factor, temperature coefficient (K⁻¹)