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Solar Still Productivity Improvement Techniques and Recent Advancements: Review Study

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Abstract. The growing demand for freshwater is a challenging task facing human society due to the rapid rise of the global population. Solar distillation emerged as an economical, environmentally friendly practical technology to produce freshwater. Solar still is a proven technology to produce clean water and removing dissolved and solid impurities as well as chemical hazardous, organic bacteria, and non-organic contaminants. Rural and remote regions that suffer from impure water can beneficiate this technique. However, the daily productivity of single slope solar still SSSS is questionable. Hence, several researchers focused on enhancing the productivity and efficiency of SSSS through adopting a wide range of modifications. This review reports various modification techniques that have been investigated to improve SSSS efficiency and clean water productivity. It mainly considered modifying the absorption plate, thermal energy storage, utilization of reflectors, adopting nanotechnology, integrated condenser, cover cooling, Humidification-dehumidification HDH, and Basin water preheating technique.

Keywords: Solar Sill; Absorber Plate; Heat Storage; Nanotechnology; Preheating; Glass Cooling

Nomenclature

$A_{b,ss}$	Area of the basin, m2
$A_{g,ss}$	Area of the glass cover, m2
T_{amb}	Ambient temperature, K
$T_{b,ss}$	The temperature of the basin, K
$T_{g,ss}$	The temperature of the glass cover, K
T_{sky}	The temperature of the sky, K
T_w	The temperature of the water, K
P	Pressure, N/m^2
M_w	Mass of distillate produced, kg
h_{fg}	Latent heat, KJ/Kg
ε	Emissivity
σ	Stefan-Boltzmann's constant, W/m^2. K^4
V_w	Wind speed, m/s
k_{ins}	Thermal conductivity for Insulation, W/m.K
Q_c	Convective heat transfer, W
Q_r	radiation Heat transfer, W
Q_e	Evaporative heat transfer, W

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h_{c,w_g}	Convective heat transfer coefficient between water and glass cover, W/m^2.K
h_{r,w_g}	Radiative heat transfer coefficient between water and glass cover, W/m^2.K
h_{e,w_g}	Evaporative heat transfer coefficient from the water surface to glass cover, W/m^2.K
h_{c,g_amb}	Convective heat transfer coefficient between glass cover and Ambient, W/m^2.K
h_{r,g_amb}	Radiative heat transfer coefficient between glass cover and ambient, W/m^2.K

1. INTRODUCTION

Water covers over three-quarters of the earth's surface, despite this the majority of it is considered to be undrinkable water since it is oceans salty water. The remained water available in rivers, lakes, ice, and groundwater is not fully potable since various human activities contaminating it day by day. Polluted water has a significant impact not only on human lives, but it influences animals and the quantity and quality of agricultural products. World health organization statistics highlighted 2 billion people around the globe relays on contaminated water sources and over 785 million people lack access to drinking water [1]. The percentage of the global population having access to clean water services is graphically represented in figure (1)[2]. Drinking contaminated water can cause several serious diseases such as cholera, dysentery, polio, and typhoid [1][3]. The most affected regime among the population is children under 5 years, as they might be exposed to water-borne diseases or limited learning ability for the rest of their lives[4]. Hence, nations have to adopt massive desalination plants to cover the needs of their population of potable water. It can be said that desalination plants have a severe impact on the environment and energy-intensive systems [5]. Several developing countries lack proper desalination plants or proper water distribution systems. Hence, individuals would have to own portable water purification systems such as reverse osmosis sort of systems. Despite that, systems of this type are expensive for many people, they need frequent maintenance, which will establish extra charge on the families[6][7]. Recently, the increasing scarcity of freshwater due to drought and energy crises around the world becomes a global crisis especially in the rural and arid areas such as the regions of the Middle East and North Africa[8].

Figure 1. The proportion of Population Using Safely Managed Drinking Water Services, 2017 (%)[2]

Hence, water desalination is a challenging task regarding the growing population, energy crises, and climate change. A sustainable desalination system/device would be of high utility to assist in mitigating these effects. Renewable energy sources can be exploited for potable water production[9]. One such source is solar energy which is an abundant, environmentally friendly, and economical energy source. Solar distillation is recognized as a potential brackish water desalination methodology relays on solar energy. The system harnessing solar energy to produce fresh water is commonly known as Solar still (SS)[10]. Hanson et al. 2004 argued that solar still can separate organic bacteria, non-volatile contaminants, and inorganic, bacteriological from the brackish water[11].

Based on the operation mode of the still, solar still can be categorized into two main groups Passive and active. Passive solar still refers to the in which thermal treatment and distillation procedures take place within the still enclose[12], whereas active sort of Still contains an extra thermal energy source to increase basin water temperature or enhancing evaporation/condensation rate. For instance, a still could be integrated with a solar pond, external condenser, solar collector, or waste heat of a power plant, or industries[13]. The main disadvantage of the Active solar still system is the relevant high cost of fabrication, although it can produce more quantity of clean water in contrast to passive still. Thus, the solar desalination technique can be a viable approach to produce potable water. Nonetheless, the Distillation quality and productivity is a major concern for scientists and researchers. Recently, researchers showed significant technological advancements in terms of productivity and efficiency enhancement of SS. Other researchers reported sterilization effects if water interacted with radiation can through the termination of microorganisms as a result of the applied heat to the contaminated water [14], [15].

The basic design of a solar still (SS) is recently known as a conventional solar Still (CSS) which is a rectangular plane sheet at the bottom commonly made of galvanized steel. A transparent cover with a slop is placed on top of the rectangular sheet commonly made of highly transmittance glass. The basin of the sill filled with shallow brine water. The radiation penetrant through a glass cover that partially interacted with the shallow water, while most of the radiation is absorbed by the rectangular bottom plane. The absorbed energy radiated and interacted with basin water, and then water evaporated. The vapor-air mixture transfers to the glass cover by convection current. Since that, the glass surface is cooler than Vapor, then vapor condensate, and freshwater produced. The generated water flows down as droplets to side collectors at the lower end of the slope cover [16]. A general layout of CSS with heat transfer processes can be seen in Figure (2). The physics of heat transfer processes inside and outside SS are important to understand to obtain higher efficiency by reducing thermal losses and enhance thermal energy restrictions. The processes take place between the inner glass surface and water referred to as internal heat transfer, while thermal loses through sides and bottom represents external heat transfer. Table 1. Highlights the main mathematical formulas that can theoretically predict the thermal behavior of SS.

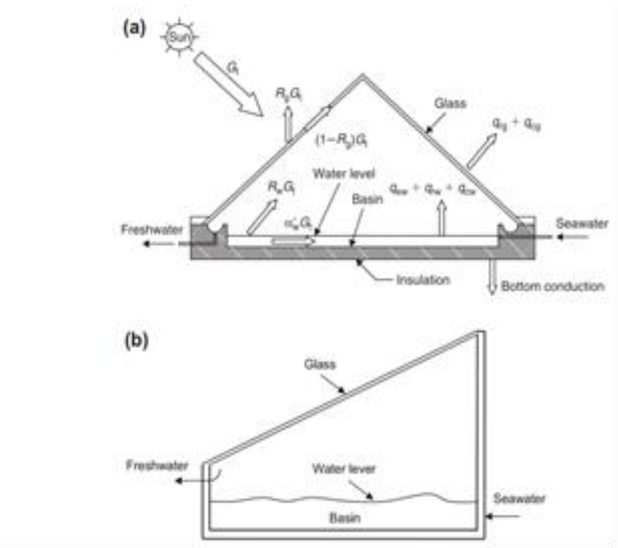

Figure 2. A General Layout of CSS and it's Basic Operation [16]
a) Double Slope Solar Still
b) Single Slope Solar Still

Table 1. Mathematical Representation of Heat Transfer Procedures of Solar Still [16–18]

Heat transfer	Equation	Heat transfer coefficients
Internal heat transfers Convective heat transfer between the bottom surface of the glass cover .and the basin water surface.	$Q_{c,w\_g}=h_{c,w\_g}A_{b,ss}(T_{w,ss}-T_{g,ss})$	$h_{c,w-g} = 0.884 * \left[(T_{w,ss}-T_{g,ss}) + \frac{(P_{w,ss}-P_{g,ss})(T_{w,ss}+273.15)}{268.9 * 10^3 - P_{w,ss}}\right]^{\frac{1}{3}}$
Evaporative heat transfer between the glass cover and the surface of the water.	$Q_{e,w-g} = h_{e,w-g}A_{b,ss}(T_{w,ss}-T_{g,ss})$	$h_{e,w-g} = 16.273 * 10^{-3} h_{c,w-g}\frac{P_{w,ss}-P_{g,ss}}{T_{w,ss}-T_{g,ss}}$ **The hourly distillate per unit basin area is obtained as, Mw $=\frac{h_{e,w-g}(T_{w,ss}-T_{g,ss})\times 3600}{h_{fg}}$
Heat transfer from the water surface to the glass cover by radiation	$Q_{r,w-g} = h_{r,w-g}A_{b,ss}(T_{w,ss}-T_{g,ss})$	$h_{r,w-g} = \varepsilon_{av,w-g}\sigma[(T_{w,ss}+273)^2+(T_{g,ss}+273)^2]$
External heat transfers The radiative and convective loss to Atmosphere through the glass cover.	$Q_{g-amb} = h_{r,g-amb}A_{g,ss}(T_{g,ss} - T_{amb})$ $Q_{c,g-amb} = h_{c,g-amb}A_{g,ss}(T_{g,ss} - T_{amb})$	Top loss coefficients, $h_{r,g-amb} = \frac{\varepsilon_g\sigma\left[(T_{g,ss}+273)^4-(T_{sky}+273)^4\right]}{(T_{g,ss}-T_{sky})}$ $h_{c,g-amb} = 2.8 + 3.0v_w if\ wind\ speed\ v_w \leq 5m/_s, and$ $h_{c,g-amb} = 6.15{v_w}^{0.8} if\ v_w is\ greater\ than\ 5m/_s$
Heat transfer from the basin water through the side and bottom insulations to the surrounding atmosphere.	$Q_{b-amb} = h_{b-amb}A_{b,ss}(T_{b,ss} - T_{amb})$	Heat loss coefficient from basin liner to the atmosphere, $h_{b-amb} = \left[\left(\frac{L_{ins}}{k_{ins}}\right)+\left(\frac{1}{h_{b-amb}}\right)\right]^{-1}, h_{s-amb} = h_{b-amb}\times\left(\frac{A_s}{A_b}\right)$

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		If the side area of the still (A_s)is very small compared to the basin area($A_{b,ss}$) then the side heat loss coefficient can be neglected

The present work reviews recent enhancement approaches incorporated SS focusing on productivity and efficiency improvements. The article covers a wide range of proposed techniques including preheating, incorporated reflectors, humidification-dehumidification (HDH), thermal storage medium, Nanoparticles, etc. This review can be a valuable source for researchers interested in technological advancements regarding solar distillation.

2. SOLAR STILL DEVELOPMENTS TECHNIQUES

Researchers and scientists from around the globe have made tremendous efforts to improve the performance of Conventional Solar Still (CSS). Their researches focused on promoting either the internal heat transfer coefficient or reducing energy losses. Various techniques active and passive have been adopted, such as external reflectors, preheating of saline water, external condenser, heat storage medium, etc. the following section will explore the productivity optimization techniques, which have been recently reported.

2.1. Absorber Plate Modifications

Numerous researchers have focused on developing the absorption plate of solar still. Generally, the penetrated radiation from the glass cover interacts with the absorption plate and raises its temperature, thus increase saline water temperature then evaporated. The evaporated water concentrates on the cooled inner side of the glass cover and condensation induced. The condensate water is directed with the slop of the glass as a result of gravity toward a collection channel beneath the glass [19]. To maximize the absorptivity of SS, black paint is to be added to the basin's inner surface. However, black paint is not adequate to boost significantly the productivity of CSS, hence absorber plate optimization would be of high interest.

Hansen and Murugavel 2017, demonstrated an attempted to improve SS productivity through testing various absorber plate geometries (Namely flat, grooved, and fin-shaped absorbers) [20]. The proposed absorber plate geometries are shown in figure (3). The use of such configurations increases the evaporation rate as a result of the increase in the interacted area between water and the absorber layer. The reported daily productivity was 5.2 L/d for a sill area of 1.3m^2, which represents an increase of 74.25% of a CSS. Similarly, the recorded efficiency was 34.1% higher than the efficiency of CSS. This improvement can be argued to increasing the interference area between saline water and absorber plater thus heat transfer. Panchal et al. 2020 examined the significance of adding inclined and vertical fins on the performance of single slope solar still[21]. This experiment runs for six months, where three modules have been examined. It has been noted that inclined fin integrated solar still has the best performance among other stills. The average recorded productivity was 2.375 L/m^2.day, 2.322 L/m^2.day, and 1.873 L/m^2.day for inclined fins solar still, vertical fins solar still, and CSS, respectively. Nevertheless, there is hardly any difference between the productivity of Solar still equipped with vertical or inclined fins.

Figure 3. Different Shapes of Absorber Plate [20]

2.2. Solar Still with Thermal Energy Storage

As an enhancement technique, several thermal storage mediums have been investigated across the globe to enhance the productivity of solar still. The main purpose of utilizing thermal storage material is to store energy during daylight and release it after sunset to improve the nocturnal evaporation. Thermal storage mediums can be classified into two main groups. The first group includes sensible heat storage materials such as Stones, Metal Scraps, Concrete, Sand, etc., while the second group comprises the latent heat storage kind of materials that mainly include phase change materials (PCM) for instance inorganic salts, polymers, paraffin wax, etc.[17].

Dumka et al 2019 explored the improbability of conventional solar still by utilizing 100 cotton bags filled with sand as a thermal storage medium [Modified Solar Still (MSS)][22]. They have distributed the bag uniformly in the basin in the vertical direction, as well as, altering water quantity in the basin as 30Kg and 40kg. Their investigation showed a noticeable improvement in the productivity of MSS in contrast to a conventional solar still. They have reported enhanced productivity of MSS by 30.99% and 28.56% as compared to CSS for basin water of 40Kg and 30Kg respectively. A schematic diagram of the MSS can be seen in figure (4). An enhanced nocturnal production has been recorded in solar still equipped with a layer of paraffin wax as a PCM underneath the basin. Saeed et al. 2019 reported a noticeable improvement in the productivity of PCM augmented single slope SS in contrast to a CSS[23]. Their experimental and theoretical studies showed that the rise of productivity relies on the utilized amount of PCM. The reported daily productivity of PCM-solar still was 5.6 L/m^2 and Conventional Solar 5 L/m^2. This is stated for an amount of 1 kg of PCM for a basin area of 1 m^2. Figure (5) shows the relation between increasing PCM amount and daily productivity. It can be said that PCMs have been widely used as thermal storage materials.

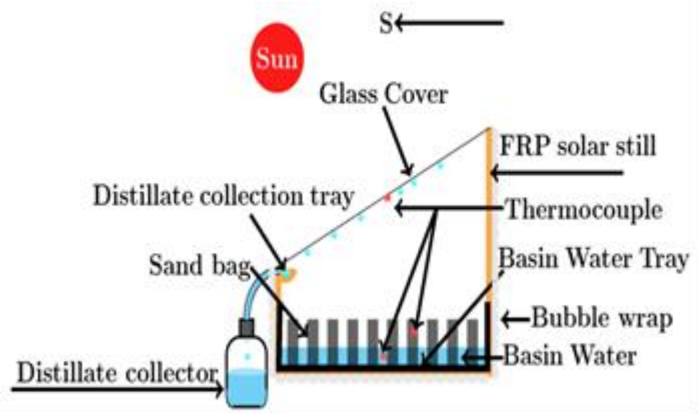

Figure 4. Schematic Representation of MSS. [22]

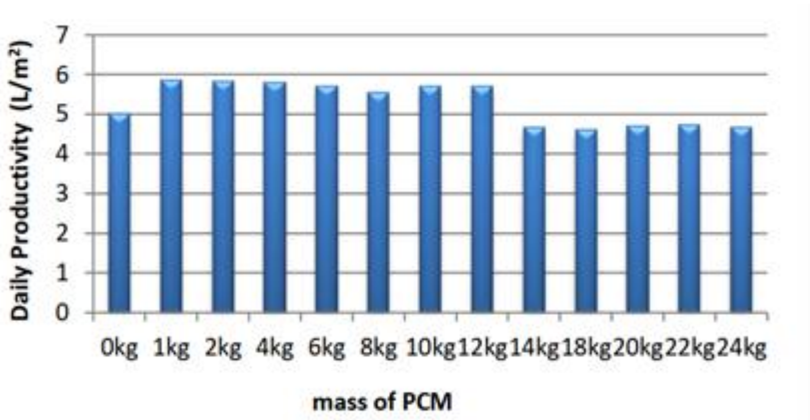

Figure 5. The Relation Between Increasing PCM Amount and Daily Productivity [23]

2.3. Nanoparticles in Solar Still

Nowadays, nanoparticles stand as one of the promising technologies that have been widely adopted in various research fields. Similarly, in the field of solar distillation, numerous researchers investigated the potentials of this technology. Saeed et al 2019 theoretically and experimentally explored the significance of mixing Aluminium Oxide (Al_2O_3) nanoparticles with paraffin wax (nano-PCM) to enhance the energy storage capacity of PCM[23]. They studied the effect of dispersion of Al_2O_3 as 3% of the total volume and altering masses of the PCM. It has been noted that the productivity of Nano-PCM solar still was 20% higher than in the conventional solar still. The maximum recorded productivity was 6 L/m^3.day, 5 L/m^3.day for solar still (augmented with Al_2O_3 and PCM) and CSS, respectively. Abdulla et. Al 2020 examined the influence of mixing copper oxide (CuO) nanoparticles with coating paint as well as (Nano-CuO) mixed with paraffin wax [24]. The surfaces of solar still coated with black paint- Nano-CuO mixture to improve the heat transfer properties. They have reported an improvement of 14% of the productivity of the coated solar still compared to traditional solar-still. However, their investigation has also studied adding CuO nanoparticles to paraffin wax as developed phase change material. Their investigation showed a significant improvement in the productivity Nano-CuO-PCM combination in contrast to conventional solar still. Whereas, the productivity was reported as 37% ahead of that of Conventional solar still. Sharshir et al. 2020 examined the spreading of Iron oxide (Fe3O4) nanoparticles and copper oxide (CuO) nanoparticles on the top surface of hanging cotton pads with various percentages between 25 g/m^3 to 300 g/m^3[25]. The cotton pads have threads that are immersed in the basin water; as a result of capillary property, the water arises toward the top surface where the evaporation will take place. Their studies reported a noticeable productivity improvement when dispersing metallic nanoparticles on the cotton pads.

The highest recorded productivity of Nano-CuO solar still type was 56.6% of that of a CSS, while Iron oxide augmented solar still productivity reported as 42.3% in contrast to the productivity of CSS. However, the productivity of solar still equipped with cotton pads without any metallic coating was recorded as 17% in contrast to CSS. This indicates that CuO nanoparticle coating has doubled the efficiency of cotton pads only type of solar still. Hence, Al_2O_3, CuO, Fe_3O_4 as nanoparticles have contributed to enhancing the storage of Solar Still with PCM.

2.4. Solar Still Integrated with Preheating System

It has been proven that the evaporation rate and eventually the production rate of solar still is directly proportional to the temperature of basin water. Several pieces of research illustrated the potentials of utilizing basin water preheating techniques. Deniz 2016 considered a flat plate solar collector as a preheating system assisting single slope solar still [26]. The general layout of the proposed system can be visualized in figure (6).

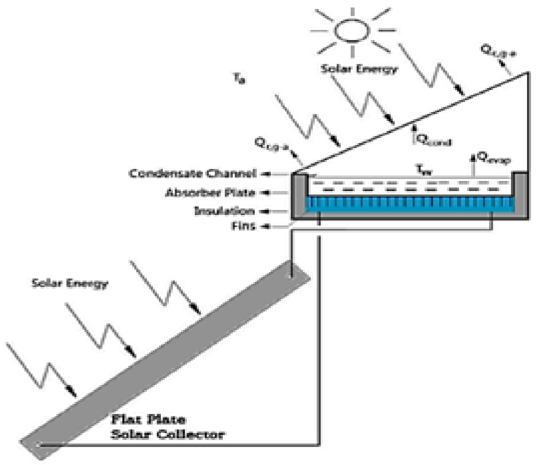

Figure 6. Schematic Diagram of Flat Plate Solar Collector as a Preheating System Assisting Single Slope Solar Still [26]

Deniz's experimental and theoretical analysis reported a noticeable increase in the daily energy efficiency of 48% for solar still with preheater in contrast to a CSS. The reported exergy efficiency was as low as 2.76%. Additionally, the designed system produced about 500 ml of potable water after sunset as a result of the stored energy by the flat plate. Bani-Hani et al 2017 reported an improvement of 10% when integrating a solar collector as an auxiliary preheating unit[27].

Al-Harahsheh et al. 2018 examined adding a built-in heat exchanger to increase the water temperature in the basin [28]. The offered heat exchanger circulates hot water that has been thermally treated by a solar collector. Their investigation showed a linear proportion between the circulation flow rate and evaporation rate, in other words, the productivity increases with the increase of the flow rate. Although, Al-Harahsheh et al augmented the design still with PCM and glass cover cooling techniques to boost the condensation rate at the lower surface of the glass; the optimum productivity was reported as 4.3 L/m^2.day, where around 40% of the water was desalinated after sunset.

Kabeel et al. 2019 proposed three different configurations of single slope solar still [29]. The three modules were one solar dish with an SS module, two solar dishes with a solar still, and two parabolic dishes besides a heat exchanger powered by a 1000w PV array. Figure 7 provides the design of the investigated system. The dish modules are used to enhance the evaporation rate by spraying basin water that has been circulated to cone tanks. Besides, varying water depth showed a noticeable effect on the productivity rate. The investigation showed that daily productivity when having a basin water level of 1cm was 8.8 Kg/m2.day and 13.63 Kg/m2.day in case of one dish and two dishes, respectively, with the aid of an incorporated heat exchanger. Similarly, having a water level of 2 cm the recorded productivity was 5.45 and 7.69 Kg/m2.day for one and two dishes, respectively. This means using two dishes can boost the productivity of about 35% in contrast to a single parabolic dish. It is clear from the graph shown in figure (8) that the productivity of the system integration of two dishes was widely boosted compared to the productivity of CSS.

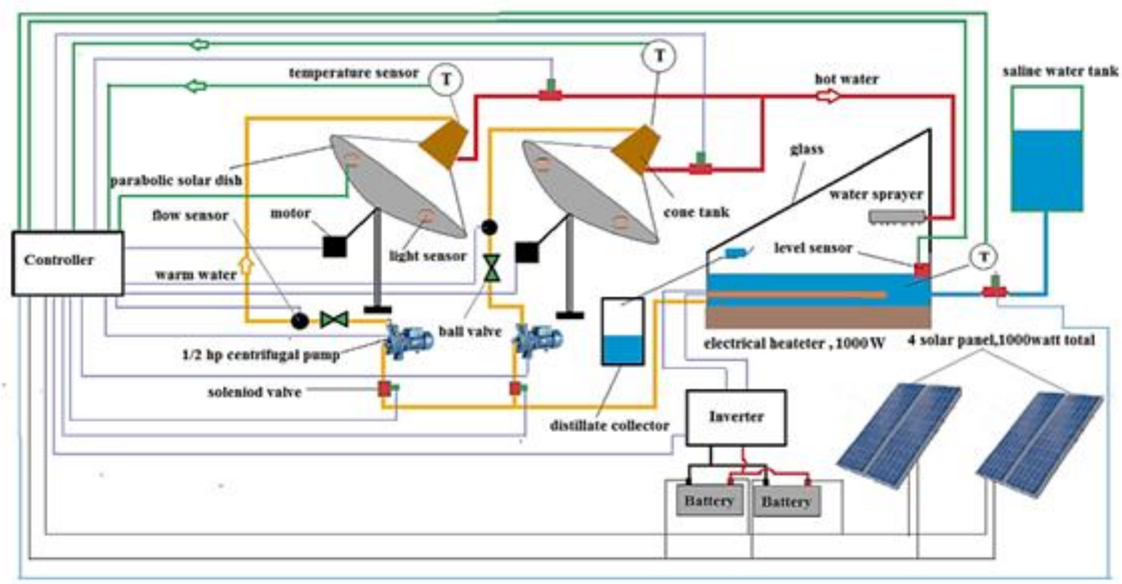

Figure 7. Schematic Diagram for an Integration of Two Parabolic Dishes and Heat Exchanger PV - System with Single SS [29]

Hassan et al. (2020) investigated the influence of utilizing parabolic trough solar collector (PTC) on the performance of conventional solar still (CSS)[30]. Their studies demonstrated a thorough comparison of six different types of optimized conventional solar still modules. The productivity of a CSS was the benchmark to decide the best-enhanced module. They utilized preheated oil by PTC and circulated through a mesh of pipes located in the basin to increase the saline water temperature. However, their studies showed that conventional solar still coupled with parabolic trough solar collector has great potentials. The best performance was of CSS+ PTC when integrated with the sand layer (SD) as a thermal storage medium in the basin (CSS + SD + PTC). They reported daily productivity of (CSS + SD + PTC) as 8.77 Kg/m2.day, while the productivity of CSS is 3.96 kg/m2.day during summer. Similarly, winter daily productivity of (CSS + SD + PTC) and CSS was recorded as 4.34 kg/m2.day and 2.18 kg/m2.day, respectively. This suggest a posting technique where the productivity of the enhanced solar still (CSS + SD + PTC) is about double of the conventional solar still in both seasons.

2.5. Glass Cover Cooling

Solar still continually loses a low amount of heat-induced by evaporation through the glass cover. Although these radiation and convection losses are of low rate, they will increase the temperature of the glass cover reducing the temperature difference (∆T) between the external surface of the cover and the inside temperature of the still [31]. Morad et al. 2015 experiment revealed a noticeable temperature difference between the glass cover surface and the evaporation layer when applying a surface cooling technique[32]. They installed two solar still modules, one type was a conventional type and the other was SS integrated with Flat plate solar collector and glass cover cooling. The reported productivity was 10.06 l/m2.day and 7.81 l/m2.day for Enhanced solar still and CSS, respectively.

Sharshir et al. 2017 explored the significance of applying cooling water film to the glass cover[33]. Their experiment involved examining the influence of varying the flow rate of the film. Besides adding different concentrations of graphite and copper oxide micro-flakes to be mixed with the basin water as wick material. The glass cover flow rates ranged from 1 to 12 L/h, while the concentration of the micro-flakes was ranged from 0.125% to 2%. The acquired results showed an efficiency enhancement of 14.91% for solar still having copper oxide and graphite micro-flakes, respectively, without cooling compared to CSS. Based on the demonstrated study using those materials alone showed a noticeable increase, while adopting the glass cover cooling technique boosted the production efficiency of about an extra 4% with or without wick materials.

The productivity rate of a tubular solar still (TSS) stimulated with water-spray cooling as a cover cooling technique [34]. The proposed TSS is presented in Figure (8). The component of the system was a black painted basin to improve evaporation rate and enhance radiation absorptivity surrounded by a transparent solar tube. The author altered the basin water level (0.5, 1, 2, and 3 cm) and water-cooling flow rate (1, 2, 3, and 4 L/h) to gain optimal performance. The results exhibited that the productivity of TSS without cooling technique was 3 L/m2.day and 4.5 L/m2.day for water levels of 3, 0.5 cm, respectively. However, the experimental work also showed that having spray cooling technique increased the daily productivity was recorded as 5.85 L/m2.day for the lowest basin water level. This highlights an efficiency improvement of about 32.6% of the proposed TSS.

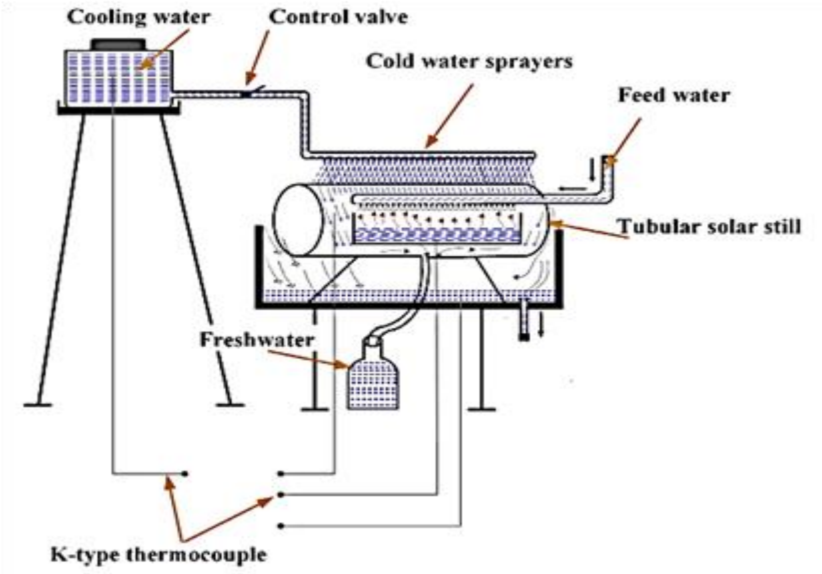

Figure 8. Schematic Diagram of Tubular Solar Still [34]

Nazari et al 2019 tested single slope solar still equipped with copper(I) oxide Cu_2O nanofluid in the basin and integrated with glass cover thermoelectric cooling channel[35]. The maximum productivity improvement of 81% noted of SS equipped with Cu_2O nanoparticles and the external thermoelectric cooling channel in contrast to a CSS. While, energy and exergy efficiencies were up to 80.6 and 112.5%, respectively, of that of a CSS.

Shoeibi et al 2020 explored the influence of thermoelectric heating and cooling on the performance of double slope solar still[36]. The thermoelectric heating and cooling system are shown in Figure (9). The thermoelectric system is utilized to preheat basin water through a helical exchanger, simultaneously, cooling the glass cover by water stream passing over it. The obtained result revealed an improvement of 2.32 times the productivity of a CSS. The system efficiency noted as 79.4% efficient. Nevertheless, thermoelectric devices are considered to of high relative cost[17].

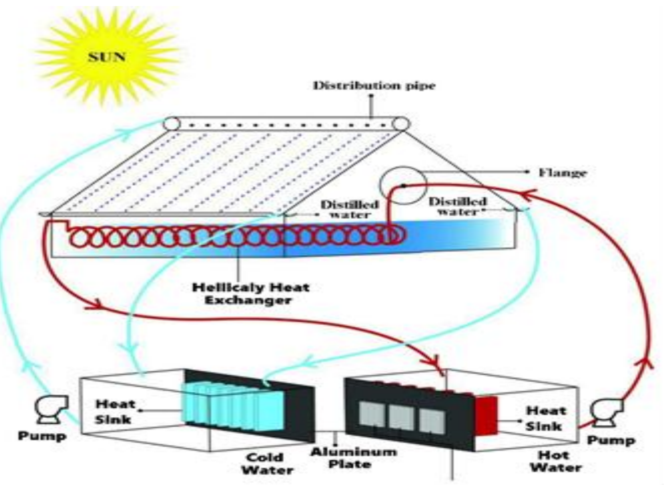

Figure 9. Thermoelectric Heater and Cooler Integrated with SS Module [36]

2.6. Solar Still Integrated with Condenser

Several researchers proposed and evaluated various improvements to enhance the performance of SSs. One such approach is to integrate internal or external condensing auxiliary equipment. This section will discuss the status of various condensation techniques. Fath and Elsherbiny, 1993 showed the tendency of hot vapor in a cavity, where it tends to move toward the coldest surface and condenses on that surface as a result of natural circulation, purging, or diffusion[37]. Kumar et al. 2016 modified single basin single slope SS by adding an external condenser and an agitating rotor shaft coupled extraction fan[38]. The fan used to force the vapor to move from the still toward the condenser. The agitation effects help to increase the contact area between air and water and to disturb the boundary layer of basin water. The results showed an enhancement in the condensation rate and the circulation of vapor. Where the recorded productivity improved by 39.49% in contrast to a CSS as can be seen in Figure (10) that compares the hourly productivity of the modified SS and CSS.

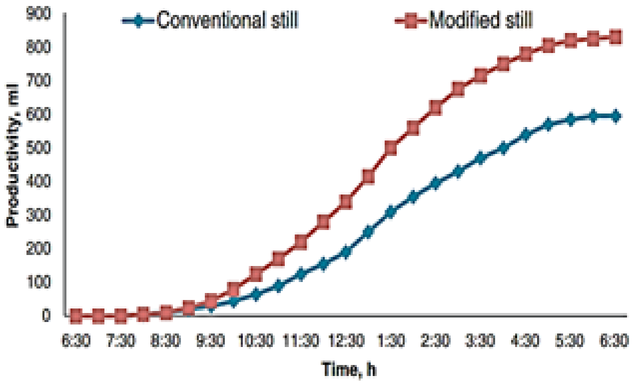

Figure 80. Comparison of Productivity of CSS and Modified SS Proposed by Kumar et al [38]

Rabhi et al 2017 designed a single slope SS augmented with a pin-fins absorber and external condenser [39]. Their investigation involved the examination of each of the proposed techniques as a separate enhancement to test the performance of the still, Figure (11) shows the layout of the designed system. The vapor evacuation improved by adding an airflow source. The experimental results determined that the daily productivity of SS equipped with a condenser was 3.146 l/m2.day, while 2.38 l/m2.day for CSS. Whereas, the addition of pin fins absorbing layer besides the external condenser slightly improved the production rate. The recorder productivity in the latter case was 3.492 and 2.46 l/m2.day for the enhanced SS and CSS, respectively.

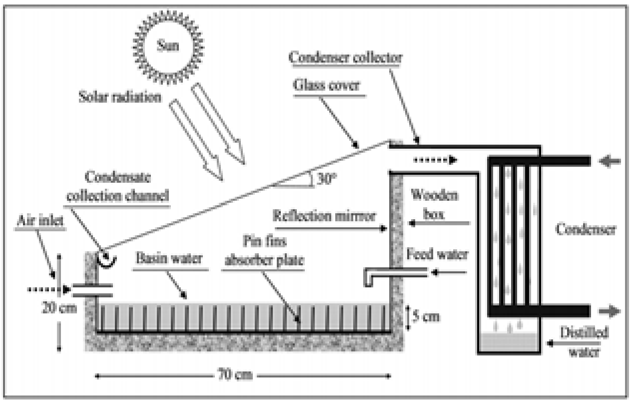

Figure 91. The Layout of a Single Slope SS Augmented with a Pin-Fins Absorber and External Condenser [39]

The radiative cooling technique has been reported as a potential condensation process[40]. The proposed design included 4 main parts evaporation tank, integrated collector, air-condenser, and PCM condenser as presented in Figure (12). The PCM-condenser contained 6 stainless steel cylinders filled with PCM. During the daytime, PCM absorbs the thermal energy of vapor pass through its surrounding. While night time the PCM-condense will lose the gained thermal energy because of radiative cooling induced by the flow of the water through a set of pipes interacting with the six cylinders. The system efficiency was observed as 30.7%, whereas the efficiency of the non-radiative cooling system was 23.9%. The productivity rate was noted as 2.805 Kg/m2day and 2.139 Kg/m2day for radiative cooled and without radiative cooling, respectively. However, the author reported that radiative cooling has a limited cooling capacity, which highlighted a need for using the air-condenser.

The significance of adopting an external passive condenser was evaluated [41]. The proposed design included stepped solar still integrated with an external condenser consisting of 15 aluminium horizontal tubes and an aluminum air duct. The tubes were connected to the top end of the still from one edge, while the other end of the tubes a distillate water collector. The result illustrated an overall efficiency increase of 10.6% and 12.2% during summer and winter, respectively, for solar still equipped with the external collector.

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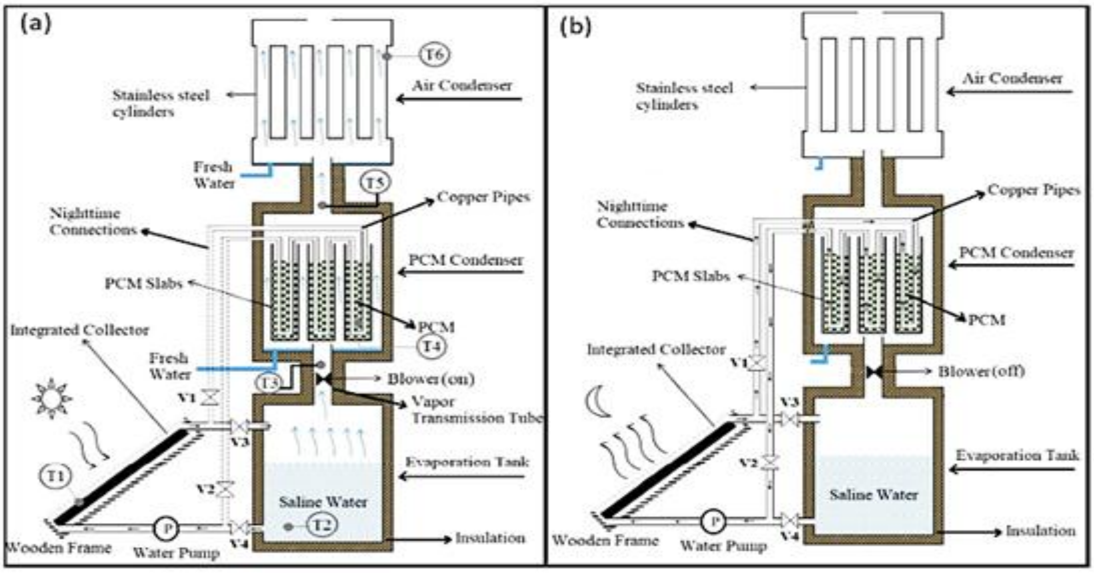

Figure 102. The Schematic of Radiative Cooling Experimental Setup [40]
(a) day-time
(b) Night-time

2.7. Solar Still Integrated with Humidification – Dehumidification (HDH) System

It can be said that the adoption of HDH provides several advantages including simplicity, conservative insulation, economic design, and the exploitation of sustainable power sources [42]. Tabrizi et al 2016 examined the integration of cascade SS with the HDH system[43]. They considered two main parameters in their experiments to investigate the daily production rate, which was air flow rates and water flow rate. An air blower is used to generate and control a closed-loop airflow. The utilization of the HDH system improved the daily productivity of SS by about 133% higher than the productivity of cascade solar still without the HDH system. Mahmoud et al 2018 proposed a novel solar sill coupled with two steps HDH system, two thermally cooled solar panels, and a solar collector [44]. They theoretically and experimentally examined the proposed array. The proposed model was examined under various operation conditions including solar concentration ratio CR, air-mass flow rate, water depth. Based on the result air mass flow rate is inversely proportional to productivity. The optimal operation conditions reported as that the water level = 0.15 cm, CR =3 and coupled with PV/T and HDH system. Based on the result the water level is relatively high, which has been argued to the relatively high temperature that could relatively damage the still. The maximum operating temperature for a solar still was reported as 85 C, any increase other than this would induce potential damage to the still[45].

The major disadvantage of HDH systems is their low thermal capabilities. Elzayed et al. 2020 conducted a theoretical investigation to design a thermodynamic-balance system with and without extraction[46]. The performance of Zero-single and double-extraction systems were evaluated based on the temperature-enthalpy model with regards to a minimum and maximum basin water temperatures and enthalpy pinch of the system. Schematic diagrams of the proposed models are provided in figure (13). The size of the HDH system was determined after investigating the details of the proposed design regarding various operation conditions.

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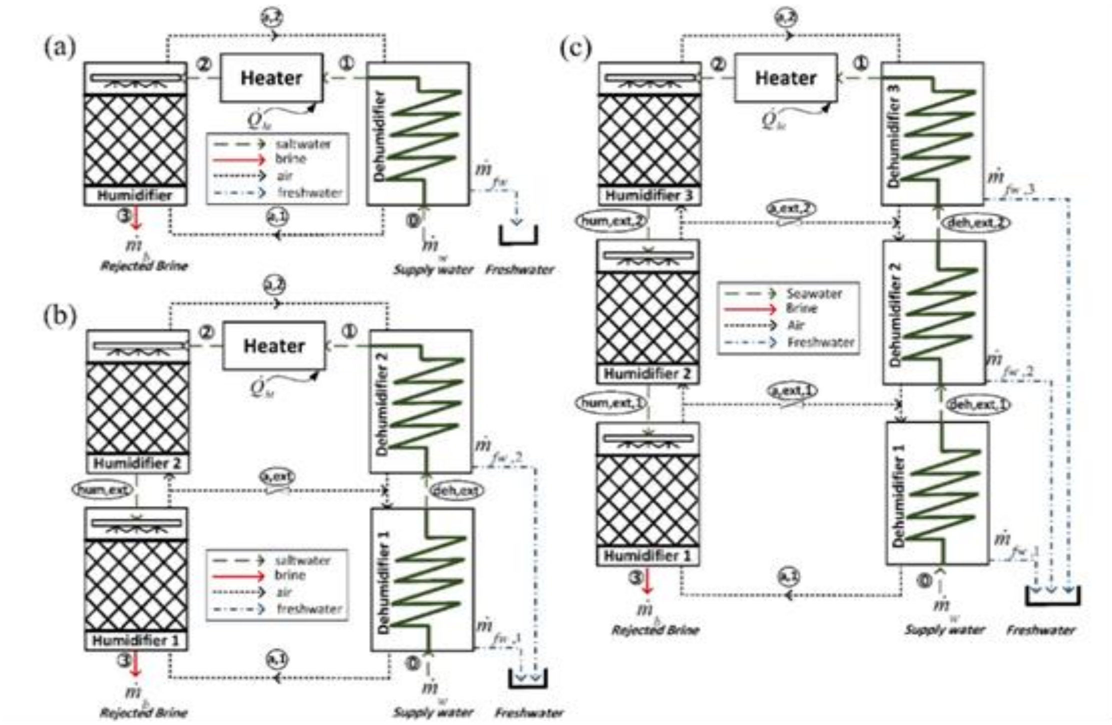

Figure 113. Schematic Diagram of a Thermodynamic-Balance System [46]
(a) Zero-Extraction
(b) Single-Extraction
(c) Double-Extraction

This investigation indicated that increasing the size of the used HDH will improve the performance of the system. The final results revealed an improvement of the output ratio 91% and 112% of single-, and double-extraction systems, respectively, higher than that with zero extraction.

2.8. Reflectors

Internal reflectors can be considered as potential optimization techniques to be integrated with solar distillation. Internal reflection surfaces coupled with corrugated SS (CrSS) have been investigated [47]. The author considered double-layer wick material and also internal reflectors. They also inspected the influence of varying basin water depth. The results displayed a noticeable enhancement in the average productivity of SS with reflectors and wick material. The daily productivity of CrSS was 145% higher than that of CSS with a basin water level of 1cm. Estahbanati et al. 2016 conducted an experimental and theoretical investigation to examine the influence of using internal reflectors (IR) on single slope solar still [48]. The author proposed a mathematical model that takes into consideration the influence of the sidewalls of SS on the received amount of radiation. The gained results revealed an efficiency improvement of 18% when using IR on the front wall. However, the annual efficiency increased by 22% once installing IR on the back wall. Potable water production could be increased more if IR is to be installed on all walls compared to CSS. The recorded productivity enhancement was reported as 65%, 22%, and 34% for Winter Summer and the entire year.

The utilization of Fresnel lens as an improvement technique has been investigated. Sriram et al. 2019 studied the significance of integrating Fresnel lens with double slope solar still to purify Industrial wastewater [49]. Gang et al. 2019 presented a multi-effect tubular still, where thermal interaction relays on the linear Fresnel reflector field (LFR) [50]. The scientific principle behind the proposed design is concentrating direct heating multi-effect tubular falling film distillation. However, the investigation results disclosed a production capacity of 68 Kg/day. Despite the relatively high productivity incorporated with the relatively small area, direct heating can easily damage SS components.

Patel et al. 2020 showed an attempted to enhance the production rate of double slope solar still by coupling it with externally mounted reflectors[51]. A side view of the experimented system is presented in Figure (14). The author reported an optimized reflector orientation angle out of several experiments. The daily production rate was 4.58 l/m2.day and 3.32 l/m2.day during summer and winter, respectively.

Hence, average daily productivity can be enhanced with the aid of internal and external reflectors. Das et al 2020 argued a major disadvantage in adopting similar systems. Internal mirrors can enhance distillation, but they can easily spoil. Similarly, external reflector orientations needed to be adjusted most often regarding the sun location throughout the year to maximize the production capacity [17].

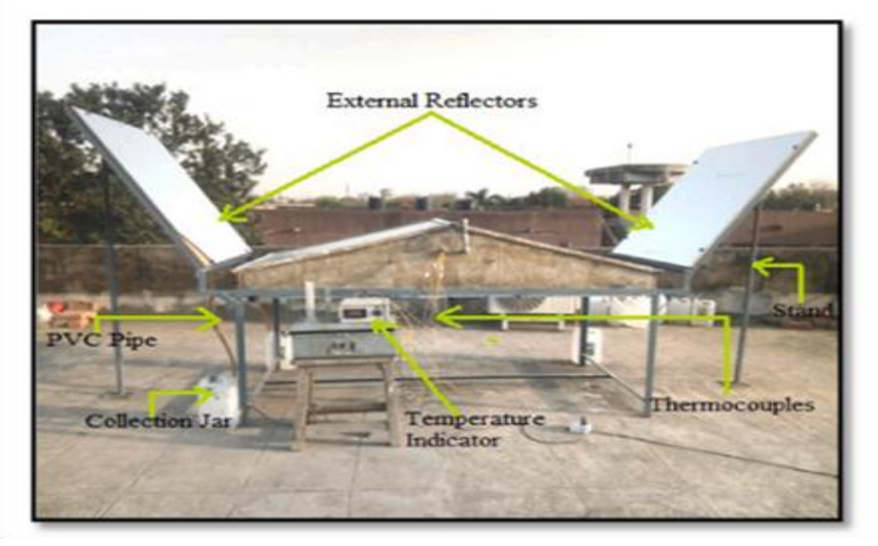

Figure 124. Double Slope Solar Still Integrated with Externally Mounted Reflectors [51]

2.9. Integration of PV with SS

Several of the aforementioned configurations and proposed improvement requires power sours, which increase the operational cost of the system. The utilization of a photovoltaic hybrid system can mitigate this issue [52], [53]. Various studies showed the potentials this configuration can made on the productivity of SS. Rajaseenivasan et al. 2017 mathematically and experimentally investigated the influence of integrating PV array with SS and basin water variation [54]. The PV array powers an electric motor that stirrings basin water. This had increased the evaporation rate by 30% higher than that of CSS. Mazraeh et al 2018 explored the significance of integrating PCM-PV with SS[55]. The proposed design included a single slope SS, where the basin covered by PCM and the still augmented with evacuated tube collector (ETC). The glass cover was replaced by a semitransparent photovoltaic module. Figure (15)provides a Schematic of the system. The result indicated that the PV does not influence Desalinated water, while it is the main power source. Increasing the number of evacuated tubes can improve water production, while inversely affecting the energy/exergy efficiencies. The optimum recorded productivity was 4.5503 kg/m^2·day for the parameter 0.03 m, 30 tubes, and Paraffin wax as PCM.

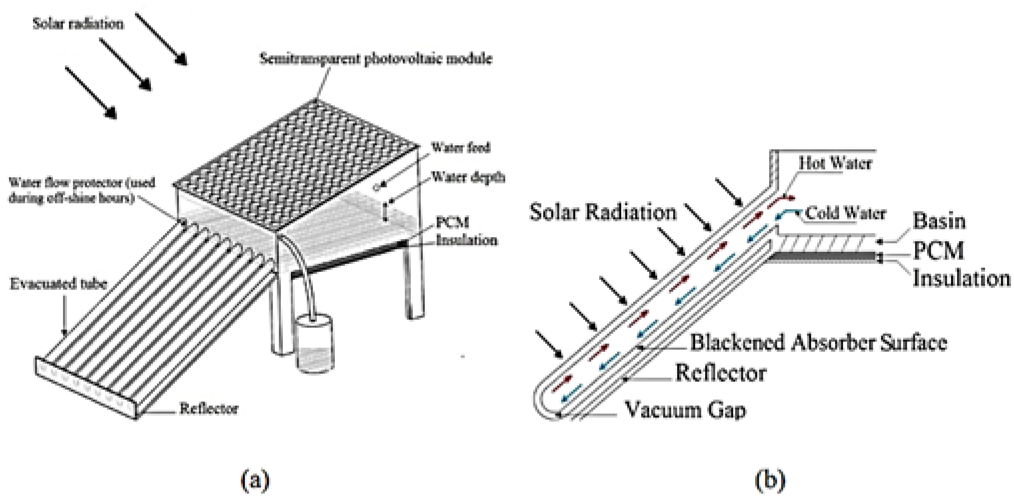

Figure 135. a. Schematic Diagram of a Solar Still Integrated with ETC, Semitransparent PV Module and PCM, b. Schematic Diagram of Thermosiphon Process in Single Tube [55]

Elbar and Hassan 2020 evaluated the performance of integrating PV over the high end of glass cover of single slope solar still[56]. The PV's main function is to power an embedded electrical resistance located inside the still basin to preheat basin water, besides reflecting solar energy to the water as well. The study included placing black steel wool fibers in the basin (BSWF), as well as investigating air cooling techniques (FAC). The results revealed an increase in the productivity of 9% and 23% for PV-SS and BSWF+PV-SS, respectively. The addition of FAC increase the beak hourly production of the system, where the reported values was 0.535, 0.52, 0.485, 0.426 kg/m^2/hour for (CSS + PV + BSWF + FAC), (SS + PV), (CSS + PV +BSWF), respectively.

3. CONCLUSION

This work covers various technological advancements and recent researches to improve the efficient production rate of SS. The review included but was not limited to modifications such as the integrated condenser, Humidification-dehumidification (HDH) system, basin water preheating, and utilization of phase change materials. Based on the reported literature important observation can be summarized.

1. The production rate is directly proportional to the temperature difference between the glass cover and basin water; it increases with a wide difference and vice versa.

2. The integration of solar dishes as preheating technology with PV array can boost productivity to a high production rate.
3. Using thermal storage material can enhance daily productivity mainly after sunset, paraffin wax is one of the most reported materials in this field.
4. A combination of PCM material and nanoparticles can generate a better thermal storage medium.
5. Although thermoelectric glass cover cooling is an effective enhancement that can be adopted, the relatively high operation cost is questionable.
6. The utilizing of the Fresnel lens can significantly increase basin temperature even bubbles can be observed, but there is some concern regarding damaging the Sill configuration.
7. Having stepped basin arrangement can increase the resident time and interference of water with basin, hence enhancing productivity.

3.1. Future Scope and Recommendations

Solar still development is facing several challenges that require further investigation to improve the productivity of such systems. One such aspect is enhancing the internal heat transfer rate. In most of the efforts made to investigate heat transfer, Natural convection between water and inner glass cover was taken into consideration as the main evaporation-condensation inducer. Hence,

1- Increasing the area of condensation surface would be of high interest.
2- Built-in evaporators to work as an additional booster to increase the evaporation rate.
3- Reducing the side effects of using a Fresnel lens would be beneficial.
4- A solar chimney could be used to cool down the glass cover so that enhancing the condensation rate of CSS.

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