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Passive Solar Desalination Systems. Classification, Study Parameters and Future Enhancements.

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A R T I C L E I N F O

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A B S T R A C T

The scarcity in fresh water worldwide led to a great interest for the desalination systems. Passive desalination is a category of the desalination systems that fits the brackish and saline water desalination in the isolated zones without external energy source. This article introduces a comprehensive discussion of the existing designs of passive solar desalination systems. This includes the classification of different designs as well. The different parameters affecting the performance of the passive solar desalination systems are explored and discussed. The minimum water depth found to perform better than large water depths in the still basin. The wind speed found to affect positively on the desalination rate due to increasing the condensation rate. Using the fins on the surface of the cover found to enhance the desalinate productivity. Using of the heat storage found to improve the productivity during nighttime. Using reflectors to increase the solar energy incident on the basin increases the desalinate productivity. the inclination angle of the still found to improve the productivity if it is near the location latitude. However, the cover inclination has a negligible effect on the productivity. The cover material is preferred to be transparent with high thermal conductivity and lower thickness. Upon the findings based on the different parameters, some research points were suggested to enhance the performance of such systems.

1. Introduction

Water desalination became a vital source of fresh water all over the world especially in Middle East countries. These countries suffer from water scarcity because of the shortage of the fresh water sources. The available water in the world can be divided in to three parts; water in oceans, polar region and fresh water in rivers. The fresh water that can be used by humans represents about 0.36% of available water on the earth [1]. Therefore, the need for water desalination becomes a necessity. The operation of these systems depends on evaporating the fresh water from brackish or saline water and then condensing it to get the fresh water. There are variety of operation principles that will be explored in the following section.

The organization followed in this paper is as follows:

a) The classification of different designs over the last years for the passive solar desalination systems.
b) The different parameters investigated by the literature in last years and the discussion for the results of each study.
c) The conclusion part which describes general findings concluded form the presented literature.
d) The future possible enhancement for the presented systems.

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2. Classification of Different Designs

Solar Desalination Systems (SDS) can be divided into two main categories according to the location of the solar collector and the condenser. These two categories are direct and indirect systems. In direct systems, the collector and condenser are included in the same device. While in the indirect systems, the evaporation and condensation units are separate. Moreover, the indirect systems usually use external energy source for pumping or compression [2].

The direct systems are divided to active and passive system. In the active systems, an additional collector or condenser is used to increase the evaporation or condensation rate respectively. This in turn increases the freshwater productivity. While in the passive solar systems, limited modifications are applied in the basin for increasing the productivity [3]. However, other researchers like [4] postulated that the passive distillation systems are those at which solar energy is the only form of energy for creating the distillation action. While in the active systems, an auxiliary source of thermal energy is used for increasing the evaporation rate. The passive systems exist in one of three manners. The direct systems are divided to active and passive system. In the active systems, an additional collector or condenser is used to increase the evaporation or condensation rate respectively. This in turn increases the freshwater productivity. While in the passive solar systems, limited modifications are applied in the basin for increasing the productivity [3]. However, other researchers like [4] postulated that the passive distillation systems are those at which solar energy is the only form of energy for creating the distillation action. While in the active systems, an auxiliary source of thermal energy is used for increasing the evaporation rate. The passive systems exist in one of three manners. A Solar Still (SS), integrated with collector, and collector-condenser units without SS. Figure 1 illustrates the classification of the desalination systems.

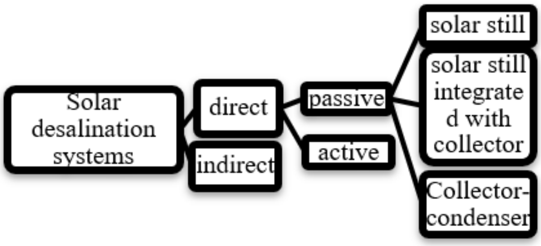


Figure 1. Classification of the solar desalination systems

This study is interested in the passive type of the SDS. So, the different designs of the passive desalination systems will be discussed in this article. Then the study parameters that were investigated will be explored in the different designs. Then the proposed enhancement according to the different designs will be noted about at the end of the article.

2.1 Solar Still

A SS is a desalination unit composed of two main parts. The first part is a basin contains the saline or brackish water that is required to be desalinated. The second part is a cover for that basin (that is normally glass). This cover permits the entrance of solar energy and the condensation of the evaporated water from the basin on its inner surface. The SS absorbs the sunlight through the glass cover [1]. The SS can exist in different shapes according to the form of the transparent cover or the geometry of the basin. A layout for the SS is shown in figure 2.

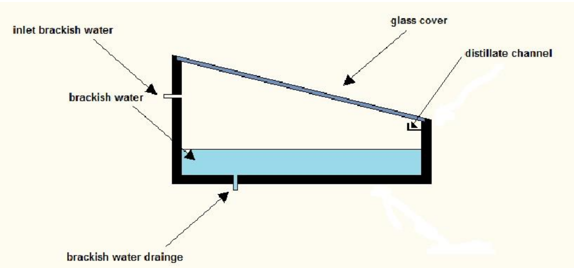
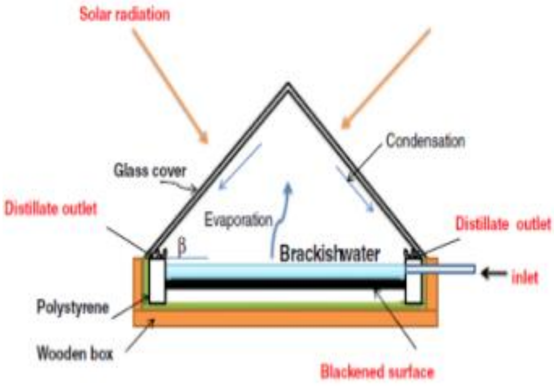


Figure 2. Simple layout for a SS

2.1.1 Solar Still Cover Geometries

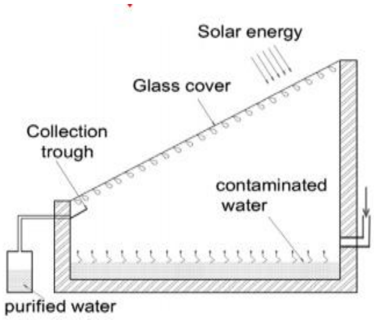
The cover of the SS is often a transparent glass plate to pass sun rays through it and hence heat up the water in the SS basin. Also. It works as a condenser over which the water vapor condenses and collects as desalinated water. The shapes of the SS cover that exist are as follows:

Single Slope Solar Still (SSSS), Double Slope Solar Still (DSSS), Double Effect Solar Still (DESS), Pyramid Shape Solar Still (PSSS) and Hemispherical Solar Still (HSS). These shapes are illustrated in figure 3

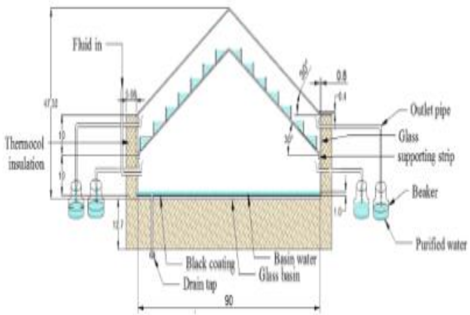


Double slope Solar Still [5]

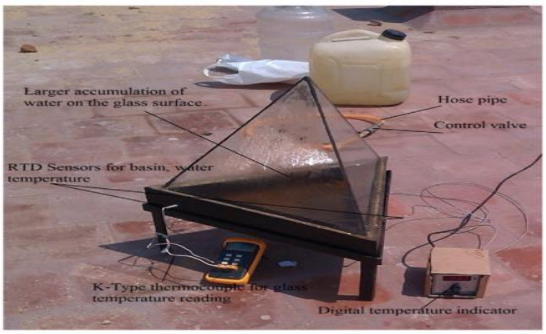
Single slope Solar Still [6]



Solar Still with double effect [7]



Pyramid shape Solar Still [8]



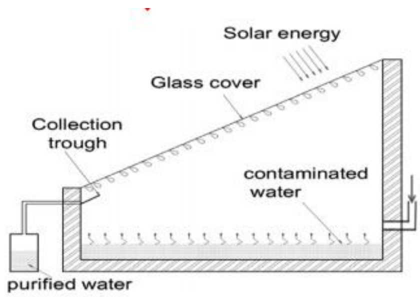
Hemispherical Solar Still [9]

Figure 3 Solar Still cover shapes

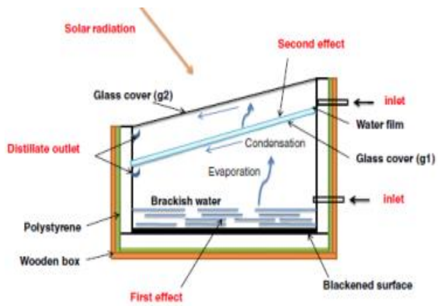
2.1.2 Solar Still Basin Geometry

The SS basin is the main part that contains the saline water which evaporates under the solar rays acting on it from the cover. The shapes of the SS basin that were investigated are as follows:

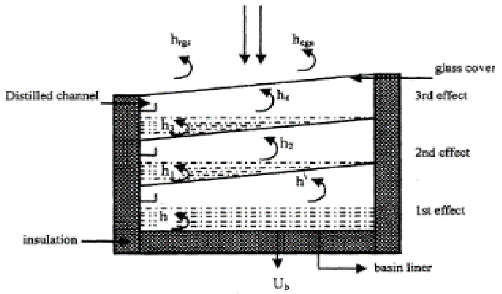
Single Basin Solar Still (SBSS), Double Basin Solar Still (DBSS) and Multi Basin Solar Still (MBSS). These shapes are illustrated in figure 4.



Single basin Solar Still [6]



Double basin Solar Still [5]

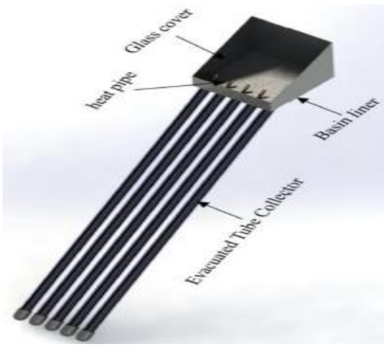


multiple basin Solar Still [10]

Figure 2 Solar Still basin geometries.

2.2 Solar Still Integrated with The Collector

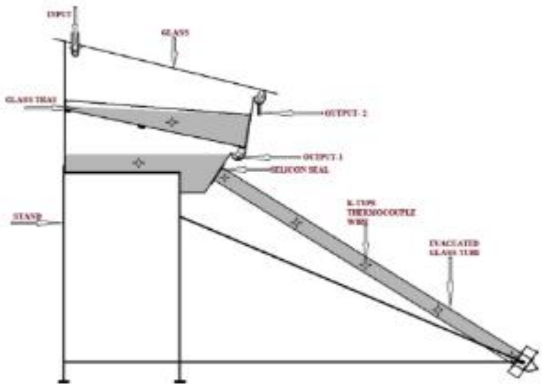
To enhance the performance of the SSs, additional heaters were integrated to the SS to increase the evaporation rate. A conventional SS can be connected to a Flat Plate Collector (FPC) like in [11],[12],[13] or Evacuated Tube Collector (ETC) like in [14],[15],[16],[17],[18],[19],[15]. Those collectors are used to enhance the efficiency of the SS [20] [21]. The different designs of the SS integrated with ETC and FPC are shown in figures 5 and 6.



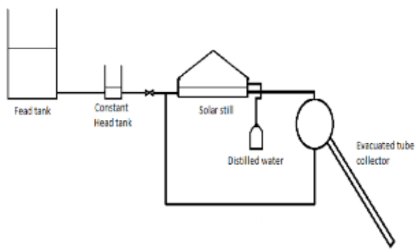
Single slop Solar Still with Thermo syphon heat pipes [15]

Single slop Solar Still [16]

Solar Still and evacuated solar water heater [19]

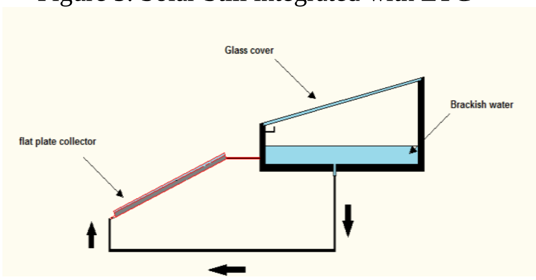


Double Basin Solar Still [17]



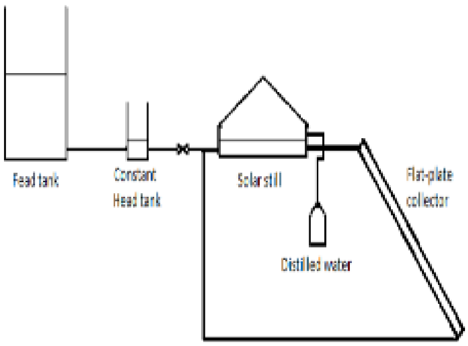
Pyramid-shape Solar Still [11]

Figure 5. Solar Still integrated with ETC

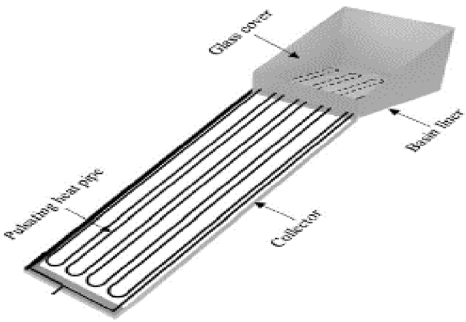


Single slope Solar Still

Double slope Solar Still [13]



Pyramid-shape Solar Still [11]



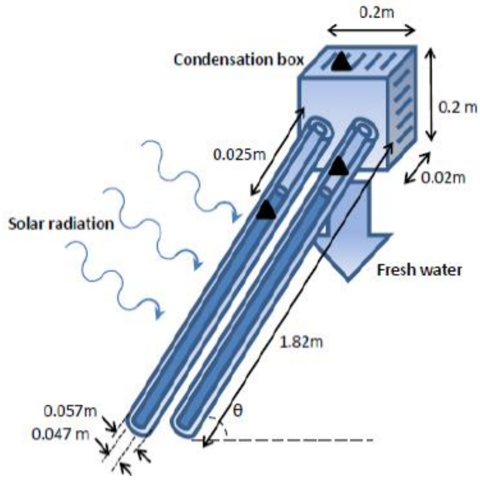
Single slope solar still with (Pulsating Heat Pipes) [12]

Figure 6. Solar Still integrated with FPC

2.3 Collector with Condenser

One of the new techniques for passive desalination is using the collector integrated with a condensation unit to act as the desalination unit. The collector is used for the evaporation process while the condenser is used for the condensation of this vapor through heat rejection to ambient. This unit does not include SS or glass covers. As the collector is used only for evaporating water, ETC were used like in [22] for its higher performance and higher temperatures. A metallic condenser was used for the condensation process for its high conductivity that aids in increasing the condensation rate. Figure 7 shows the two types of ETC with the condenser that were investigated up to now.

condenser mounted axially above with evacuated tube condenser [4]



condensation box with evacuated tube condenser [23]

Figure 7 Collector-Condenser classification

3. Studied parameters

There are many parameters that affect the production rate and efficiency of the passive desalination systems. These factors were investigated in the literature and they are as follows:

- Water depths.
- Wind speed over the cover or condenser.
- Heat storage media type and specifications.
- Fins on the surface of the cover.
- Reflector.

- Glass Cover Inclination Angle
- Collector's inclination angle
- Cover material.
- Cover thickness.

The effects of those factors are explored separately in the following paragraphs.

3.1 Water Depth

The depth of water in the SS basin is a very important parameter that controls the SS production. Changing the water depth decreases the heat capacity required to heat water and hence increases the evaporation rate. [24] studied theoretically the effect of changing the water depth in a SSSS by values of 0.56 ,1 and 2 cm. The results showed that the maximum production rate takes place at the lowest water depth (0.56 cm) and the production rate increased by 5% compared to the highest water depth of 2cm. [11] studied the effect of changing the water depth by 2, 3, 4 and 5 cm on SS production rate by using a SSSS integrated with a FPC. The results showed that the production rate increased by 16% at the water depth of 2cm compared to that at 5 cm water depth. [25] studied the effect of the water depth of 2 and 3.5 cm on the SS production rate using SSSS with asphalt basin liner. The results showed that the production rate increased by 26% at the water depth of 2cm over the 3.5 cm water depth. [7] studied the effect of changing water depth in the range of 1, 2, 3, 4 and 5cm on the productivity by using double and SBSS with double slopes. The results showed that productivity increased by 44% at the smallest depth for the DBSS compared to the largest depth. The production rate of the SBSS increased by 38% at the smallest depth for the DBSS compared to the largest depth. [14] studied the effect of three different water depths of 2, 4 and 6 cm on the production rate in a SSSS with aligned ETC. The results showed that the production rate increased by 68.2% at water depth of 2 cm compared to the 6 cm depth. [12] studied the effect of changing the water depth in the range (1, 2 and 3 cm) using SS with FPC and PHP (Pulsating Heat Pipes). The results showed that the production rate increased by 51.7% at water depth of 1 cm compared to that of 3 cm. [5] studied the effect of changing the water depth in the range of 2, 4, 6, 8 and 10 cm on the production rate in a DSSS and DESS. The results showed that the production rate increased by 62% and 43% using DESS and double slope one, respectively when using a water depth equal to 2cm in both cases compared to a 10 cm depth. [15] studied the effect of changing water depth in a SS with ETCs and thermosyphons on the water production rate. The water depths studied were in the range of 1, 2, 3, 4 and 5 cm . The results showed that the production rate increased by 70% at water depth equal to 2cm compared to that of 5 cm. At the water depth lower than 2cm, the entire heat pipe condenser is not completely submerged under the water level, so the water depth of 1cm did not guarantee acceptable evaporation rate of the water from the basin as a part of the thermo-syphon condenser is out of water.

[26] studied the effect of changing water depth in the range of 2, 3 and 4cm on the productivity of a SSSS with a black gravel heat storage system as shown in figure 8.

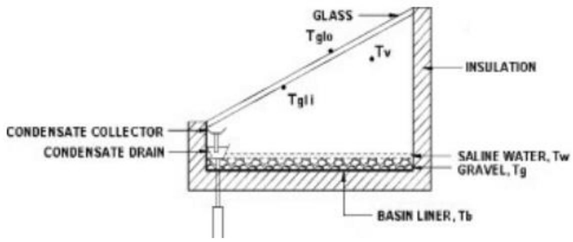


Figure 8 The SS with gravel, [26]

The results showed that the production rate increased by 19.6% at water depth equal to 3 cm when compared to 4 cm water depth. The water depth 2cm performed the highest production rate for the first four hour of the experiment. however, the water depth 3cm gave the highest productivity over the day. This performance may refer to the time taken from the black gravel to store heat. The black gravel is used for absorbing the excess heat energy from solar radiation during the noon hours. [13] studied the effect of changing water depth by 1 and 3 cm on water productivity by using double slop SS with FPC. The results showed that the production rate increased by 7.5% at 1cm compared to 3 cm. [27] studied the effect of changing water film thickness in the range 2-40mm on the production rate using regenerative SS system shown in figure 9. The unit consists of two basins and these arrangements have an advantage over the SBSS because of increasing the temperature difference between water and glass cover. The results showed that there is a marginal increase (2.8%) for the 2mm film thickness over the 40mm film thickness in the second effect. This very small effect is due to the moving water film in the second effect which did not permit large heating for the second effect but decreases its glass temperature which aid better in the condensation of the vapor than the first.

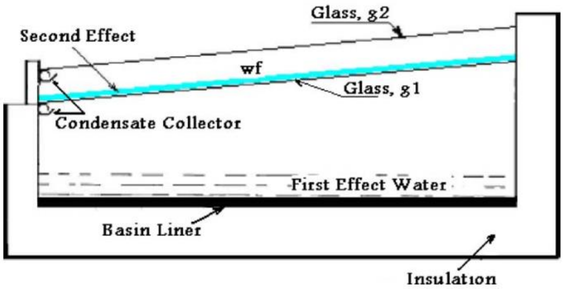


Figure 9 Regenerative Solar still (double basin), [27]

[28] studied numerically the effect of changing water quantity in the range of 10, 20 and 30 kg/m2 on the productivity of a MBSS system 9. They used multi-effect SS with separate collector and condenser as illustrated in figure 10. The results showed that the overall systems production rate increased by 16% at the lowest quantity of saline water in basin 1, and enhanced by 11% when using the minimum quantity of water for basin 2. For basin 3, the enhancement was very low as 3% for the lowest water quantity used because it is not exposed to the direct sunlight. These enhancement ratios was calculated compared to the largest water quantity in the basin. The productivity of a triple-basin SS at different water depths was investigated by [10] as shown in figure 4. Numerical calculations were performed at different water quantities (25-50-75-100-125-150-175-200 kg) on typical winter and summer days. The results showed that the overall productivity in kg/m2.hr increased by 280% at the lowest depth in comparison with the highest depth when changing water depth in lower basin and maintain the water depth in the two-other basins of 25 kg. The productivity increased by 74% and 8% at lower depth when changed the depth at the middle and the upper basin, respectively maintaining the water quantity of 25 kg for the untested basin in each case. [16] Studied the effect of changing water depth in the range of 5, 6, 7, 8, and 9 cm on a SS with ETC productivity as illustrated in figure 5. The result showed that the productivity increased by 76 % at 5cm compared to the 9 cm for the conventional SS. And the productivity increased by 40% l/m2.day for water depth of 5cm compared to 9 cm for the system coupled with ETC.

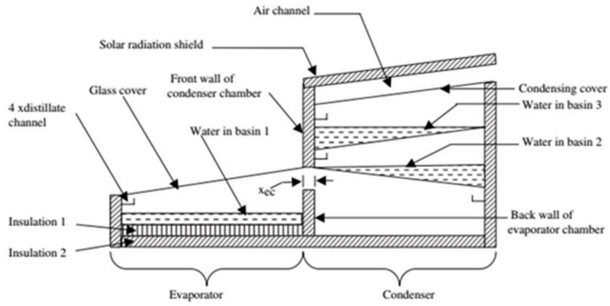


Figure 10 Multi-effect SS with separate collector and condenser [28]

3.2 Wind speed

Wind speed plays an important role in removing heat from the SS cover increasing the condensation rate. This in turn enhances the overall efficiency of the desalination system. some investigations were performed to test the effect of wind speed on the performance of the passive desalination systems.

Single slope SS was investigated under different wind speeds [25]. Wind speed was varied in the range from 2 to 5 m/s. The results showed that the production rate increased by 55% at wind speed of 5m/s compared to that of 2 m/s. [27] studied the effect of wind speed variation on the desalination system productivity using regenerative SS. The wind speed range was from 0 to 10 m/s. Production rate increased by 50% at the maximum wind speed compared to the minimum one. A triangular PSSS production rate at different wind speeds was studied by [8]. Different wind speeds of 1.5, 3 and 4.5 m/s were generated by a fan. The results showed that increasing the wind speed increased the still productivity and 15.5% at 4.5 m/s compared to 1.5 m/s. [29] and [30] showed that as the wind velocity increases, the production rate increase. These studies performed at wind speeds from 0 to 30 m/s. They claimed that it is better to install SS in a windy place because the production rate increases with wind speed. The production rate increased by 51% for the maximum wind speed compared to the minimum one

3.3 Heat storage

Desalination by SS system becomes more efficient. one of the system disadvantages is waste heat from the upper glass cover. SS can produce fresh water during daytime but the problem is during the night [18]. So, it is need to store energy to produce water during night. Storage energy during day time to the night time can be divided to sensible and latent heat [18]-[31]. Sensible heat was stored in Jute cloth, charcoal particle, and sand and quartzite rock. These materials are placed inside the SS basin and absorb solar energy during daytime then restore it at night. [32] Studied the effect of jute cloth as an energy storage medium on the SS production rate. Jute cloth which is put vertically in the middle of the SS basin and attached with the rear wall of the still. Jute cloth also represent a cheap, available material and easily to install without disturbing the basin area as shown in figure 11. Results showed that the water production rate increased by 12% when using jute cloth. Saline water temperature in the still with jute cloth was raised to about 74 °C which reduces the heat losses from the still compared to the conventional still water temperature.

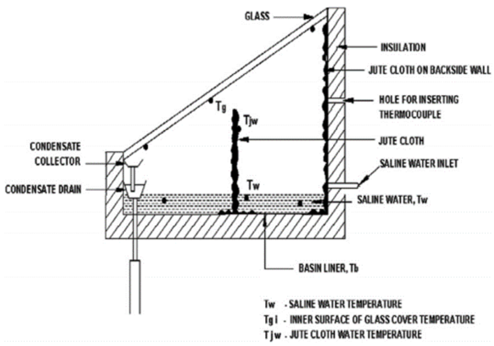


Figure 11 Single slope SS with vertical jute cloth in the middle of basin, [32].

The effect of sand as an energy storage medium on the SS productivity was studied by [33]. They claimed that the SS continues to produce fresh water after the sunset. More than 12% of total water production was pertaining to this time. [26] Studied the effect of using black grovel in the SS basin on water productivity. Results showed that the production rate increased by 40% at grovel depth equal to 25mm.

The latent heat storage systems present another heat storage technique that used in SS system. Latent heat storing can be handled by using phase change materials (PCMs). [34] Studied the effect of using PCM (Paraffin wax loaded in copper balls) in a SSSS system on the production rate, the obtained results show that the excess energy produced during sunshine times is stored in a PCM for use later during the night. Results showed that the use of PCM increases the production rate by 27%.[35] Used three types of paraffin wax with different melting temperatures of 42, 52, and 56 □C and depth of 8cm in the SS integrated with SSSS. They claimed that the use of the paraffin with 56 ⁰C melting temperature increased the production rate by 42%.

3.4 Fins

Fins represent a very good way to increase the productivity of convectional SS. It was found that using fins decreases the pre-heating time needed to evaporate water in the SS basin [36]. figure 12 shows a schematic diagram for SS integrated with fins.

The effect of adding fins inside the SS basin on a SSSS on water productivity was studied by [36]. Results showed that the water productivity increased by 49.5% by using fins. The effect of a single slope DBSS integrated with ETC . the used fins was 3cm mild steel integrated inside basin. A DBSS integrated with fins was studied by [37]. The results showed that the productivity using fins increased by 25% in comparison with the productivity without fins. A theoretical study the productivity of a single slope basin integrated with fins attached to the condenser was performed by [24]. The results showed that the productivity increased by 55% in comparison with the convectional system.

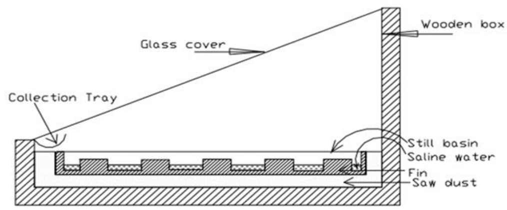


Figure 12 Cross-sectional view of SS integrated with fins [36].

3.5 Reflector

Internal and external mirrors integrated with the SS were used to reflected solar radiation on the SS to increase its solar energy input for water evaporation [38]. figure13 shows a schematic diagram for SS integrated with reflectors. [38] Studied the effect of reflectors integrated with SSSS on water productivity. The results showed that the combination of internal and external reflectors has better effect on the productivity than using the internal reflector or no reflector at all. The productivity increased by 26% with both internal and external reflectors.

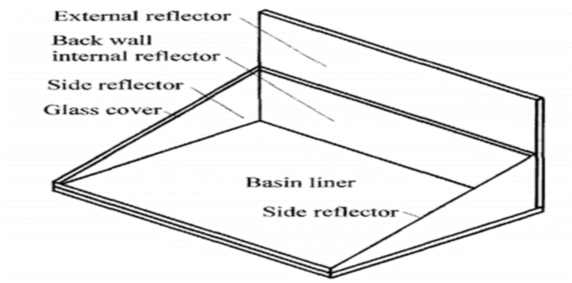


Figure 13 Schematic diagram of the basin type still with reflectors [38].

Another study was performed by [39] using combination of internal and external reflector at different condenser configuration. Results showed that the productivity increased by 80% in comparison with no reflector at all. [40] Studied the effect of using reflectors on the productivity of the PSSS. Results showed that the productivity increased by 90.8% in comparison with PSSS without reflectors.

3.6 Glass Cover Inclination Angle

The glass cover of the SS plays a vital role in its productivity. [24] studied theoretically the effect of changing the inclination angle of the glass cover in a SSSS on the SS productivity. They used different inclination angles of 15°,30°, and 45°. The results showed that the productivity increased by 35% at inclination angle of 15° compared to that of 45°. figure 14 shows a schematic diagram of a single slope passive SS.

[41] Studied experimentally the effect of the glass cover inclination angels of 15°,30° and 45° in a SSSS on the productivity. The results showed that the productivity increased by 30% at angle 45° compared to that of 15°. [5] studied computationally the effect of change the inclination angle of the glass cover by 10°, 30° and 45° for a DSSS and DESS on the SS productivity. The results showed that the productivity increased by 28% and 40% for DSSS and DESS, respectively at 10° compared to that of 45°.

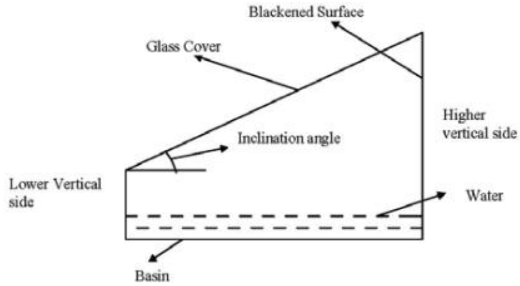


Figure 14 Schematic diagram of single slope passive SS [24]

The computational studies presented claimed that the productivity increases with decreasing the inclination angle, the conclusion is based up on the experimental study presented and the logic explanation that when the inclination angle is larger, it permits the slide of more quantity of desalinate bubbles which give available space for condensing larger quantity of vapor on the surface of the glass cover.

3.7 Collector's inclination angle

[19] studied the effect of changing the SS base inclination angle on the SS productivity. This study was performed at latitude angle 31° 20‘and the inclination angle used were 0°, 20° and 30°. figure 15 shows the different basin configuration of the used SS. Results showed that the highest productivity took place at inclination angle equal to 30°.

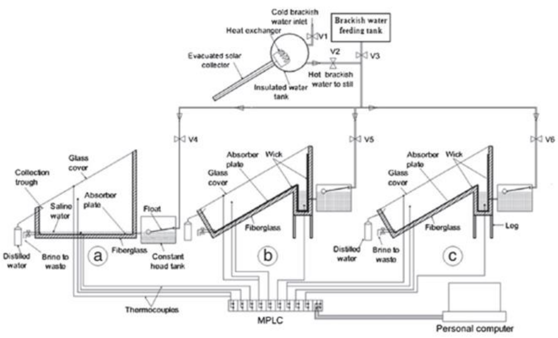


Figure 15 Different basin configuration for SS, [19]

The effect of inclination angle of a FPC on the SS productivity was studied by [12]. This study was performed at latitude of 35° 43' and the inclination angle used were 35°, 45° and 55°. The results showed that the productivity increased by 44.6% at the inclination angle of 35°. [4] studied the effect of changing ETC inclination angle on the SS productivity. This study was performed at latitude angle 35° 43' and the inclination angles used were 25°, 35° and 45°. The results showed that the productivity increased by 35.5% at inclination angle of 35°. It can be concluded that the best inclination angle of the collector or the SS basin is the latitude of the test place as showed in the presented studies.

3.8 Cover material

In this section, the effect of changing the condenser's cover material on the SS productivity is explored. [42] studied the effect of changing the condenser's cover material (glass and metal) on a single basin double slope (asymmetric) SS with a condenser-evaporator plate and a condenser plate productivity. figure 16 shows a schematic photo of SS. The performance of the introduced SS was estimated and compared to that of a conventional one under the same conditions. Results showed that the productivity increased by 55% when using a glass cover over the metallic cover.

The effect of changing glass cover material in a SS integrated with a thermo-syphon ETC was studied by [15]. Glass, aluminum and steel were the cover's material tested in this study. The results showed that the productivity of the glass cover was higher by 150% compared to the steel cover.

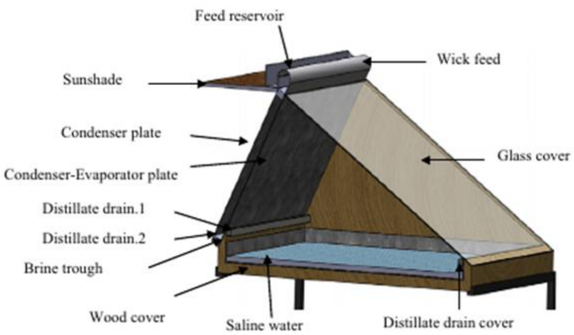


Figure 16 schematic photo of SS, [42]

3.9 Cover thickness

[13] Studied the effect of changing SS glass cover thickness by 3,4 and 5 mm on the SS productivity. This study was performed by using convectional DSSS and double slope SS integrated with FPC. A glass cover was provided by a cooling system having a period of 5, 10 and 15 mins on/off. Results showed that the maximum production rate occurs at cover thickness equal 3mm. The productivity increased by 18% at the smallest glass cover thickness compared to the largest one.

4. Conclusion

The passive desalination systems have various designs and types. Each of the presented design has its advantages and disadvantages. Some parameters were tested in these different designs which was discussed in the section. The conclusion of each test parameters is as follows:

- Water depth in the SS basin was investigated in the range from 0.56 to 18 cm. The studies showed that the maximum production rate occurs normally at the lowest water depth that causes the lowest heat capacity absorbed by water at smaller depths.
- Wind speed is considered the main source of the condensation of the vapor on the SS cover. As the wind speed increases, the heat convection from the condenser and the condensation rate increase.
- Heat storage media were used in the SS to extend its performance to the night time and to decrease its maximum temperature to decrease its losses. The use of sensible and latent heat storage media was found to increase the productivity of the SS over the day.
- Using fins in the basin of the water still and on the condenser's cover was found to increase the productivity of the SS. This is because the fins extend the surface of the heat transfer and increase the evaporation rate when used in the basin and increase the condensation when used on the SS cover.
- Internal and external reflectors integrated with the SS was found to reflect solar radiation into the SS and increase its solar gain and productivity.
- The slope of the glass cover has a significant effect on the productivity. It was found experimentally that as the inclination angle increases, the productivity increase. This was explained by the increase of the slip rate of the condensed drops on the surface of the cover. This was not agreed by the computational

studies. However, the experimental studies presented claimed that.

- The collector or the SS basin inclination angle was found to be optimum when it is equals to the latitude of the location.
- The effect of the SS cover thickness and material also have an effect on the SS productivity. The productivity of SS was found to increase when using a glass cover instead of metals to permit the solar radiation entrance to the still basin. As the glass cover thickness decreases, the productivity found to increase due to lower thermal resistance of the smaller thickness.its losses. The use of sensible and latent heat storage media was found to increase the productivity of the SS over the day.
- Using fins in the basin of the water still and on the condenser's cover was found to increase the productivity of the SS. This is because the fins extend the surface of the heat transfer and increase the evaporation rate when used in the basin and increase the condensation when used on the SS cover.
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5 Suggestions for Future Enhancements

One of the promising systems found in the literature is the collector-condenser desalination system without SS. This is because the SS participates in losing a great quantity of energy in heating the water in the basin and the air space inside the SS. The collector of the system of this type was an ETC. This is because the ETC has high efficiency at high temperature (evaporation). Some enhancement modifications on this system is suggested as follows:

- To investigate the effect of changing water film thickness inside the ETC using inserted cores of low thermal conductivity and low heat capacity materials on the performance of the system.
- To study the effect of varying wind speed using natural wind and fan on the performance of such systems.
- Investigate the effect of using PCM with deferent melting temperatures larger than 56□C inside the ETC on the over-day performance of the system.
- To perform an investigation regarding the effect of fins on the outer surface of the condenser to increase the condensation rate.
- To perform a study on the effect of different inclination angles for the condenser on the performance of the system.
- To test the effect of changing the material of the metal condenser by different thermal conductivity materials on the performance of the system.

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