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Solar distillation Systems Design and Enhancements Review

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A B S T R A C T

While water covers more than two thirds of the planet, drinking water scarcity is now a severe problem that too many countries face. A large gap in the need of clean water has been resulted due to worldwide rapid growth of industry and population. There is shortage of fresh water in many regions such as rural areas, remote regions. These areas also suffer from lowering in the acceptable quality of drinking water. Solar distillation has been found to be eco-friendly and effective method to produce fresh water to satisfy these communities demands. Solar still is one of the technical applications of solar desalination. Several types and designs of solar stills must be developed to increase the production of the still, because of its lower productivity. An extensive review for solar desalination technologies has been carried out in this research.

1.Introduction

Scarcity of water is a growing problem for large regions around the world, water scarcity caused by population growth and the higher consumption resulted by rising standards of living [1], which results in an increase to water consumption per capita from 75 to 100 L per day in the 20th century [2]. Demand for drinking water is increasing, and its shortage is a problem that has remained to disturb humanity even in our day [3]. There are approximately 2.1 billion persons through the globe without access to clean water [4]. Most of Middle-East people and third of Africans live without enough water [5]. More than 71% of the surface of the earth is covered by water, and 97% of this water (salty, non potable and inappropriate for irrigation) is found in the oceans, while freshwater is makes up only 3% of total amount of water on our planet, rivers and lakes making up 0.3% of this low percentage and polar ice making up the remainder [3,6,7]. People who live near the coast often have taste discomfort and stomach problems due to excessive salinity, the range of seawater salinity is 35000-45000 ppm but according to World Health Organization (WHO), the acceptable limit of salinity is 500 ppm [8,9,10]. People in most countries who live in the salinity boundary depend only on rainwater and surface water from ponds, but most of these ponds also have significant levels of turbidity beside salinity and high pH which have serious health effects as a result of using in drinking and cooking [11]. Drinking water requires removal of (i) suspended substances (ii) dissolved substances and (iii) harmful microbes [12]. As a result of water scarcity several methods are applied to convert wastewater into drinking water [13]. Among of these methods the desalination methods. Desalination is the process of purifying seawater or other saline water by removing the salts [14,15]. It is resulted that over 75 million persons through the world use desalinated seawater or brackish water to get their fresh water [16]. Desalination technologies are divided into two categories, thermal distillation and membrane separation, thermal systems that heat seawater or brackish water and separate the pure vapor by condensation. Membrane separation technology is usually depending on electric energy to force high-pressure pumps that overcome osmotic pressure differentials [1]. Different desalination processes like reverse osmosis (RO), forward osmosis, electro dialysis,

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vapor compression, multi stage flash distillation (MSF) and multi effect distillation (MED) are employed to supply clean potable water but they are costly technologies and energy intensive [4,17]. Fossil fuels and electricity are used in desalination and other purifying processes [18,19]. Table 1. Show various desalination technologies with their energy demands. Kalogirou [15,20] concluded that 10,000 ton of petroleum oil were required to produce 1000 m^3 of fresh water. This amount of oil is very critical because it contains repetitive vitality costs that are insufficient to solve the global water shortage. Fossil fuels are gradually declining over time as a result of rapid consumption, and in 2040, the discharge of CO2 will reach 218 million tons annually. Therefore, another renewable energy sources required [4,18,20,21]. Renewable energy is used to save conventional sources of energy and also reduce the cost of distilled water [21]. Renewable sources of energy such as solar energy, wind energy, geothermal energy and biomass are alternative ways to eliminate reliance on fossil fuels [14]. Solar distillation is the process that converts the impure water to fresh water using solar energy [22]. Distillation is among the most attractive methods that applied to achieve the need of fresh water in dry regions and distant areas at a very economical cost [17]. It is a vital alternative to expensive methods to overcome the water shortage in low-income areas [23]. Distillation means removing salts from seawater or brackish water. The purified water has zero salts and this process happened in regions of water scarcity, which get a huge amount of solar intensity annually such that some of the countries placed in the North Africa and the Middle East where solar intensity ranges are between 1100–2800 kWh/m^2/year [10]. Solar energy can be harnessed in electrical or thermal forms to produce fresh water. Examples for solar thermal power systems are flat plate solar collectors, evacuated tubes and solar ponds that harvest solar energy and turned it into thermal power that drive thermal desalination operations [24]. The desalinated utilization of solar energy could be divided into direct and indirect use. For direct use the solar energy is directly harvested by the salt water such as in solar stills and solar ponds and for indirect use solar energy is harvested by a collector and then turned to sea water [24]. The main objective of this research is to study low cost solar still equipment that can purify sufficient amount of fresh water for a family with five members. It acts as hydrological cycle in nature, it is a very large-scale technology for solar distillation that produces drinkable water. Solar radiation reaches the sea's surface and absorbed as heat, and then causes the water's surface to boil, the vapor rises above the surface and carried by winds. The vapor condenses when it reaches its dew point, and the result is fresh water precipitating as rain. [9,14]. Zein and Al-Dallal [9] designed a solar still and revealed that the impurities like nitrates, chlorides, iron, and dissolved particles in the water are completely removed by the solar still.

Table 1.Ranges of energy demands for various desalination technologies

Technology	Energy demand(kwh/ m^3)
Multi-stage flash distillation (MSF)	9-60
Multi-effect distillation (MED)	7-59
Reverse osmosis (RO)	2-7
Electrodialysis (ED)	0.3-8.8
Capacitive deionization (CDI)	0.1-2.05

2. Solar energy

Utilization of solar energy in desalination of water process is widely divided into two primary categories, direct systems where the extraction of heat is direct from sun without external heater. The processes of condensation and evaporation both occur in the same device. It is best suitable for small communities and rural household and indirect methods which divided into two subsystems, external heat system and desalination unit [3,15,25,26]. Table 2 &3 presents a summary of each process.

Table 2. Summary of direct processes.

Method	Operation	Advantages	Disadvantages	Ref
Conventional solar still	The transparent tilted cover allows the sun's rays to enter and heat the water, small portion of solar rays is reflected and the inclined glass cover absorbs another small part of the radiation, the amount that absorbed depends on the quality and impurity of glass material and also cover thickness of the solar still. Water that has been heated evaporates and condenses into the interior side of an angled glass cover. The condensate water falls down the interior side into trough and then collected in storage containers.	Simple to fabricate on small scale, requires little maintenance, gives high quality of distilled water, availability of materials, low cost, lower energy than other desalination methods, environmental -friendly technique and operating by saline water or brackish water.	Low productivity, high initial costs, large area requirements, and production depends on sun intensity.	[5], [4], [7], [17], [20], [22], [27], [28], [29], [30], [31], [32], [33], [34].
Wick type solar still	Wick still mostly put under inclined type still. The basin liner is angled with respect to the horizontal. Its operation is almost similar to conventional solar still but the different is that feed water slowly moves in a porous pad (the wick).	The wick still made an angle with the horizontal which improves the feed water's angle to the sun, reduces reflection and creates a larger effective area. A smaller amount of feed water in the still at any given time so the basin water is heated more quickly to a higher temperature.	Development of dry spots, difficult in control over brine flow, clogging of wick material pores due to salt contamination and using of fiber cloth like jute for wicking degrades with time. The still does not produce distillate water after passing a cloud or sunset, but due to the heat absorbed in the basin's water the productivity continuous for some time.	[5], [35], [36]
Solar pond	In natural solar pond radiates of sun reached to the pond's bed and heats up the feed water, the heated layer of water rises to the surface because it is lighter than the upper layer and causes convective motion and heat losses to the atmosphere.	Solar ponds provide the most economical alternative for heat storage with solar powered desalination processes. Thermal energy from a salinity-gradient solar pond may be used to power traditional thermal desalination technologies including MSF, MED and VC, it is less expensive than other solar-powered devices. In comparison to other solar collection desalination options, solar ponds have the advantage of being able to store the sun's thermal energy for months even in adverse weather.	Large area requirement	[24], [25]

Table 3 Summary for Indirect processes.

Method	Operation	Advantages	Disadvantages	Ref
Multi stage flash distillation (MSF)	In MSF, feed water passes through pump to be pressurized water and also heat exchanger to raise the water temperature up to its saturation point using solar collectors. MSF consists of a series of units called stages. At the first stage, water flashes into steam when enters the first stage because of reducing its pressure. The vapor then transferred through a demister to remove water bubbles and then the vapor allowed to condense through a condenser and collected on a distillate tray. The remaining part of feed water passes through second stage at lower pressure than first stage, so feed water flashes into vapor. The process done as well until we reached the last stage.	Produce large capacities of fresh water, independent on salinity of feed water, simple in operation and maintenance, high quality of produced fresh water and scale control.	High thermal energy, low recovery ratio, high cost of operating and building.	[3], [14], [25], [37]
Multi effect distillation (MED)	MED is a low- temperature thermal technique obtaining fresh water from boiling sea water in a sequence effects by lowering temperature and pressure than the last effects. In the MED process, the entering brine runs through a number of heaters of solar collectors and used as heat exchanger in the first effect. Feed sea water entering the first effect sprayed through nozzles onto the surface of bank of tubes inside which steam is flowing. Sea water is partially evaporated, and the remaining amount is collected at the bottom of the first effect. Steam condensed in the tubes and is withdrawn for recovery. The collected water in the first stage is sprayed in the second stage and the evaporated water is used as heat exchanger in the second stage.	High purity of distilled water, simplicity of its operation and maintenance, high amount of distilled water.	High energy requirement, scaling problem, bulk fluid.	[5], [8], [14], [35], [38].
Vapor compression (VC)	Desalination by Vapor compression classified into mechanical or thermal vapor compressor. In MVC, feed sea water passes through preheated system and sprayed by spray nozzles onto tubes that contain a vapor of sea water by solar collector and compressed by mechanical compressor. The pressurized vapor is used as a heat source in the vessel. A portion of feed sea water tuned to vapor and the rest in the bottom of the vessel. The vapor of feed sea water is retuned to compressor system and the vapor in tubes condensed and passes through preheated system to release its latent heat as fresh water.	Confined process, use as small scale, can be added at wide ranges of temperature.	High energy requirement, scaling.	[3],[24],[25].
Membrane distillation (MD)	The combination of thermal distillation process and membrane process is called Solar membrane distillation (MD). The MD separated process is driven by the differential in vapor pressure across the membrane's sides. Vapor flows through membrane from the side of high vapor pressure to the side of low vapor pressure. Solar energy is used to heat sea water or brackish water and then transferred to a warm saline.	This process uses a lower range of temperature compared to traditional thermal distillation systems and reduced pressure compared to reverse osmosis desalination, it is suitable to be heated by solar energy due to lower temperature, including the ions and colloids rejection.	Fouling, high cost of membrane.	[3],[10],[24]
Humidification-dehumidification (HDH) desalination	HDH system consists of two sides. The first called evaporator side or humidifier where preheated sea water is sprayed from the top through nozzles. Evaporates and circulating air stream carried out water vapor from the saline water side to the condenser side, where vapor condenses into purified water on tubes where feed Sea water is flowing. Solar energy power is used to heat saline water using flat plat or evacuated tube solar collectors.	operates at low temperature	lower thermal efficiency and the cost of the system rises because a lot of metallic surface area is required to condense water vapor in the air stream over metallic tubes.	[14], [24], [25]

3. Different designs and configurations of passive solar stills

The choice of a solar still design is influenced by a number of criteria including location, kind of salt water, material availability, and cost.

3.1 Single basin single slope solar still (SSSS) (conventional solar still)

Figure 1. Shows Single basin single slope solar still. The evaporated pan is commonly covered by a layer of clear glass or plastic that is tipped at a modest inclination to permit the fresh water that condenses on it fall into the bottom side and down into a collecting trough [39]. There are three holes in the sidewall of the basin; one hole allows sea water to enter the tank and two of them allow to drainage wastewater and distillate water get out. Silicone rubber sealant is utilized to seal off to prevent the water leakage between the sidewalls of the still. The holes are covered with an insulating substance to avoid leakage of heat and vapor [40]. The output of a single-slope solar still was higher than double sloped solar still as single-slope obtains more radiation than double slope at both low and high latitude stations [41]. In order to remove fluoride from drinking water, Sahoo et al. [42] integrated single slope solar still. The reduction in fluoride was found 92–96% compared to contaminated samples.

3.1.1 Efficiency of solar stills

The performance or efficiency of solar still is defined as amount of distilled water as output to Solar energy absorbed within time interval as input [39,43]. It can also be defined as the ratio of latent heat energy of the condensation at inclined cover to the total amount of solar energy located on the still [33]. The performance of the still is calculated as illustrated in Equation 1[7,44].

Equation 1: $$\eta = \frac{Mh_{fg}}{A_{st}\sum I} \quad (1)$$

η: efficiency of solar still.
M: total output of the still through the day (kg/m^2/day).
h_{fg}: latent heat of evaporation of water(kJ/kg).
A_{st}: area of solar still in m^2.
$\sum$I: total amount daily solar radiation (KJ/m^2/day).

3.1.2 Materials of different sections of solar stills

• Cover
The inclined cover surface absorbs the radiation from the sun and then transmits it to the basin linear and also, it receives heat from the basin and transfer it to the atmosphere During these processes, it also allows the vapor to condense and collect it in collection through. The cover should be efficient to allow energy flow in both directions for the exact work of the solar still [45]. Although, plastic is cheap, light weight, not brittle, low cost and easily available materials, it is not recommended to be used for the reason of its lower productivity because electromagnetic forces produced between molecules of water and the cover material. So inclined glass cover is better than plastic [46]. Glass has Properties such as: Low water absorptance, high thermal conductivity and Can withstand with the performance of weather, wind, sunshine, rain, dust [47]. It can easily create a difference of temperature on the top and bottom [11].

• Basin liner
The main goal of the basin is to receive the entire radiation passing into the still through the cover with minimum reflectance loss and conduction loss to the surroundings, it should store the energy when it is available in excess and also release the energy when demand was increases and availability was decreases [45]. Material should be able to absorb solar radiation, must also be watertight, should be able of resist high temperatures and have high thermal conductivity [41]. Some material applicable to store heat and release it when the heat source is not available [48]. Materials that be used are Aluminum, galvanized iron, stainless steel, plexiglass, reinforced concrete, glass-reinforced plastic (GRP) and FRP (fiber-reinforced plastic) and brick.

• Sealants
Using sealants to avoid vapor leakage such as tars, tapes and rubber silicon [41].

• Drain Pipe, outlet pipe, inlet pipe made of PVC because it is Stable to corrosion, not poisonous to water, cheap and readily available [23,47].

• Collection trough made of glass, Stainless Steel because it is stable to corrosion, not poisonous to water [47].

• Insulator such as fiber glass and play wood because it is very cheap and poor conductivity [47].

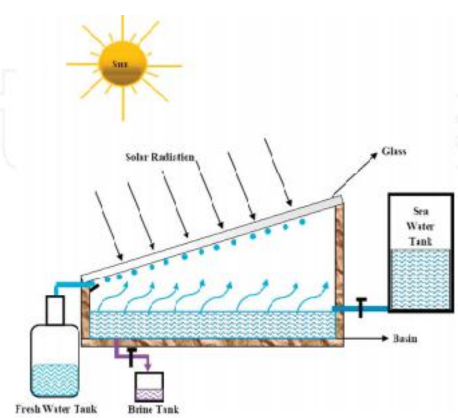

Figure 1. Single basin single slope solar still.

Figure 2. Tabrizi's double slope solar still

3.2 Single basin double slope solar still

Single basin double slope solar still was tested by Tabrizi and Sharak [42] with a heat reservoir in the basin. The results showed that for a 14hour experiment, the output was 3000 cm^3 $/m^2$ with a 75% improvement in productivity over the traditional still. Figure 2.Shows Single basin double slope solar still which was designed by Tabriz.

3.3 Hybrid solar still

The hybrid solar stills are traditional solar stills combined with an external heater such as solar collectors (flat plate collector, evacuated tubes) or a conventional system coupled with another type of solar integrated system to optimize the distillation process. The production of connected devices is discovered to be two times greater than that of conventional systems [41].

3.4 Hemispherical solar still

The hemispherical still's basin is painted black to increase absorptivity, and saline water was added to the still [40]. Figure 3. Show hemispherical solar still. Arun Kumar et al. [2,35] studied water desalination using a solar still with a hemispherical top cover with and without water flowing over the cover and they discovered that the top cover cooling effect enhanced the system's daily distillate production and increased the efficiency from 34% to 42%. A simple type hemispherical solar still is constructed and developed by Ismail [42]. The still composed of an absorber plate filling with saline water, circular basin, hemispherical cover, the distillate output container. During the daytime, the daily productivity was observed to range between 2.8 to 5.7 L/m^2 with a daily efficiency 33%.

3.5 Spherical solar still

Figure 4. Show diagram form of spherical solar still. Dhiman Naresh [2,20]. Introduced a mathematical model for predicting the efficiency of a spherical solar still. He discovered that spherical solar still have a 30% higher efficiency than the traditional solar stills. The spherical solar still has a shallow round absorbing basin that is painted black for optimal solar radiation absorption. A top cover composed of low-density polyethylene (LDPE) sheet covered the spherical mesh and the circular basin in the center of the spherical mesh [40]. The absorber basin is not in contact with the top cover. The water vapor that condensed on the top cover flows down through the gap between mesh and cover and onto the distilled water collector [20,40,49]. The rate of condensed distillate output is larger in a spherical surface still than in a solar still with a single slope because it has more air contact.

Figure 3.hemispherical solar still.

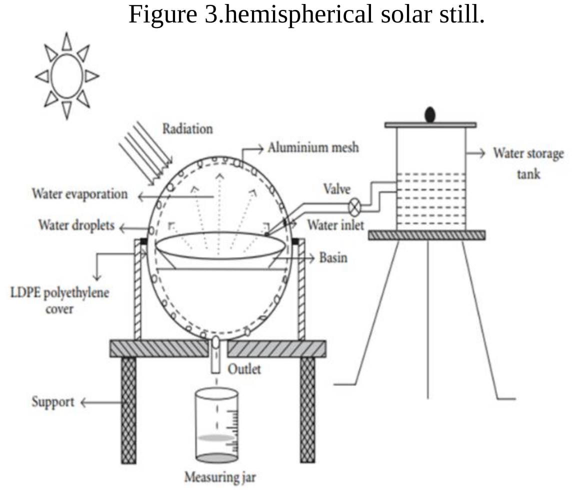

Figure 4 spherical solar still.

3.6 Hemispherical Concentrator Solar Still

A single-slope solar still coupled with hemispherical concentrator and hemispherical basin absorber is shown in Figure 5. There is no water leakage because the absorber is welded to the bottom of the still. For maximum solar absorption, the basins and outer surface are painted black [40].

3.7 Multiple-effect stills

Design of multiple basins is made up basins put on top of each other. The latent heat of condensation in one basin heats the water in the basin on top of it, making it an efficient method in purifying water [25,36,41]. Figure 6. Show Single slope double basin solar still. A study of comparison on single-effect and double-effect solar still is illustrated by Al-Hinai et al. [49]. They found that yield of potable water was 4.15 kg/m^2 per day for single effect solar still and 6 kg/m^2 per day for double effect solar stills. An analysis of a double basin solar still was examined by Sodha et al. [50]. They studied the performance for various climatic conditions. The results showed that a double basin produces 36 percent more than a single basin and productivity rises as insulating thickness rises. Sebaii et al. [20] studied the water productivity of a triple basin still and they observed that the output was inversely related to the water mass contained in each basin, and that the output of a triple-basin still was higher than that of a double-basin or single-basin still.

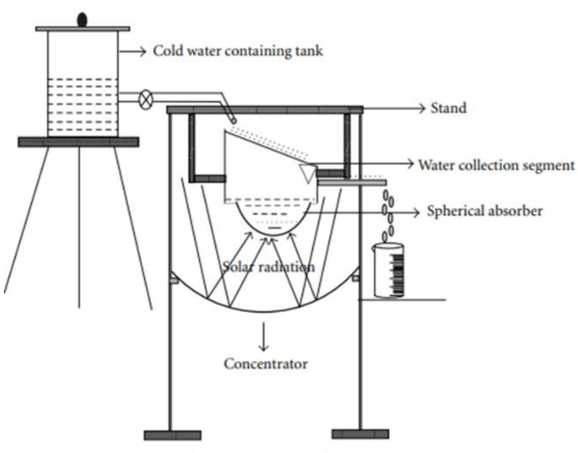

Figure 5. Schematic view of spherical basin solar still.

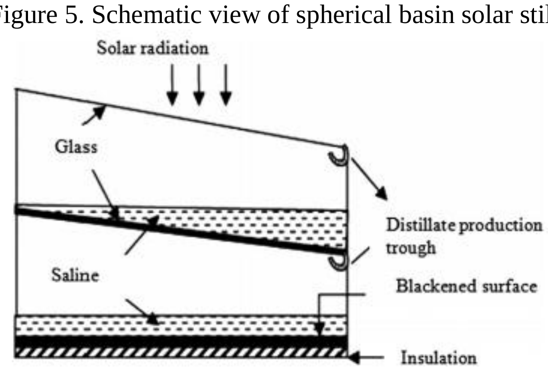

Figure 6 single slope double basin solar still.

3.8 Stepped solar still.

As illustrated in Figure 7. The stepped solar still is similar to a typical solar still in terms of construction and geometrical dimensions, with the exception that the absorber plate is formed of steps. The dimensions of the steps are (10 cm) horizontal and (5 cm) height and are covered with a layer of cotton cloth or black paint for higher absorption, and the absorber plate's backside wall is insulated [51]. In the traditional solar still, the glass cover's degree of inclination causes a big gap between the cover and the basin so the gap distance cannot be kept at a minimum. This problem may be solved by using small trays on an inclined basin [11].

3.9 Tubular solar still (TSS)

Tubular solar stills are made up of an exterior transparent tubular cover that surrounds a blackened metallic tray that runs along the tube's length [20]. The inner and outer circular tubes connected by a gap that allows water and air to cool the inner tube's outer surface. There is a storage tank for maintaining a continuous supply of water to avoid dry spot [40]. A constant flow of saline water entering and leaving the tray maintains the depth of the saline water contained in the tray. Condensation forms on the cover's inner surface. The water particles condensate and move down to a collected trough at the tube's bottom [20]. Elashmawy [49]. Studied tubular solar still connected with a semi-circular trough filled with a black cloth, as shown in Figure 8. He found 676% rise in productivity. Ahsan et al. [2] Studied and tested the better design of TSS. They used Vinyl chloride sheet as a cover material that replaced with polythene. The new TSS was proved to be less expensive, lighter and more useful than the old TSS.

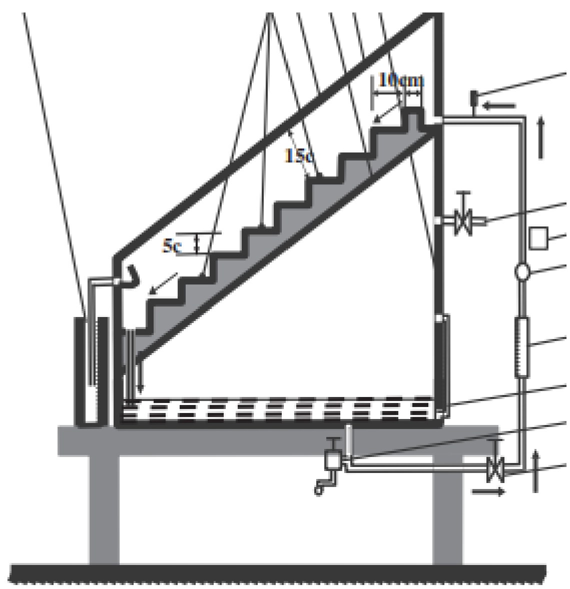

Figure 7. Stepped solar still.

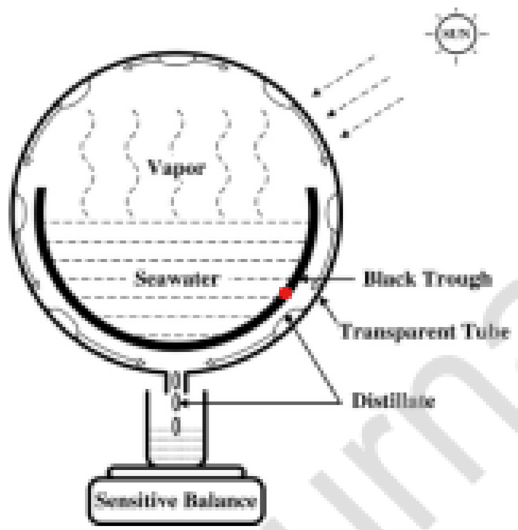

Figure 8. Tubular solar still.

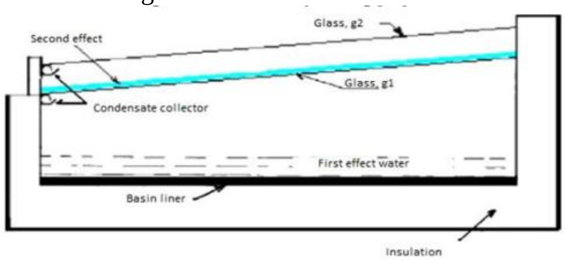

Figure 9. Single slope solar still coupling with two effects of glass cover.

4. Factors affecting on productivity of solar stills

4.1. Climatic condition

These parameters cannot be controlled

- Solar radiation, it has a direct impact on the still's performance, and still generation rises as incident solar irradiance rises [11,41].
- Wind speed, still output increases with decreasing cover temperatures, cover temperature decreases with higher wind speeds and the vapor pressure rises with increasing wind speeds. The temperature differential between the water in a basin and the inside surface of a glass has an impact on distillate productivity. The temperature difference can be increased by wind movement, which increases the yield [11,41,52].
- Ambient temperature, there is an improvement in productivity due to an increase in ambient air temperature [53]. The results indicated that increasing air temperature from 26.7°C to 37.8°C improves output by 11% [1,23].
- Dust and cloud, the deposition of dust on a glass plate reduces solar transmittance, it had been reported that glass transmittance lowered by 10% in the summer and 6% in the winter owing to dust accumulation [11,41].

4.2. Design condition

- Water depth
  Solar still's production is inversely related to water depth and yield of the still have been nearly constant up to depths over 0.1 m [11,12,51,54,55,56]. The volumetric heat capacity of the still basin increases as water depth increases, while water temperature decreases. The heat contained in water is released in large amounts when there is no sunlight, and production continues even at night [45]. But it is discovered that productivity is strongly influenced by the water's initial temperature in the basin where daily output rising with depth for brine temperatures more than 45°C and falling with depth for brine temperatures lower than 40°C [57]. Rajamanickam and Ragupathy [15]. Analyzed two stills of equal areas and tests were examined at varied water depths. The findings revealed that when the volume of water increased, it was inversely related to the solar still production. The highest productivity was 3.10 l/m^2.day and 2.30 l/m^2.day for double and single slope solar stills at the minimal water depth. Anil and Tiwari [15] investigated the annual and the seasonal performance of a standard solar still with a 30° titled cover at various water depths. The findings indicated that the highest daily productivity in every month for the lowest depth of water during the year. In summer, the daily yield at the lowest water depth was determined to be 32.57% and in winter, it was 32.39 %.
- The cover's orientation and inclination
  It depends on the location's latitude angle [45,58]. The slope of glass cover of the solar cell has a significant impact on its production. It had been discovered that the maximum glass inclination angle for optimum annual output should be equivalent to the location's latitude. [45,49]. Daily productivity increased with inclination in winter while the reverse is true in summer according to Egypt's climatic conditions [11,19,41,52,53]. Water droplets did not drip on the condenser's surface at very small angles, and at larger angles, the side walls' big shadow was observed [59].
- Thickness of cover
  When compared to a 6 mm thick glass cover plate, a solar still with a 3 mm thickness for glass cover plate increased the production rate by 16.5 % [41,45,60]. The total permeability of the glass and condensate film is mostly determined by thickness of the transparent cover, increasing the thickness lead to lowering the transmission for solar radiation [61].
- covering temperature
  Reducing the temperature of cover increases the still's productivity, as well as raising the temperature difference between the water in the basin and the glass. This enhances the still's natural air mass circulation, which allows for more convection and evaporation heat transfer from the basin water to the cover. The amount of condensation is increased by continuously flowing a layer of cool water over the inner glass surface [45].

Wind velocity has a great effect on reducing cover temperature [62]. Yousef and Mousa [15,49] experimented two glass cover effects on a solar still. As shown in Figure 9. According to the findings, from the first effect, cool water was pumped in and out. The output of the modified still was 20% higher than that of the non-modified still.

- Externally and internally reflectors
  Reflectors have an impact on the amount of sun light absorbed, affecting the basin lining and outputs. It had been discovered that distillation increased by about 48% by using reflectors [41]. Using Side mirrors affected to reflect sunrays fall on the side plate and back plate to the basin area. When compared to traditional stills, experimental results indicated that stills of the vertical walls' reflecting mirrors improve production rate by 22% in winter and 86.2 % in the summer [45].
- Gap distance
  In the still system, there is a gap between the condensing cover and the water's surface and minimizing this gap will improve the still's performance. It was found that the best gap distance is between 8cm:13cm so, a graded solar still should be employed to keep the gap distance to a minimum [11,41].
- Insulation thickness
  Insulation thickness is shown to be directly proportional to still production [41]. The following are examples of materials that can be used: Cotton, clothes, rubber, glass wool, mica sheets and wood [11]. Al-Karaghouli and Alnaser [15] planned and built a double and single basin solar still of identical dimensions, one with insulation and the other without. In June, the yield of a double basin still of insulated walls was 1.76 l/day while the productivity of a non-insulated side was 1.41 l/day and the daily production of a basin type still of insulated sides was 1.28 l/day and 1.11 l/day in a still with uninsulated walls.
- The basin's evaporation area
  The airflow inside the still that is subjected to natural convection will capture more water particles because a large amount of water is available in the basin [45,57]. Increasing evaporation area increased still yield however for infinite area, the rise in productivity owing to increased evaporation area is restricted to roughly 30.2 % because the water temperature (Tw) was lowered and the temperature difference (Tw – Tg) dropped [63].
- condensing area
  In a traditional single slope solar still, the only region available for condensation is the inner part of the transparent cover which has a small temperature differential due to its small thickness, resulting in a reduction in the rate of condensation. This makes the solar-powered still inefficient and decrease its overall performance [45]. Increasing the condensing area by supplying more area available for condensation increase the productivity as represented in Figure 10.When a double slope still is employed for locations at higher latitude, one side roof receives sunlight almost as usual while the second side cover is in the shadow zone for sun rays, allowing it to be used as a condenser [60]. E1-Bahi and Inan [35,49] studied a stainless steel reflectors were added to a solar still attached by an external condenser in order to gather additional solar irradiation and act as a shadow for the condenser. The results show a distillate yield of approximately 7 $kg/m^2/day$ and a 45.83 %increase in still efficiency.

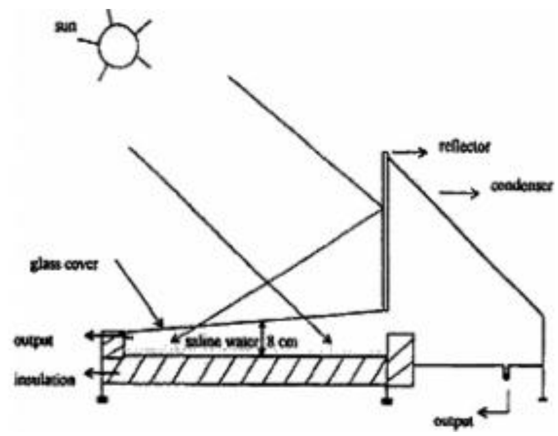

Figure 10. Solar still with additional condenser.

4.3 Operational condition

These parameters can be controlled at the time of operation [11,15].

- Salt concentration
  It had been discovered that raising the salinity of the water reduces the production of the still and more over causes corrosion damage to the still's elements [11,41,51].
- Water flow
  The production of a solar still is determined by the temperature differential between water and the glass cover and it was discovered that water flows down the glass cover affects on the performance of the sun still [41,64]. The rate of condensation increases when the temperature of the glass cover reduces as a film of cooling water continuously flows over the glass at a large heat capacity of the water mass in the basin. [35,60,65].
- Heat transfer
  Several variations of exterior heat transfers from the glass cover to the atmosphere and interior heat transfers from water basin to the glass cover should be optimized to increase the still's production [60].
- No. of slopes
  Single-slope solar stills absorb more solar radiation than double-slope basins so the preferred still is the single-slope still [11].
- Coloring of water
  The majority of solar-generated heat is absorbed by the basin's bottom surface instead of the clear water, adding dye to water will cause the water to absorb the majority of energy from solar radiation [11].
- Phase change material (PCM)

The use of PCM can increase daily rate by up to 85.3 %. PCM is an organic substance such a
s fatty acids and inorganic such as salt hydrates, manganese nitrate [11].

5. Enhancement of solar stills

Improving the efficiency and daily output of various passive solar stills by reducing the water capacity in the basin, providing different dyes to the water mass, adding different absorbing materials on the basin liner, collecting reflection radiation by installing reflectors on the inner wall surfaces, and lowering conductive heat transfer losses from the sides, etc. [27]. Improving the simple passive solar still is by changing design or materials of the still and by adding heat energy storage elements [13]. Active Solar still can also be improved by connecting the still with flat-plate collector, heat exchanger, etc [27,42]. The disadvantages of the solar stills are the lowering in efficiency and production rate, so scientists have been concentrating on means and ways to increase the capacity of passive solar stills and also improving active solar still by adding additional heating power.

5.1. Solar still with heat energy storage

5.1.1. Solar still with PCM (latent heat energy storage)

The phase change material (PCM) such as paraffin wax, fatty acids, inorganic salts, salt hydrates, polymers, polyalcohols, etc [4,43]. Increases in PCM resulted in a rise in nightly and total daily productivity, but declines in daytime productivity [65]. Kabeel and Abdelgaied and Kabeelet al. [66] used PCM to do studies with solar stills, the SSSS has dimensions of 0.6 m × 1.2 m and the PCM was paraffin wax. The connection of SSSS with PCM yielded 7.54l/m^2/day contrasted to conventional solar still [66]. Paraffin wax has been discovered to be among the most effective heat storing media used in SS. Sand could be utilized as a thermal storage medium to lower the system's total cost [4]. Kabeel and Mohamed [15] studied the solar still performance by integrating a PCM as a thermal storage media to a traditional still. They employed two similar solar stills for comparison: the first was a standard still, and the other was a conventional still with PCM. According to findings, the output of a solar still combined with PCM was 67%–68.8% more than a conventional still.

5.1.2 Solar still with sensible heat storage materials

The storage medium absorbs energy and releases it when the temperature decreases and the sensible heat is stored either in a liquid or solid medium [53]. Sensible thermal substances such as fins, sponges, marbles, pebbles, iron scrap, wick, charcoal, corrugated absorber, black cotton cloth, jute wick, clay pots, mild steel pieces and black gravel granite [4,11,18,67,68]. In Comparison with the standard single slope solar still, the evaporation rate increases by 53% with the additional surfaces. Researchers showed that yield has been increased generally by the addition of charcoal pieces and this is most presented in the mornings or on cloudy days when amount of direct radiation are low [69].

5.1.3 Solar still with nanoparticles mixed in brine

Omara et al. [67] looked at a solar still with brine that contained Al_2O_3 and CuO nanoparticles, three distinct water depths (1 cm, 2 cm, and 3 cm) were maintained in each of the solar stills, which each had a construction area of 0.5m^2. The findings indicated that still with Al_2O_3 and CuO nanoparticles increased the yield. The Al_2O_3 still produced 7.570 l/m^2/day while the CuO nanoparticles still generated about 7.360 l/m^2/day. Sahota et al. [4] studied the performance of three nanofluids on double basin type solar still. The nanofluids had concentrations of 0.2% for Al_2O_3, 0.25% for TiO_2 and 0.3% for CuO. Greater heat energy efficiency was obtained by using nanofluids in relative with conventional solar still. When compared to the other two nanofluids, Al_2O_3 reported the highest productivity. It has been discovered that the total output with aluminium Oxide nanofluid was found to be 29.95% higher than the standard still. Elango et al. [56] investigated the efficiency of SSSS using several water nanofluids of tin oxide (SnO_2), aluminum Oxide (Al_2O_3), and zinc Oxide (ZnO) with varying concentrations. The results reported that the yield of the SSSS with tin Oxide (SnO_2), aluminum Oxide (Al_2O_3), and zinc Oxide (ZnO) nanofluid were 18.63%, 29.95%, and 12.67% more than the traditional still.

5.1.4 Solar still with fins

Fins are primarily used for enhancing the heat transfer area. Srivastava and Agraval [67] tested the single slope solar still (SSSS) connected with porous fin absorbers. The production of the solar still with permeable fin absorber was 7.5 kg/m^2/day comparing with a traditional solar still. The production improved to 75% when solar still containing five solid rectangular fins [44].

5.1.5 Solar still with sponges

Ensafisoroor et al. [67] studied the solar still with steps and sponge cubes placed in the basin to improve evaporated heat flow in the solar still. They discovered that the output of stepped solar still with sponge and CSS was 5.37 l/m^2/day and 4.8 l/m^2/day. Researcher Hamza et al. [53] showed that using sponge cubes can greatly improve daily production. The increase was 255% in the output of distillates compared to the same conditions to a water basin without sponge cubes.

5.1.6 SSSS coupled with dye

Around 11% of radiation reached to the basin of the solar still has reflected back to the atmosphere without using it. This loss can be minimized, if the still basin's and water's absorption coefficients are raised. Several techniques have been used for improving the basin's absorption capacity. In order to raise the basin water's absorption rate, dye has added to it. The basin absorbs more radiation when different dyes are used [23]. It has been found that when compared to red and dark green, black napthylamine dye gives a 29% larger increase in production rate [14,15,45,60]. Sodha and et al. [53] investigated the effects of violet, black, and other dyes on the operation of the sun distillation system. The results revealed that the black and violet dyes have greater impacts on increasing the production than the other colors. A single effect solar still made of stainless steel developed and built by Akash et al. [15] they studied the impacts of using dyes on the still's performance. In each run, three different types of materials have been used with the same water depth. The first run was made of black-absorbing rubber, the second was made of a black-ink solution, and the third run was made of a black-dye solution. The results indicated that the production increased by 60% when black dye was utilized, using black ink increased it by 45% and using black rubber material increased it by 38%.

5.1.7 Solar still with various absorbing materials

Rajaseenivasan et al. [67] conducted and tested experiments with various absorbing materials on both the single and double basin solar stills. They used black cotton cloth, jute cloth, cotton pieces, clay pots and mild steel particles to rise the evaporated heat transfer in the basin. According to researchers, the mild steel particles in the double basin solar still have the optimum production of 5.68 l/m^2/day. Shanmugasundaram [35] tested the influence of black granite gravel as a storage medium and it was shown that the still output rose by 17–20 % to standard stills. Shanmugan et al. [56] used pebbles, calcium stones, white marble stones, black stones, and iron scraps as thermal energy storage medium in a single slope solar still to maximize the production rates to 1.81, 4.28, 1.89, 2.35, and 1.68 kg/m^2/hr for each material.

5.2 Single slope solar still

5.2.1 SSSS with vees "v"-corrugated basin

Figure 11. Shows SSSS with corrugated basin. El-Sebaii and Shalaby [67] investigated the solar still production using a "v"-corrugated SSSS. The corrugated basin had 0.437 m^2 area. The heat transmission area doubled when the number of "vees" increased from 5 to 31, and the results indicated that corrugated solar still produced the optimum output at an optimal rate of 8.679 kg/m^2/day. [67,70]. Omara et al. [56] studied the impacts of an SS corrugated absorber with reflectors and wick at a 1 cm brine depth on the still production. The productivity was 145.5% more than the CSS. The daily efficiency determined to be between of 59% and 33%.

5.2.2 Absorber plate modifications coupled with SS

Nafey et al. [4] studied an experiment using a black floating absorber plate with perforations. Aluminum was used to make the absorber plate, which has holes that are 0.5 mm in diameter. Five floating objects were used to suspend the plate. To get the highest level of solar irradiation absorption, they used ordinary black paint and blackened jute wick. It has been discovered that using a suspended absorber of Black coated metal boosts productivity by 40% for a 6 cm water film and 15% for a 3 cm water film [45,53,60].

5.2.3 Solar still integrated with reflectors

Khalifa and Ibrahim [67] investigated the single basin-type solar still with interior and exterior reflectors. The solar still's designed basin area was 1 m^2. 4 mm thick interior and exterior reflector mirrors were employed. The highest solar still yields were 6.08 l/m^2/day, 6.26 l/m^2/day, and 6.70 l/m^2/day with no reflector, external reflector, and internal linked with external reflector, respectively. [45,67]. Figure 12. Shows solar still connected with top and bottom reflector.

5.2.4 Solar still connected with flat plate collector (FPC)

Badran and Al-Tahaineh [71] modified a traditional passive solar still by including a flat plate collector and found about 36% rise in productivity. Rai and Tiwari [35] tested the average distillate output of a still with a single basin attached with a flat plate collector and a detached still. According to findings, the distilled yield in the still with a collector was 24% better than SSSS without a flat plate collector. Badran et al. [15] experimented the influence of coupling conventional solar still with flat plate collector using saline water at local atmospheric conditions. Three different operating settings were studied such as: remaining connected to the collection throughout the day, remaining connected to the collector only during daylight hours, and remaining without the collector throughout the day were investigated. The results indicated that still connected with collector led to rise in the water temperature which maximize the change in temperature between water and transparent cover. The production of the still attached to collector for 24 hr improved by 231% and efficiency was reduced by about 2.5% in case of the SSSS lonely. When a collector was added to a solar still during daylight hours, the yield rose by 2%.Figure 13. Illustrates SSSS with flat plate collector.

5.2.5 Integration of condenser with solar still

Figure 14. Shows increasing the condensation area in SSSS. Bhardwaj et al. [4] tested the impacts of enlarging the condensation area on fresh water output from a solar still. They discovered that the water production increased by more than 50% when there was no additional area of condensation. Condensation rate is a significant determinant of distillate productivity. It has been demonstrated that adding plastic channels to an inflatable solar still as a passive condenser increases production to 750ml/h, which is significantly greater than a traditional still [11].

5.2.6 Solar still with collector

Coupling evacuated tube collector (ETC) is illustrated in Figure 15. Sampathkumar et al. [67] studied an experiment of coupling SSSS with a solar still water heater (ETC). They discovered that SSSS combined with ETC produced the greatest productivity of 5.6 kg/m^2 on the full-day treatment.

5.2.7 Solar still connected with parabolic concentrator

Gorjian et al. [67] studied tests of a parabolic solar still for desalinating sea water. The parabolic reflector has a 2 m^2 surface area and a focused length of 0.693m. The results indicated that with 7 hours of operation, the parabolic solar system produced the highest production of 5.12 kg/m^2/day. Bechir Chaouchi et al. [35] built a parabolic concentrator with solar desalination system. It has an evaporated area in the form of a boiler, a solar concentrator to direct sunlight into the saline water contained in the boiler, a container at the bottom of a condenser that has a heat exchanger. The researchers noted that the method worked at its peak because brackish water has a large evaporate surface area.

5.2.8 Solar still with air blower

Joy et al. [67] studied the experiment of SSSS with hot air blower to improve the still production. According to results, the SSSS with air blower pumping at the solar basin still produced 5 l/m^2/day.

5.2.9 Single basin single slope solar still with shallow solar pond

SSSS with solar pond with a shallow depth is illustrated in Figure 16. El-Sebaii et al. [67] studied the thermal behavior of a shallow solar pond (SSP) with an SSSS. The experiment was conducted in an SSP with an SSSS with six different flow rates (0.001, 0.002, 0.003, 0.004, 0.005, and 0.10 kg/s), and the results showed that the production of the SSP coupled with SSSS was 5.014 kg/m^2/day at 0.001 kg/s rate of flow mass. With a mass flow rate of 0.005 kg/s, the findings revealed that the maximum yield was 6.68 kg/m^2 per day. [35,67]. It was found that the daily production and efficiency of the still with the SSP are 52.36% and 43.80% higher than those achieved without the SSP [71].

5.2.10 SSSS with sun tracking system

Enhancing the efficiency of traditional solar energy by combining the still and the sun-tracking device to optimize the amount of solar energy captured. Abdullah et al. [53,56] The system's motion is analyzed in relation to the sun. A comparison of sunshine and static solar tracking revealed that the use of sun-tracking resulted in a 2% gain in overall efficiency and a 22% increase in output [19]. It is noted that the stationary device is less effective than the sun tracking system. The temperature of water increases by sun tracking. Salah Abdallah et al. [2,6] discovered that combining the still design with a solar tracking system resulted in a 380 % rise in distilled water output.

5.2.11 Conventional solar still with water sprinklers and cooling fan

On solar still, Ahmed et al. [35] planned, built, and tested an experimental assessment to increase condensation, the condensing glass cover's outer surface temperature was lowered with the use of a cooling fan and water sprinklers. The experiment's schematic illustration is displayed in Figure 17. For a stable glass cover angle of 32.51° and a constant water depth of 1 cm, the trials were conducted individually on three ordinary single slope stills: a passive still, an active still with water sprinklers, and an active still with a cooling fan. With respect to traditional solar still, the output was raised with 8 % and 15.5 % by raising the total wind speed from 1.2 m/s to 3 m/s and 4.5 m/s, and by 15.7 % and 31.8 %by employing water sprinklers at 20 minute and 10 minutes intervals.

5.2.12 Integrating sand beds over the basin liner.

Water output rises as sensible heat rises, and sand was employed as a heat storage media. It was discovered that the height of the sand beds has an inverse relationship with the daily production of a sandy solar still, and the employing of black sand beds in the solar still boosts productivity by 42% over normal stills [72,73].

5.2.13 Solar still with inverted absorber

As illustrated in Figure 18. The solar radiation reached to the inclined surface g1 and the inverted absorber of a solar still receives the rays that are reflected back. The obtained solar energy is transported to water above the inverting absorber and heats it then water evaporation condenses on the inside surface of the condensing cover [2,27]. An evaluation of solar stills using inverted absorbers is introduced by G.N. Tiwari and Sangeeta

Suneja [2,27]. They discovered that the inverting absorber solar still gives around twice as much as the traditional solar still. An inverting absorber solar still, according to Sangeeta Suneja et al. [27] produces outputs more than a normal double-effect solar still. The inverting triple-effect absorber solar still has a 30 % better overall daily yield than a standard triple effect solar still.

5.2.14 Trays solar still TSS

Schematic diagram of TSS is shown in Figure 19. TSS is a traditional solar still that has been improved by attaching plates to the inside of walls and employing interior and exterior top and bottom mirrors to reduce the losses to the environment. The primary function of the lateral plates is to improve the evaporating area and solar radiation exposure by extending the basin's water area without increasing the designed size of the SS. The results indicated that the average output of trays still continued to rise with tray heights of up to 2 cm whereas tray heights over 2 cm had no effect. Tray production was determined to be most productive at 49.5% at a tray height of 0.5 cm and least productive at 32.5% at a tray height of 2 cm. In comparison to CSS, the average productivity of TSS is boosted by 58% when inside mirrors are added, by 75% if internal and exterior top mirrors are added, and by 84 % when TSS is combined with internal and external bottom mirrors. [74].

5.3 Single slope (SS) multi basin solar still

5.3.1 SS multi basin solar still with evacuated tube collector

Shatat and Mahkamov [67] experimented tests on a multi-stage solar still with an integrated evacuated tube collector, the rectangular multistage still has dimensions of 1200 mm in length and 400 mm in width. They discovered that the multi stage solar still produced 10 kg of potable water each day. studying the influence of connected single slope single basin or double-basin-solar still with evacuated tubes experimented by Patel et al. [20] and they noted that the preheating impact increased water output in both types of stills, and the productivity of the double-basin still was around 14.7% better than the single-basin still. Figure 20. Show coupling of multi stage flash distillation with ETC.

5.3.2 SS multi-stage solar still with FPC.

Reddy et al. [67] studied the operation of a multi-stage solar desalination unit using an FPC. The FPC's surface area was $1m^2$, and the multi-stage unit's components included an evaporative unit, a condenser unit, and FPC. The multi-stage solar desalination system's total daily production was 28.04 kg/m^2. The impact of double basin still with FPC and water flowing over through the cover's glass surface was analyzed by Tiwari [50]. It has been shown that employing FPC results in a 50% higher production than using a standard double basin.

5.3.3 Multi basin solar still with additional condenser.

Rate of condensation may be improved by adding an additional area of condensation [50]. The behavior of the two effect solar stills were studied by Fath [50]. The first effect's evaporated vapor is utilized in the second effect. A finned outer surface on the top effect cover allows for extra condensation. The daily productivity was observed as 10.7 kg/m^2/day.

5.4 Stepped solar still

5.4.1 Stepped solar still combine with reflectors, absorbent material and cooled device.

Omara et al. [67] studied the efficiency of internal reflectors in a stepped solar still under climate of Egypt. The stepped solar still had a $1.16m^2$ absorber area. It was found that the stepped solar still produced 6350 ml/m^2/day more than it produced without internal reflecting mirrors (5840 ml/m^2/day). Maiti et al. [67] studied the stepped solar still with outside reflectors and five steps with 0.06 m^2 for each step. The basin area was $1m^2$. It is found that the production was 5.07 l/m^2/day. With various modifications, including the addition of inside and outside reflectors, absorber materials, and an external condenser cooling unit, the authors conducted trials in a stepped solar still. 1.16 m^2 was the area of the absorber plate used in the stepped solar still. The results indicated that the improved stepped solar system still produced a higher production of 8.9 kg/m^2/day [52].

5.4.2 Integration of condenser with Stepped SS

Researchers experimented with several configurations to raise the distillation yield of stepped solar stills (SSS). A stepped SS experimentally investigated by El-Samadonyetal et al. [4]. Reflectors and an exterior condenser were included in the still. In the manufactured SS, the tray width equal to (100 mm). The water vapor was directed into the condenser by a suction fan. The experimental analysis found that the condensate production of the stepped still with condenser was 66 percent more than that of the traditional still. When both (interior and exterior) reflectors and the exterior condenser are used, there is a 165 percent increase in distillate production.

5.4.3 Stepped solar still with a solar air-heater

As seen in Figure 21. A stepped solar still with a solar air-heater was tested by Abdullah [49,75] and demonstrated the new still's efficiency in comparison to traditional stills. The thermal performance's hot air passes through the stepped still's base, raising the temperature of the salty water and increasing the rate of evaporation by using aluminum filler as an energy storage substance beneath the absorber plate. When the system was combined with a heat exchanger, water yield increased by 112 %, and the yield of the stepped still was enhanced by roughly 53 % more than conventional still by integrating aluminum absorber plate.

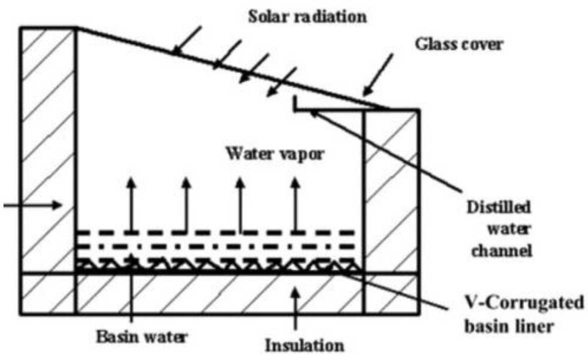

Figure11.SSSS with v-corrugated basin.

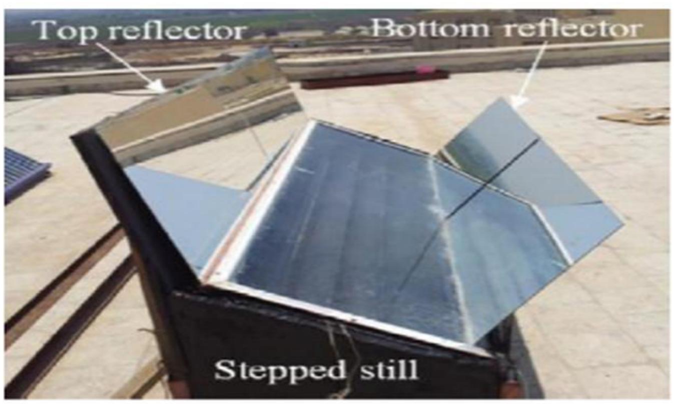

Figure 12. Modified solar still with top and bottom reflector.

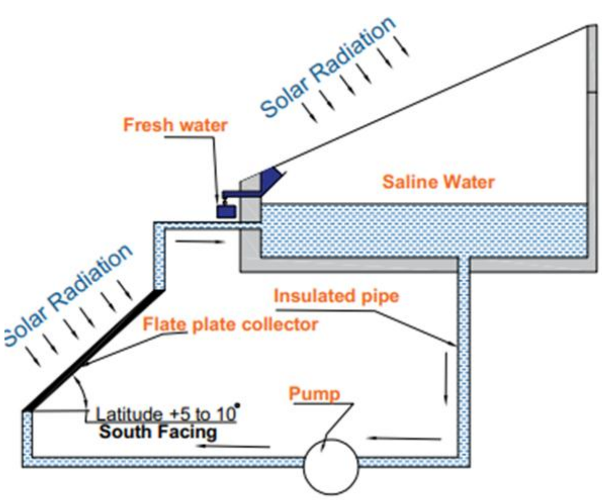

Figure 13. An active solar still coupled with a flat-plate collector

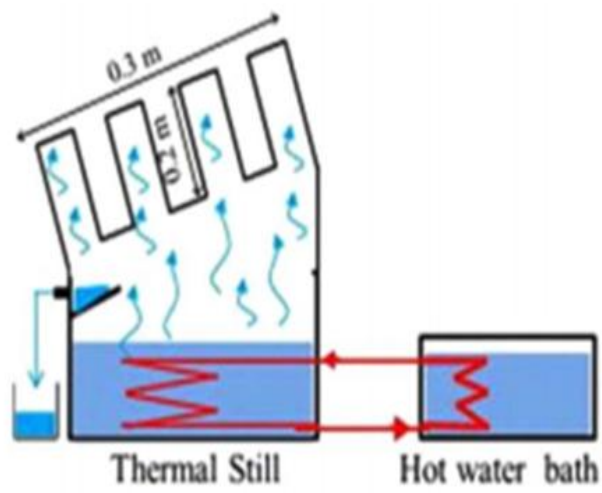

Figure 14. Increasing condensation area.

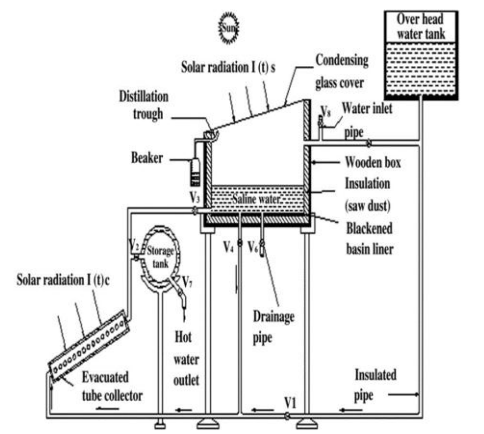

Figure15. SSSS coupled with solar water heater evacuated tube collector.

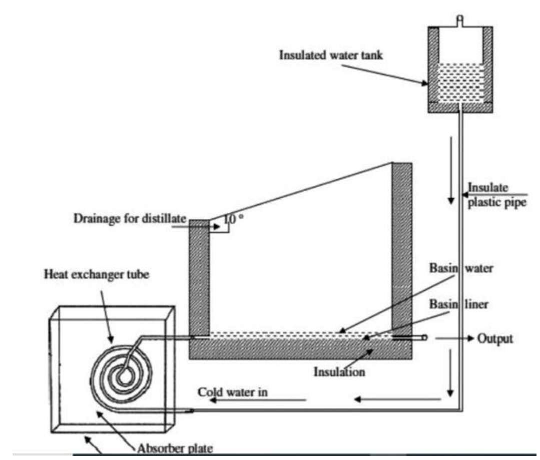

Figure 16. SSSS coupled with SSP

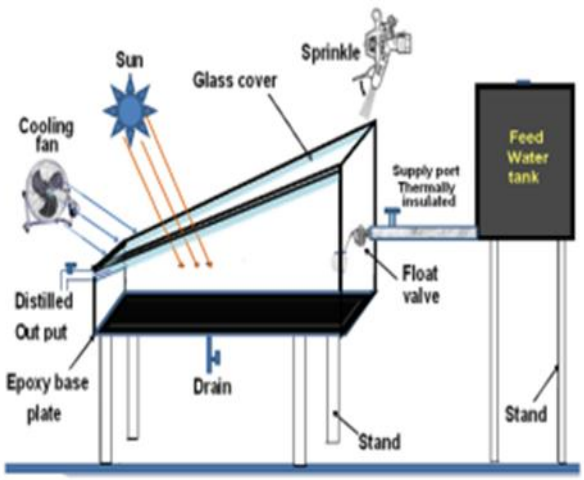

Figure 17. Single slope still withy water sprinklers and cooling fan.

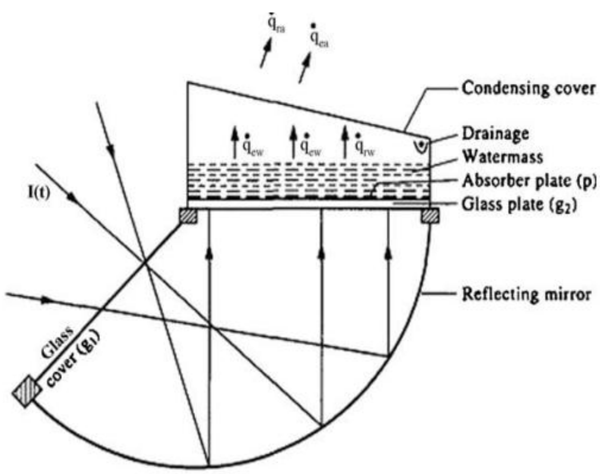

Figure 18. Inverted absorber solar still.

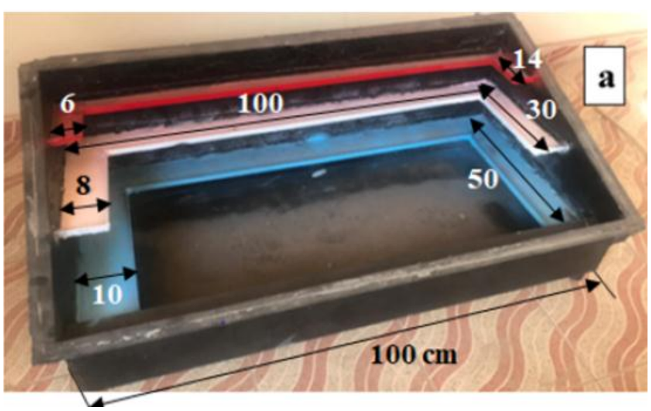

Figure 19. Trays solar still.

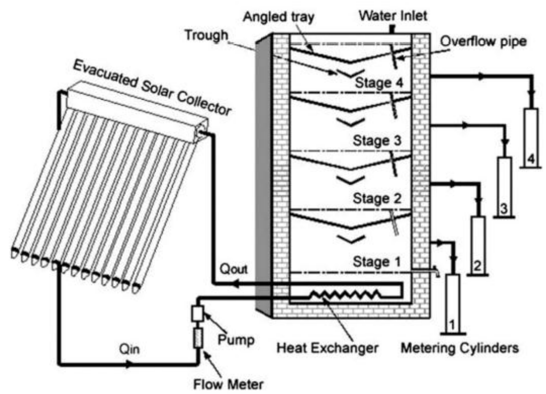

Figure 20. Multi-stage solar still with evacuated solar collector

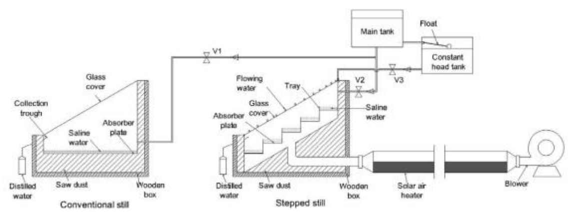

Figure 21. Stepped solar still coupled with a solar air-heater.

5.5 *Double slope solar still (DSSS)*

5.5.1 Double slope solar still with air heater

Riahi et al. [67] performed an air heater with a DSSS powered by PV, the heater inside the basin was powered by six PV panels and provided with 4 batteries. The solar sill's lengths were 1 m × 0.60 m × 0.60 m. According to their findings, the solar still with air heaters produced around 5.7 kg/m^2/day.

5.5.2 Double slope solar still with absorber materials

Pal et al. [67] researched the DSSS for producing potable water with jute and black cotton wick. The DSSS's area was 2 m^2. The highest productivity of the black cotton wick in 2 cm of water is 9012 ml/m^2/day, which is greater than the productivity of the jute wick in 2 cm of water (7040 ml/m^2/day). Kalidasa Murugavel et al. [2]. Experimented and tested a DSSS single basin with various energy storing substances in the basin. The sensible materials employed for storage were quartzite rock, cement concrete parts, red brick particles, washed stones, and iron scraps. They discovered that a still made of smaller quartzite rock was much more effective than a basin made from different materials. Akash et al. [67] investigated the single basin DSSS with black rubber inside the basin. The optimum production was 7 l/m^2/day.

5.5.3 Double-slope passive solar still with finned absorber

Single-basin DSSS with hollow square and circular cross-sectional fins is studied by Nagarani et al. [49]. They noted that the maximum production was 0.96 and 1.49kg/m^2 per day.

6. water quality

Solar still has the ability to produce drinkable water, and it can be used to reduce water scarcity in rural and coastal areas. A. Ahsan et al. [76] studied water quality before and after solar distillation system. For the feed and product water, a few water quality parameters were measured, including pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and arsenic. The product water's obtained parameters were compared to World Health Organization (WHO) standards. They found that the still was successful in removing pathogenic bacteria by more than 80% and also arsenic by 99%. A SSSS for the distillation of saline water was researched by Pillai et al. [77]. The pH, TDS, and EC of the treated water before and after treatment met WHO-2017 requirements. J. N. Baticados et al. [78] tested and studied the parameters that affected on water quality through solar distillation system. They found that the average reduction in EC was 96.52% and the average reduction of salinity of 96.52%.

7. Conclusion

Scarcity of clean water, high cost of energy and environmental problems encouraged the researchers to create effective ways to solve these future challenges. Therefore, research in this field is being aimed at maximizing the use of solar energy. Although the renewable energy is the cleaner form of power accessible on the earth, it is rarely employed extensively due to expensive desalination system equipment. Researchers tried to develop the solar still by various approaches to get a high level of performance. The solar stills are most appropriate for small community and coastal areas and we can obtain water free from minerals and salts. The efficient utilization of the solar energy could minimize the requirement for using high expensive conventional sources of energy. From this review on solar still, there are different methods and modifications used to improve efficiency and we concluded that:

- The solar still's production declines as the depth of water in daylight increases.
- Throughout the year, a cover inclination equal to latitude orientation will receive regular sunrays.
- Still productivity rises as the thickness of the glass cover is reduced and the temperature differential between the water basin and the interior surface of the glass cover rises
- Using of the sun-tracking device can boost the production of the still by about 22%
- For varied water depths, a still combined with a shallow solar pond produces more distillate and has higher performance than a passive still.
- Increased production was obtained by using heat energy substances such as jute cloths, sponge cubes, fins, flat perforated plate, and cottons, as well as PCM materials that produced continuously during the night from the solar still.
- Air cooling systems increased the difference in temperature between the water and the cover's glass, which improved the performance of any type of solar still.
- In the distillation process, increasing the salinity of the water could affect on the efficiency of the solar still.

- Compared to traditional stills, an inverted aluminum absorber sheet boosts output.
- Water flowing over through the transparent cover has a considerable impact on the basin's efficiency.
- By employing energy storage substance in the basin, solar productivity can be increased at night.

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