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A review and comparison of solar distillation: Direct and indirect type systems

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ABSTRACT

One of the fast growing problems around the world is providing drinking water. This is felt especially in arid and semi-arid areas where lots of people lack fresh water. Solar energy can be used as the heat source to distillate brackish water. In this study, a comprehensive review of solar desalination systems is presented. The solar distillation systems are classified into two groups: direct distillation systems and indirect distillation systems. Comparison of the systems is presented in the tables.

Keywords: Solar distillation; System types; Direct type; Indirect type; Review

1. Introduction

Many countries around the world have experienced droughts or water shortage with different levels of severity in recent centuries. Although water covers more than two thirds of the earth's surface, more than 97% of that is salty, and just a small fraction of available water is fresh water. Moreover, due to population increase, the irrational waste and especially severe contamination of the existing resources, the availability and quality of fresh water resources have decreased dramatically. In some cases, the increased pollution of rivers, lakes and groundwater has significantly reduced the availability of fresh water, like two major cities of Cyprus, Lefkoşa and Magosa. The main water was drinking twenty years ago, but now underground water became brackish.

Desalination is a proper solution to provide fresh water. However, desalination needs huge amounts of energy produced from fossil fuels (e.g. coal, oil) or from sustainable renewable energy sources. Solar energy is the most suitable energy to be used in desalination systems since it is free, often abundant in arid and semi-arid areas having water shortage and clean (zero emission). Also, the best feature of these systems is that the need for electricity is omitted since most remote areas not only lack water but also electricity connection. Moreover, after natural disasters, providing fresh water is necessary for remainders, like many people who were victims of the Indian Ocean tsunami and earthquake on December 26, 2004 who could not get enough sanitary drinking water during weeks or months after the disaster.

Among different classifications of solar desalination systems, the categorization based on the structure of the systems is considered for this study. According to the definition, solar desalination systems fall into two main categories: direct solar desalination systems and indirect solar desalination systems. Direct solar desalination systems refer to those whose all parts are integrated into one system meaning that solar energy is used to produce distillate mainly on the backside of the glass cover of the solar collector. Indirect solar desalination systems are those consisting of two parts — solar energy collector and desalination part. In these systems, distillate is mainly produced in a separate condenser.

The main objective of this study is to present a thorough investigation of available direct type and indirect

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type distillation systems found in the literature, and to provide comparisons of productivities of the systems.

2. A brief history of distillation

Many attempts have been made in history to distract fresh water from brackish water. People who had long journeys around the Mediterranean Sea tried to get potable water from seawater by using solar thermal radiation. The first man who mentioned sweetness of distilled water in his book on meteorology was Aristotle (384–322 BC), the ancient Greek philosopher and physician. A famous scientist Giovani Batista Della Porta (1535–1615) wrote many books; and in one of his books called Magiae Naturalis [1], published in 1558, three different desalination systems were mentioned; and in the 19th volume, a solar distillation apparatus converting brackish water to fresh water was described. He also explained how to get fresh water from humid air, which is nowadays called humidification–dehumidification system. A famous French scientist Mouchot [2] discussed the usage of polished Damascus concave mirrors by Arabs in order to concentrate solar radiation onto glass vessels containing salt water to produce drinking water. After Della Porta, no important application of solar distillation was introduced until the 19th century. Wheeler and Evans [3] introduced the first American patent on solar desalination systems in 1870. In their patent, the absorption by black surface, green house effect, and possible corrosion problems were discussed. In 1872, the first solar desalination plant was built by a Swedish engineer Carlson Wilson, in Las Salinas, Chile [4]. In order to provide fresh water for the miners and their family, this plant was built with the total land area of 7896 m^2 and was in operation for 40 years.

The real revolution in solar desalination usage occurred in the middle of the 20th century. Many small solar systems were built in Europe, USA and USSR, but just a few solar desalination plants were in operation up to the 2nd World War, when providing fresh water for soldiers in arid remote areas made the interests for solar desalination systems stronger [5,6]. After World War II, many systems were installed in different countries like United States, Australia, USSR, Greek Islands, Portugal, and India [7–9].

3. Direct solar distillation systems

Many experimental and theoretical investigations have been conducted around the world in order to increase the rate of productivity of solar stills.

A single-slope solar still (called conventional solar still) is the simplest still as shown in Fig. 1. Water in the basin is heated by upcoming solar radiation. As it is heated the rate of evaporation increases, when water vapor reaches the back side of the glass cover, since it is in lower temperature than the dew point temperature of the air–vapor mixture in the cavity, starts condensing on it. The slope of the glass cover causes the distilled water to flow down to be collected in a provided vessel.

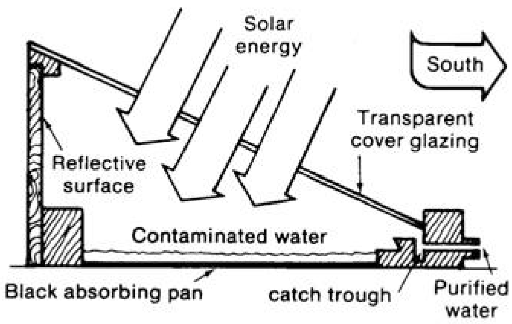

Fig. 1. Simple solar still [10].

Double basin and triple basin solar stills consist of two and three basins located upon each other, respectively. These systems use the benefit of having two, and three in the case of triple basin, evaporators and condensers. As a result, the evaporation rate will increase, and a higher condensation rate will be obtained. Al-Karaghouli and Alnaser [11] fabricated and tested a double basin solar still and a single basin solar still with side-insulation and without side-insulation, and the comparison was carried out at the University of Bahrain. The productivity rates of the double basin solar still with side-insulation was 3.91 kg/m^2.d and that of the still without side-insulation was 3.13 kg/m^2.d. The productivity rate of the single basin solar still with side-insulation was 2.84 kg/m^2.d and that of the still without side-insulation was 1.105 kg/m^2.d. Also, it was found that adding 2.5 cm styrobore insulation material can significantly increase the rate of water production. El-Sebaii [12] presented a transient mathematical model to predict the daily productivity of a triple basin solar still on a typical summer day. The productivity of it was found to be 12.635 kg/m^2.d.

Double glass cooling solar stills, as shown in Fig. 2, consist of a basin and two glass covers with a thin distance between them to let the water flow [13]. This flowing water cools the lower glass cover. As a result, the temperature difference between water in the basin and the glass cover increases, leading to a higher evaporation and condensation rate. Abu-Arabi et al. [13] studied modeling and performance of a single-basin solar still with entering brine flowing between a double-glass glazing. Cumulative productivity in June was 4.0 kg/m^2.d while for the conventional one it was 2.9 kg/m^2.d

An experimental study on an inclined basin solar still, which is shown in Fig. 3, was presented by Aybar et.al. [14]. This system actually is an inclined solar still covered with a wick which can be tested also with a bare plate. Water distributed over the absorber plate or wick which can be used on the absorber plate and flows through it. The absorbed water in the wick is heated by solar radia-

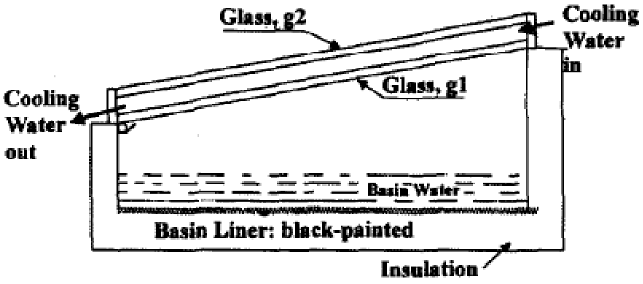

Fig. 2. Double glass cooling solar still [13].

tion and starts evaporating. When water vapor reaches the glass cover which is at lower temperature than the dew point of the air–vapor mixture in the cavity, it starts condensing on it. The condensate is collected by vessels to be taken out. Providing hot water and fresh water simultaneously is the advantage of this system. According to the results of conducted experiments, the productivity rates of the inclined solar still with bare plate, black-cloth wick and black-fleece wick were 1.29, 1.705 and 2.995 kg/m^2.d, respectively, while that of hot water were 37.925, 43.050 and 44.075 kg/m^2.d, respectively.

Janarthanan et al. [15] proposed a floating cum-tilted-wick type solar still with water flowing over the glass cover. A pyramid-shaped solar still is another innovative design which was proposed as shown in Fig. 4 [16]. Having the four side transparent glass cover, facing towards the geometrical directions, causes to get the most possible solar radiation. But high loss of reflected solar radiation leading to low productivity rate made it undesirable.

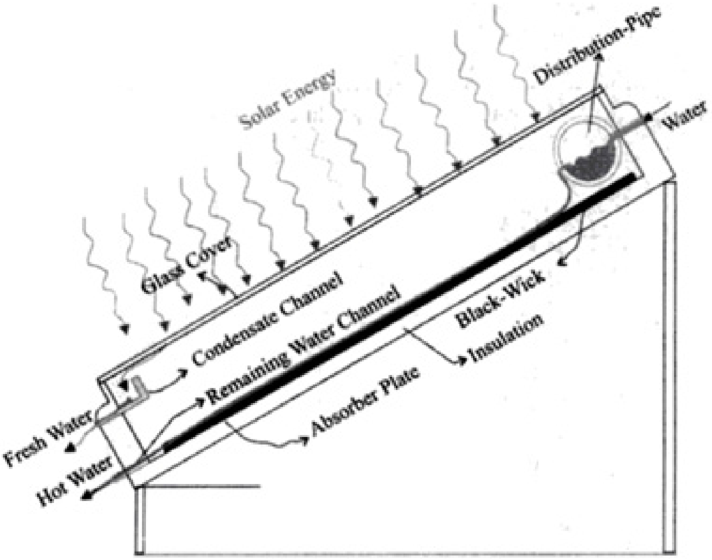

Fig. 3. Wick type solar still [14].

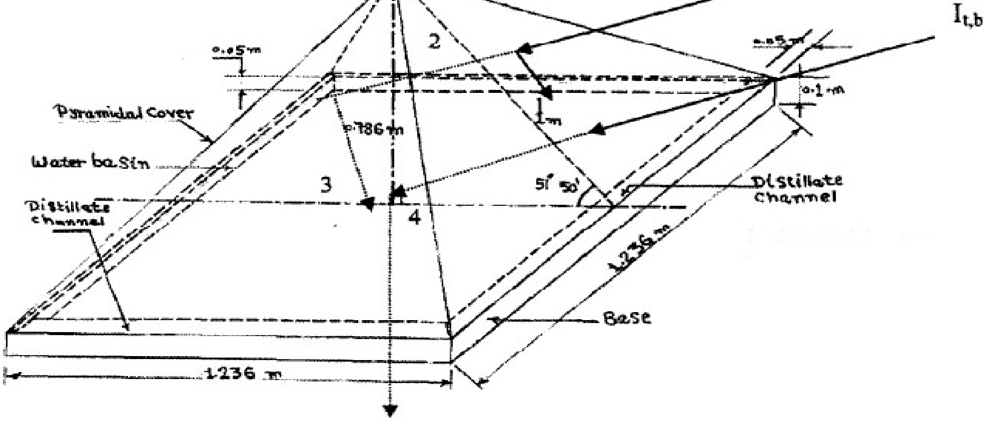

Fig. 4. Pyramid-shaped solar still [16].

An analytical study between the pyramid-shaped and conventional solar still was done by Fath et al. [16]. A mathematical model was developed to simulate two configurations. The meteorological data of Aswan City (south of Egypt) were used. The productivity of the pyramid-shaped still was 4.5 kg/m^2.d in February compared to that of the conventional still which was 3.2 kg/m^2.d. In July the productivity rate was 6.5 kg/m^2.d for both systems.

A stepped humidifier–dehumidifier solar still has been proposed by Fath et al. [17]. In this special design which has a relatively high productivity rate, the still consists of a rectangular box, and this central part divides the still into two chambers: upper and lower. The upper chamber is the evaporation chamber and lower one is the condenser of the system. The central part is constructed of some small basin as shown in Fig. 5. The shallow water in small stepped basins is heated by solar radiation and starts evaporating and humidifying the air in the upper chamber. The humidified air circulates in the system and when it contacts the lower chamber (condenser), water vapor starts condensing since the lower part is in lower temperature than the dew point of the air–vapor mixture. According to the numerical study reported by the author, the productivity of 5.3 kg/m^2.d can be achieved from this system.

Another solar still design was proposed in by Boukar and Harmim [18] which is called vertical solar still. In this type of stills, the feed water flows over the vertical spongy absorber through small holes and is heated by upcoming solar radiation. Water vapor when reaches the glass cover, starts condensing on it. A schematic diagram of the prototype is shown in Fig. 6. An experiment on a vertical solar still under the desert climatic conditions in Algeria, Adrar was carried out by Boukar and Harmim [18] in June. The total productivity of the vertical solar still was reported to vary from 0.5 to 2.3 kg/m^2.d.

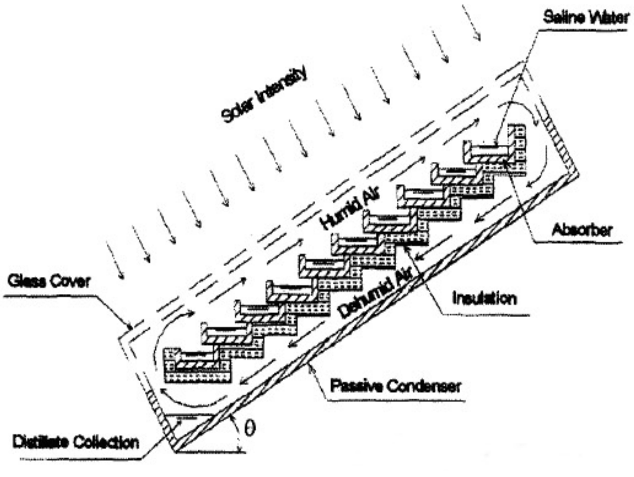

Fig. 5. Stepped solar still [17].

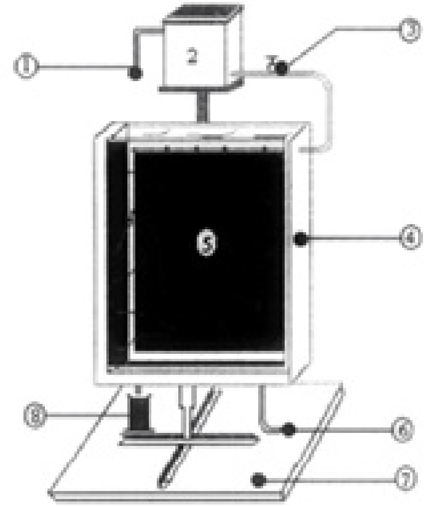

Fig. 6. Vertical solar still [18].

A distiller with a film in capillary motion (DIFICAP) was designed and patented by Bouchekima et al. [19]. A schematic diagram of the system is shown in Fig. 7. A very thin fabric which is in contact with a hanging plate is used to absorb distributing water. The interfacial tension force which is greater than the gravitational force holds the fabric. The brackish water is heated by solar radiation and the green house effect and it starts evaporating. As the water vapor reaches the condenser which is the bottom of the basin, it starts condensing on it since the condenser is in a lower temperature than the dew point of the air–vapor mixture in the cavity.

Aboul-Enein et al. [20] experimentally investigated the productivity of a single basin solar still with a deep basin in Tanta University, Egypt. The daily productivity of the system was 2.045 kg/m^2 and the maximum solar intensity was 1006 W/m^2 at 13:00. Also the reciprocal relation between the water depth in the basin and the productivity rate was reported.

Cappelletti [21] constructed and performed an experiment with a plastic solar still with two basins superimposed upon each other in Foggia, Italy. The greatest quantity of fresh water obtained by the tested solar still was 1.7–1.8 kg/m^2.d achieved in the third week of July when solar radiation was 27–28 Mj/m^2.d.

Al-Hinai et al. [22] have done a theoretical parametric investigation on a double-effect solar still and a single-effect solar still in Sultan Qaboos University, Oman. The maximum productivity of 0.5 kg/m^2.h was obtained in February when solar radiation was 16.4 Mj/m^2.d. The average annual yields of 4.15 kg/m^2.d and 6 kg/m^2.d for single and double effect solar stills were reported.

An experimental and theoretical study of a single-basin solar still was performed by Nijmeh et al. [23] in Hashemite University in Zarqa, Jordan. Potassium

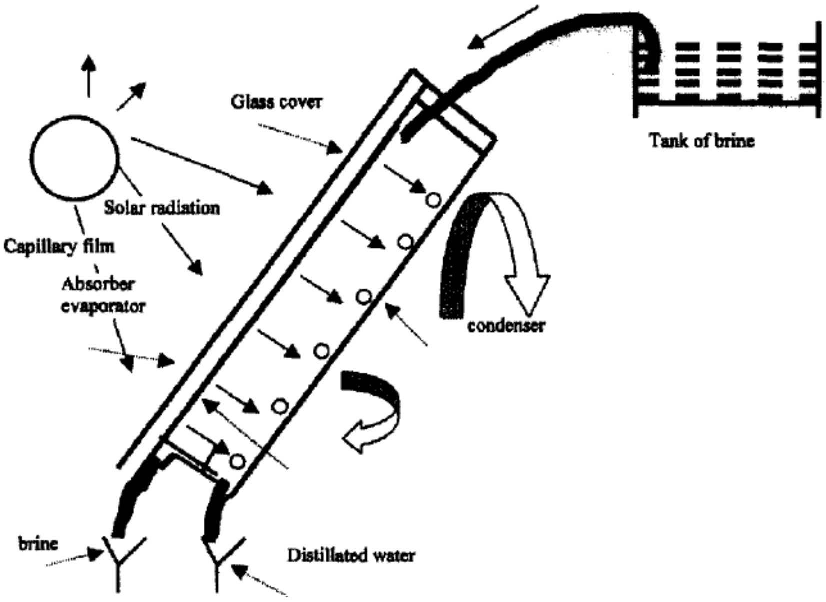

Fig. 7. Distiller with capillary film [19].

permanganate ($KMnO_4$) and potassium dichromate ($K_2Cr_2O_7$), violet dye and charcoal 50% were solved in the feed water in order to increase the final productivity. The reported productivity rates were 5.75, 5.50, 5.50 and 5.50 kg/m^2.d, respectively, while for the basin containing just water, 4.5 kg/m^2.d fresh water was reported. Also, it was found that when 50% of the basin surface area was covered with charcoal, the productivity rate was the highest compared to using other percentages of charcoal.

Tanaka and Nakatake [24] theoretically analyzed a basin type solar still with internal and external reflectors at Kurume National College of Technology in Fukuoko, Japan. It was found that the daily amount of distillate can be increased up to 48% by using external reflector and 22% in the case of internal reflector when the inclination angle is 20°.

Hamdan et al. [25] theoretically and experimentally studied the performance of single, double and triple basin solar stills in Amman, Jordan. The productivities of triple, double and single basin stills, with the base area of 0.92 m^2, were found to be 4.896, 4.610 and 3.693 kg/m^2.d, respectively, when the average solar intensity was 26.7 Mj/m^2.d.

Bouchekima et al. [26] experimentally analyzed a type of distiller called capillary film distiller (DIFICAP) with different stages in southern Algeria in an experimental station near Touggourt (Algerian Sahara). The reported productivity for the one-stage system was about 2.77 kg/m^2.d and that of the two-stage system 5.19 kg/m^2.d while the base area of the device was 0.5 m^2.

Sunja and Tiwari [27] analytically studied the effect of water depth in the basin on the productivity of an inverted absorber double basin solar still in the Indian Institute of Technology, New Delhi, India. The reported productivity for the system, when each effect contains 20 kg water, was 8.5 kg/m^2.d between 6:00 am and 6:00 pm while the average solar intensity was 12.88 Mj/m^2.day. A parametric study of an inverted absorber triple effect solar still in the same institute was carried out by the same authors [28]. It was found that the yield of an inverted absorber triple effect solar still was substantially higher than that of a double and single basin inverted absorber solar still.

The productivity rates of different systems, obtained from the experimental studies, are shown in Table 1. Although the productivity of each system depends on the climatic conditions like ambient temperature, inlet water temperature, solar radiation intensity and system properties, but having the results of conducted experiment all in one table, makes the comparison convenient. The lowest productivity rate is for the single basin solar still made of plastic and the highest one is for the single basin solar still containing water and $KMnO_4$. Single-basin solar still is one of the most suitable systems because of simple construction, low maintenance and initial cost and relatively high productivity rate. These characteristics make it a suitable system for arid remote regions where end-users mostly are low educated.

4. Indirect solar distillation systems

With the aim of increasing the productivity of solar desalination units, indirect solar units were introduced. These systems consist of a separate evaporator and condenser in order to eliminate the loss of latent heat of condensation.

The basic idea in humidification–dehumidification (HD) process is to mix air with water vapor and then

Table 1
Experimental results of different direct solar desalination systems

System	Place	Solar intensity (MJ/m^2.d)	Ambient mean temperature (°C)	Productivity (kg/m^2.d)	Ref.
Double basin solar still with side insulation	Bahrain	18.15	39	3.91	[11]
Single basin solar still with side insulation	Bahrain	18.15	39	2.84	[11]
Inclined solar still with black-fleece wick	North Cyprus	11.98	25	2.99	[14]
Vertical solar still	Algeria	17.31	40	0.5–2.3	[18]
Plastic single basin solar still	Italy	27	30	1.8	[21]
Single basin solar still with $KMnO_4$	Jordan	21.56	27	5.75	[23]
Single basin solar still with 50% charcoal	Jordan	21.56	27	5.2	[23]
DIFICAP with single stage	Algeria	N/A	40	2.76	[26]
DIFICAP with two stages	Algeria	N/A	40	5.19	[26]

extract water from the humidified air by condenser. The amount of vapor that air can hold depends on its temperature. Two different cycles are available for HD units: HD units based on open-water closed-air cycle, and HD units based on open-air closed-water cycle. Some advantageous of HD units are: operation at low temperature, ability to combine with renewable energy sources like solar energy, modest level of technology, and high productivity rates.

The process of open-water closed-air cycle is shown in Fig. 8. Seawater enters the system (5), and is heated in the solar collector (3), and then it is sprayed into the air in the evaporator (1). Humidified air is circulated (4) in the system and when it reaches the condenser (2), certain amounts of water vapor start condensing. Distilled water is collected in the provided container (6). Some of the brine can be also recycled in the system (8) in order to have better efficiency and the rest is taken out (7) [29].

Fig. 9 shows a closed-water open-air HD system. Here closed-water cycle is used to put emphasis on recycling the brine through the system ensuring a high utilization of the salt water for fresh water production. As air passes through the evaporator, it is humidified and by passing through condenser water vapor is extracted [30]. Bacha et al. [31] proposed a system with the same concept of HD units based on the closed-air open-water cycle. This system is also called solar multiple condensation evaporation cycle (SMCEC). The good quality of distilled water obtained by this concept favors its use for producing water for drinking and irrigation.

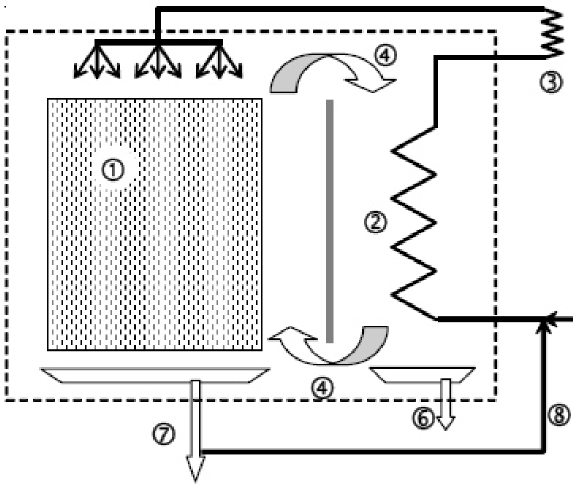

Fig. 8. Open-water closed-air HD unit [29].

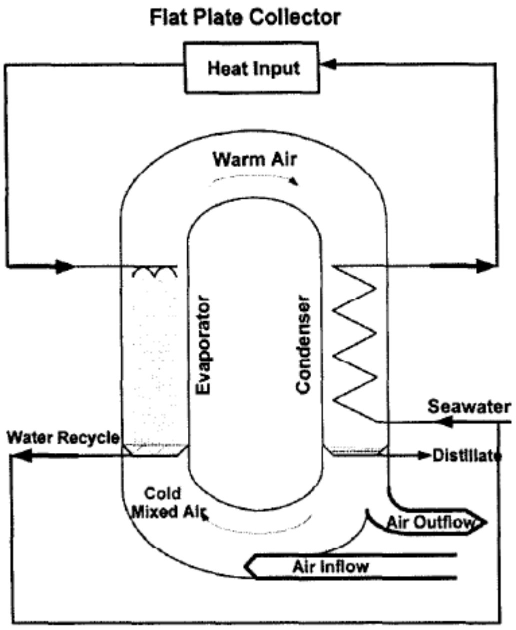

Fig. 9. Closed-water open-air HD unit [30].

According to the definition, multi-effect humidification (MEH) process is referred to those systems having more than two effects. In such systems, the hot air is heated in the tilted solar collector. The heated air coming from the solar collector is humidified in each effect by spraying cold brine water onto it. Finally the air which has most possible vapor reaches the last effect. In the last effect humidified air is condensed on the surface of a water brine vessel since its surface temperature is lower than the dew point temperature of the air–vapor mixture. The distillate is collected to be taken out of the system. Also some vapor can be distilled on the cover of baffles which are used between the effects. These baffles transfer the latent heat of condensation to the next effect which, in turn, increases the temperature of air in that effect. As the temperature of the air increases, the amount of possible absorbed vapor by air increases. A multi-effect distiller is generally more effective thermodynamically than a single-effect distiller since the former uses the available energy, which is in the form of latent heat of condensation, more than once (Fig. 10).

Yamali and Solmus [32] proposed a design with a double-pass flat plate solar air heater. This system works with the idea of closed-water open-air cycle. In their proposed design air is heated by using a double-pass solar air heater instead of a single pass solar air heater, while water is not heated. According to their study, 8% increase in productivity was achieved by using a double pass solar air heater.

Apart from HD systems, some designs have been proposed in the literature using separate evaporator and condenser. A new design was proposed by Rahim and Tagi [33] in the University of Bahrain. As shown in Fig. 11, the system looks like a conventional solar still equipped with a fan in order to create forced condensation inside the copper tubes. Copper tubes act as the condenser of the system since they are in lower temperature. Water vapor is sucked by the fan from the evaporating zone and starts condensing inside the copper tubes. Some of the advantages of this design are: a) by sucking water vapor from the evaporation area, it is not allowed to be condensed on the backside of the glass cover leading to better transparency of the glass cover leading to better efficiency, b) since forced convection is used, more vapor reaches the condenser thereby more distillate is produced, c) the re-evaporation of the produced distillate is eliminated.

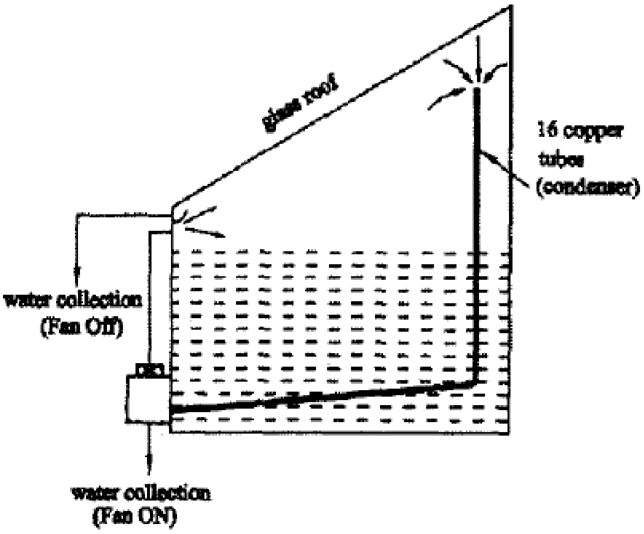

Fig. 11. Solar still with forced condensation [33].

Another design using a separate evaporator condenser is proposed by Hussain and Rahim [34]. This separation permitted the evaporating zone to be insulated to reduce the heat losses to the surroundings and to shade the condensing unit to keep it as cool as possible. According to the experimental results of their study, by a forced condensing system (fan on) 2.4 kg/m^2.d can be obtained when solar radiation is 19 Mj/m^2.d while with

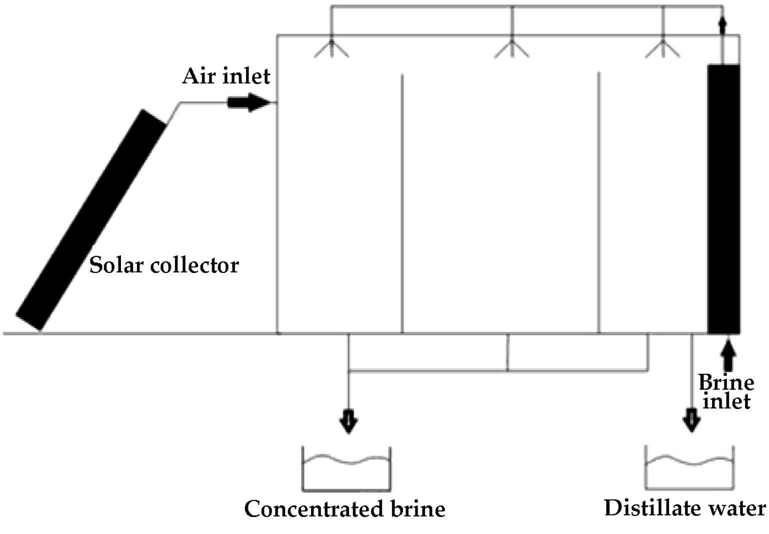

Fig. 10. Multi-effect HD unit.

natural condensation (fan off) 1.6 kg/m^2.d is obtainable. Also 28% improvement in the efficiency of the system was reported in the case of utilizing the heat absorbed by the back wall of the evaporator. A basin type solar still with minimum inclination (4°), connected to an outside condenser (Fig. 12), was designed and constructed with the aim of increasing the productivity of fresh water by El-Bahi and Inan [35]. Water in the basin is heated by solar radiation and also by the part reflected from the reflector. As water is heated, it starts evaporating, water vapor is purged to the outside condenser due to pressure difference between the evaporator and condenser, this pressure difference is due to temperature difference, since the outside condenser is colder than the evaporator. Also, a small amount of distillate is condensed on the backside of the glass cover. This modified basin-type solar still is suitable for a house to provide it with fresh water. The proposed solar still was claimed to work perfectly with the yield up to 7 kg/m^2.d under the Ankara meteorological conditions. The efficiency of the system was reported to be improved up to 75% in June, July and August.

A schematic diagram of a solar still with enhanced falling film is shown in Fig. 13 [36]. From the bottom of the vertical tube condenser, feed water enters the system (3) and through a serpentine copper tube (4) reaches the overflow weir (7). Water uniformly wets the evaporation film (8) and is heated by solar radiation to be evaporated. The leaving brine leaves the evaporation chamber (1) to the vertical tubes (6). The inner surface of the walls of the tubes is wetted by flowing briny water. Simultaneously, the air is blown into (6) by a fan to be humidified. The air–vapor mixture formed in (6) is led to the evaporation chamber (1) to absorb high temperature vapor. Then the humidified air is sent to the lower chamber (2) in which a part of it condenses and preheats the entering water. The mixture of the distillate and low temperature humid air is sent to the condenser (3). Finally, the distillate and air–vapor mixture with low relative humidity go to the provided gas–liquid separator (5) in order to extract the most possible water of the mixture. It is reported that the performance ratio of this system is about 2–4 times greater than that of a conventional basin-type solar still.

A schematic diagram of a multiple-effect diffusion type still coupled with a basin type still proposed by Tanaka et al. [37] is shown in Fig. 14. Both systems consist of a sloped double glass cover facing the sun, a horizontal basin liner and a number of vertical partitions. All partitions, except the last one, are in contact with saline-soaked wicks. The solar radiation is absorbed by the basin and first partition. The absorbed heat is transferred through the partition to the flowing water on the back side of the partition. Flowing water is heated and starts evaporating. Water vapor starts condensing on the second partition and latent heat of condensation is transferred to the flowing water on the other side of the second partition. The distillate is taken out by provided vessels. The same process occurs for all partitions. The proposed design, without a reflector having 10 vertical cells with 5 mm gaps, is theoretically predicted to have 15.4 kg/m^2.d productivity with the solar radiation of 22.4 MJ/m^2.d. The efficiency of the system was 3.5 times larger than that of a conventional solar still. Also the special type of this system, shown in Fig. 15, coupled with a flat plate reflector was designed by the same authors [38]. According to their study, the

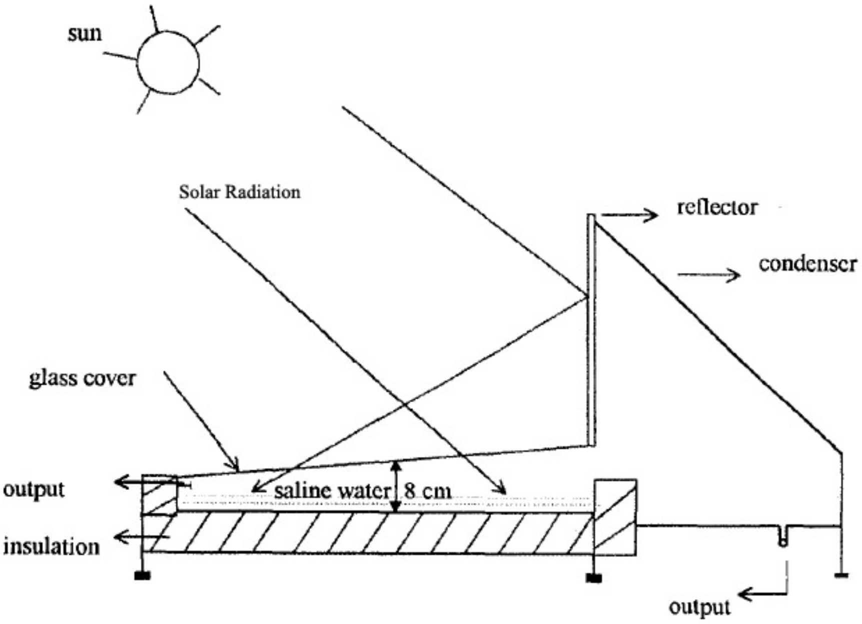

Fig. 12. Solar still with an outside condenser [35].

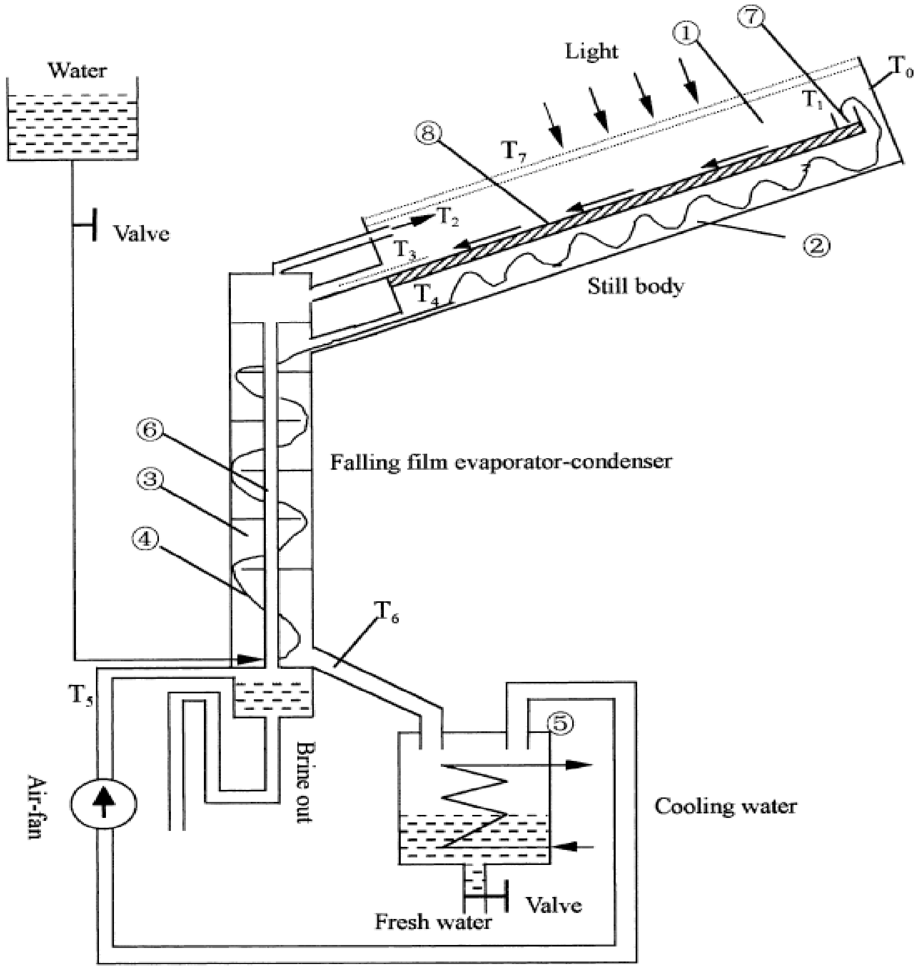

Fig. 13. Solar still with heat recovery [36].

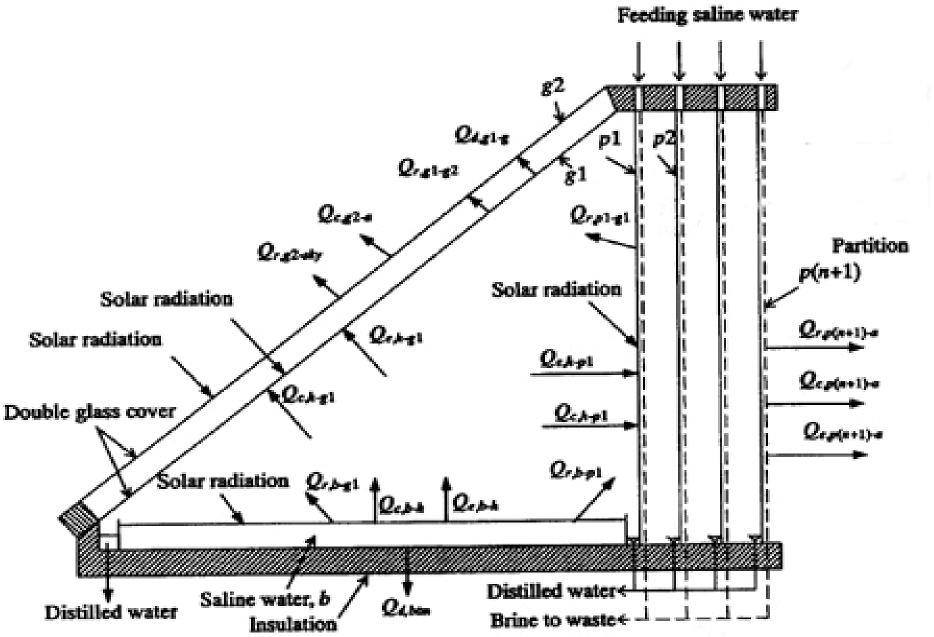

Fig. 14. Multiple-effect diffusion type solar basin [37].

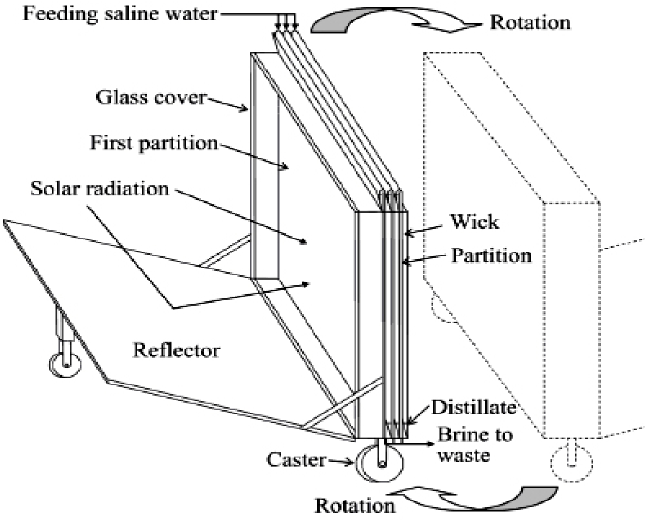

Fig. 15. VMED type still with reflector [38].

daily productivity of the proposed system with a reflector is predicted to be 18.0–21.5 kg/m^2.d. According to an experimental study conducted by Tanaka et al. [42] on multiple-effect diffusion-coupled solar still, it was found that a still having 11 partitions, with 5 mm diffusion gaps, produced 14.8–18.7 kg/d per unit area of the glass cover when solar radiation was about 20.9–22.4 MJ/m^2.d.

According to the experimental results reported in the literature, a productivity table for indirect solar desalination systems is provided in order to make the selection and comparison convenient. Table 2 shows average solar radiation, ambient mean temperature and productivity of each unit based on the area of the absorber plate. Among indirect solar desalination units, the lowest and highest productivity rates are for the solar still with forced condensation and basin type multiple-effect diffusion coupled solar still, respectively.

5. Conclusion

A comprehensive review of available solar stills in the literature according to their structural classification is provided. It is shown that among direct solar stills, the lowest and highest productivity rates are for the plastic single basin solar still and the single basin solar still with $KMnO_4$, respectively. Among indirect type solar stills, the solar still with forced condensation has the lowest productivity and the highest one is for the basin type multiple-effect diffusion coupled solar still. On the basis of the presented discussion, the following recommendations should be always considered by those dealing with solar stills to have the highest possible productivity. By cleaning the deposited dust on the glass cover of solar still, more solar radiation reaches the absorber plate leading to higher distillate rate. It is known that the inclination angle of the glass cover should be equal to the latitude of the location; the system should face to the south in the northern hemisphere and to the north in the southern hemisphere in order to have the most incident solar radiation. As a solution to prevent high amount of corrosion, all metal parts which are in contact with water should be made of stainless steel, copper or brass. Moreover, since the distillate is drinking water, all the materials and paints which are used in construction should be non-toxic. It is known that the lower the thickness of water in the basin, the higher the productivity rate.

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Table 2
Experimental results of indirect solar desalination systems

System description	Place	Solar intensity (MJ/m^2.d)	Ambient mean temperature (°C)	Productivity (kg/m^2.d)	Ref.
Solar still with forced condensation	Bahrain	19	N/A	2.4	[34]
Solar still coupled to an outside condenser	Turkey	24.19	30	6.52	[35]
Solar HD system with heat recovery	China	22.28	38	8.52	[39]
Solar HD system with water heating collector	China	20.16	N/A	6.2	[40]
Closed air solar HD system	Jordan	16.4	N/A	3.7	[41]
Basin type multiple-effect diffusion coupled solar still	Japan	20.9–22.4	24.5	14.8–18.7 kg/d per unit area of the glass cover	[42]

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