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A Review of Different Solar Still for Augmenting Fresh Water Yield

[1]Ravishankar Sathyamurthy, [1]D.G. Harris Samuel, [2]P.K. Nagarajan and [3]S.A. El-Agouz
[1]Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Kelambakkam, Padur, Chennai, 603103, Tamil Nadu, India
[2]Department of Mechanical Engineering, S.A. Engineering College, Chennai, Tamil Nadu, India
[3]Department of Mechanical and Power Engineering, Tanta University, Egypt

Corresponding Author: Ravishankar Sathyamurthy, Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Kelambakkam, Padur, Chennai, 603103, Tamil Nadu, India

ABSTRACT

Due to the greater growth of population and industrial developments especially from the early 20th century, people living in remote villages suffer with shortage of drinking water. People living in urban and rural areas depend on surface and ground water sources, where these sources are majorly polluted by industrial waste. The use of reverse osmosis technique and other conventional technique appears to be a costlier method and requires a very large land mass. An economical method of converting the saline water to portable water is by using solar energy. Solar still desalination is one method of converting saline water into potable water by evaporation and condensation. Many researchers carried out extensive studies on the solar still desalination technique and this paper communicates a detailed review about the existing desalination technique by solar energy.

Key words: Solar still, economic, water source, energy, developments

INTRODUCTION

Earth is almost covered with water of which 97% salt water, 2% trapped in the form of glaciers and polar ice caps and only 1% of water for drinking purpose for our survival. Plants, animals and human being need water to avoid dehydration, since dehydration kills faster than starvation. Consumption of unhygienic water cause health problems and even death and for a small scale production of fresh water in urban and rural areas solar desalination is the best method (Kumar *et al*., 2015; Arunkumar *et al*., 2015). As ground and surface water sources are depleting by continuous usage the need of drinking water is more. Figure 1 shows the major water sources of the world.

There is a great need of fresh water for humans, as they are the important phenomenon in day-to-day life. Due to urbanization, industrialization and increase in population growth the need of drinking water is higher. The possible ways of getting pure water is from rivers, lakes, wells, rains etc, as these kinds must be purified consuming. The purification of water involves the removal of dissolved or microbes which can easily spread water borne diseases. The insoluble substances are removed by sand filtration and the microbes are killed through chlorination and by boiling. Solar desalination does all the three function. The another method of conversion of backrish water into purified water for drinking purpose is using membrane or phase change process of desalination. Earlier these process uses boiler to generate power or heat to drive the membrane process to get fresh water. In the current context, solar energy is used to drive these techniques using solar photo

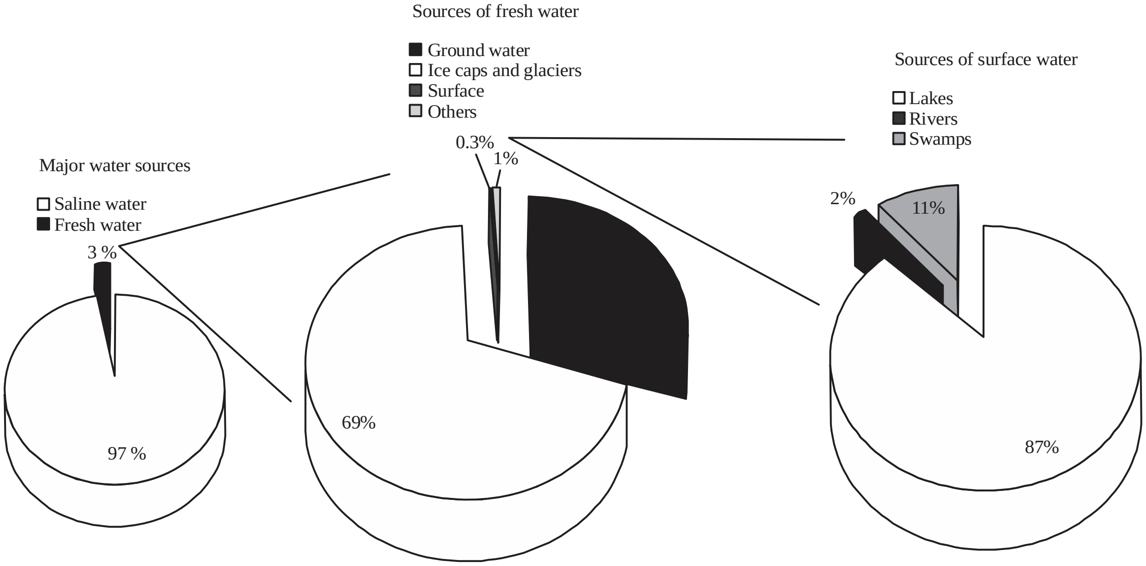


Fig. 1: World’s major water source share (http://water.usgs.gov/edu/watercycle.html)

voltaic method to produce electricity (Durkaieswaran and Murugavel, 2015). On the other aspect the boilers convert the backrish water into steam and later condensed using condenser into fresh water. As these techniques are very expensive the evolution of using non-conventional energy (solar) is applied (Sathyamurthy *et al*., 2015a, b). Later for enhancing the performance of solar still it has been classified into two systems (Kumar and Bai, 2008; Velmurugan *et al*., 2008; Velmurugan and Srithar, 2011; Sathyamurthy *et al*., 2015d):

- Direct solar desalination
- Indirect solar desalination

In direct desalination, solar energy is directly applied to solar collectors to get the distillate. As it requires large space and lower yield indirect method is applied. Whereas in this technique conventional desalination methods like MSF, VC, RO, MD and electrolysis are coupled to solar collectors for heat generation as well as for improving the yield.

Transportation of water to remote areas is very expensive where there is lot shortage of drinking water. Solar stills are more specific in their advantages as they can be fabricated using low cost materials, environmental friendly and minimum maintenance. As they are previously discussed the major drawback is that its lower yield. The comparative yield from a simple basin type solar still is about 2-5 L m^{-2} day^{-1}. As their yield is comparatively lower than conventional desalination technique, many papers have addressed solar stills of various configurations. More specific studies include a concave wick-type, hemispherical solar still, inverted absorber solar still, pyramid solar still, multi basin solar still, tubular solar stills, portable active solar still, solar still integrated to a solar heater, fin type and plastic solar still.

The present study completely aims at comparing the yield of different solar still performance of previous methods and to identify the possible methods of improving the yield of fresh water which is economically viable to people.

MECHANISM

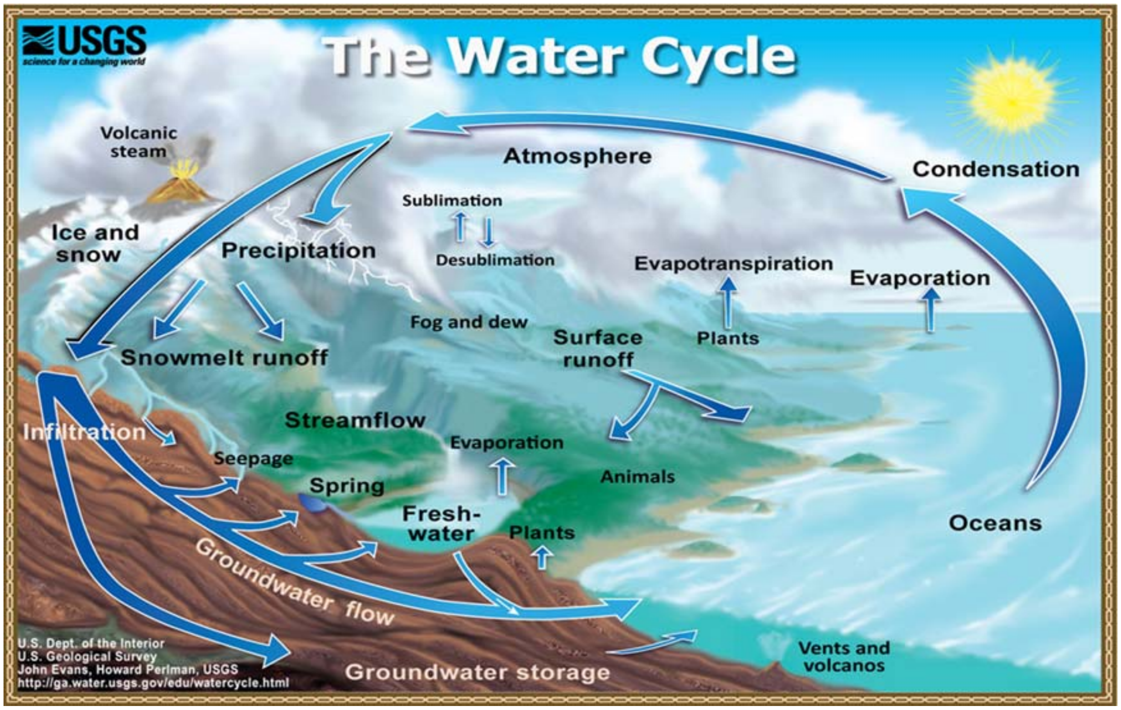
Mechanism behind solar still desalination for fresh water yield is by evaporation and condensation. The mechanism of solar still is simple as a hydrological cycle as shown in Fig. 2. From the ocean saline water is evaporated from the surface and the vapor gets trapped in the clouds and not only from the ocean even from various surface water sources evaporation take place. Due to the partial pressure developed the vapor is condensed in the clouds and returns back in the form of rain. Rain water is another kind of getting fresh water naturally.

Similarly in the solar still backrish water is fed into the absorber which absorbs the solar radiation by transmitting the radiation through the glass surface and only 5% of energy is absorbed by water and the remaining by absorber plate (90%) and glass surface (5%) as shown in Fig. 3. The evaporated water from the surface area creates the partial pressure between water surface and inner glass surface thus increase in vapor density. The vapor formed in the solar still release its latent heat through the cover to maintain equilibrium and gets condensed in the inner glass surface. The condensed water in the form of droplets in the glass glides through the smooth surface due to gravity gets collected in the distillate collector.

Different types of solar still: There are many solar still models are developed by researchers making it economical and more efficient. Solar still performances are mainly evaluated by its fresh water. Here a detailed review is conducted and results are tabulated in Table 1 and compared their performance.

The parameters that affect the yield of fresh water and efficiency are:

- Tilt angle of cover plate
- Depth of water



U.S. Dept. of the Interior
U.S. Geological Survey
John Evans, Howard Perlman, USGS
http://ga.water.usgs.gov/edu/watercycle.html

Fig. 2: Principle of hydrological cycle (http://water.usgs.gov/edu/watercycle.html)

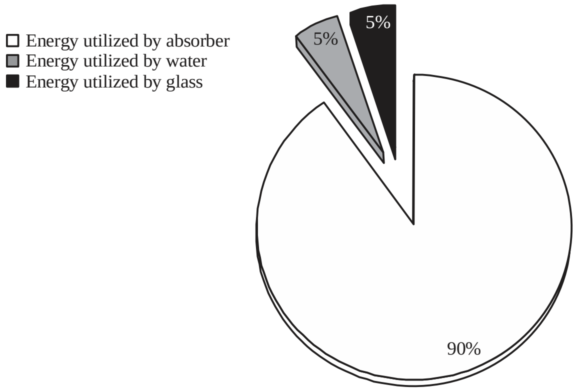


Fig. 3: Energy utilization of solar still (Sathyamurthy *et al*., 2015a)

- Feed water flow rate
- Cover plate temperature
- Convective heat transfer from cover plate and side walls
- Design of structures and shapes
- Solar tracking
- Coating
- External enhancement like heat pipe, coolers

Many researchers have conducted solar still performance evaluation based on the above said parameters and these results are discussed in the following sections.

Single basin solar still

Concave wick solar still: Kabeel (2009) investigated experimentally on the performance of a concave wick type solar still where the basin is made in the shape of concave structure with cover on four sides, which can be seen in Fig. 4. Steel frame support the pyramidal glass surface and a black cloth in kept inside the surface for better evaporation of saline water. Experimental studies concluded that the water temperature is less than the wick temperature, which the wicks absorbing emissive power creating a driving force on evaporation of water. Solar still efficiency improved by 50% than conventional single slope solar still, where the condensing and evaporation area of present model is more than basin area. Typically the total yield from the solar still was found as 4.1 kg m^{-2}. More over the spacious area and insulation thickness is reduced by 50% in case of concave basin of solar still.

Hemispherical solar still: Figure 5 shows the schematic diagram of a hemispherical dome cover solar still. Driving force is the important phenomenon on fresh water yield as it is a parameter of temperature difference between water and glass. The yield of solar still not only depends on glass water temperature difference, also it depends on wind velocity, ambient temperature and cover temperature. Arunkumar *et al.* (2012) investigated a hemispherical cover solar still with and without cooling medium. From their study the effect of cooling the surface of cover improved the efficiency from 34-42% with a fixed flow rate of water as cooling medium at 10 mL min^{-1} on the entire surface. Also, the effect shows that the yield improved by 1.25 times than without cooling.

Table 1: Performance and maintenance of different type solar still

Type	Performance	Maintenance	Remarks
Inverted absorber solar still (Suneja and Tiwari, 1999a, b)	Yield was 11.5 kg m^{-2} day^{-1} and keeps on decreasing when the depth of water increased	Transparency of the multi basin reduces due to salt deposition on each basin and requires daily maintenance	There is no significant increase in the productivity if the number of basin is more than three
Inverted absorber-single basin (Tiwari and Suneja, 1998; Dev *et al*., 2011; Dev and Tiwari, 2011)	Yield was 5 kg m^{-2} day^{-1}	Bottom absorber plate has to be regularly cleaned	Investment cost is low when compared to other solar still
Multi basin-(double basin still)	Efficiency of still is 16 % (Cappelletti, 2002) due to the low temperature in the lower basin	Life of the still is less since a plastic material is used. A regular maintenance is required	By addition of asphalt coating on the walls increases productivity (Al-Hinai *et al*., 2002). Preheating of water is required
Single basin integrated with heater	Productivity of the still is 2.5 times than the conventional solar still (Voropoulos *et al*., 2004, 2003a, b)	Corrosion and salt deposition on the basin reduces the performance and hence regular maintenance is required	Use of any other heat source such as low cost solar collectors (Sathyamurthy *et al*., 2015c), electricity and other conventional sources
Spherical solar still (Dhiman, 1988)	30% more efficient than the conventional still	Trough has to be regularly cleaned to avoid salt deposition	Use of flat plate collector, parabolic trough collector, concentrating trough collector, point focus and solar pond leads to increase in inlet temperature of saline water for better evaporation
Transportable hemispherical solar still (Ismail, 2009)	Typically produces 2.8-5.7 L m^{-2} day^{-1}	It requires less maintenance	Concentrator coupled with PCM material will increase the productivity
Hemispherical solar still (Arunkumar *et al*., 2012)	Average output of 3.5 L m^{-2} day^{-1} without cooling and 4.2 L m^{-2} day^{-1} with cooling of cover	Requires less maintenance	Temperature of the inlet water can be increased by using PCM storage tanks
Triple basin solar still (El-Sebaii, 2005)	Daily productivity equals 12.635 kg m^{-1} day^{-1} with an average intensity of 651 W m^{-2}	Requires daily maintenance and regular checking of partition and partition gap is necessary	Dry spots on each basin reduces the yield of solar still and hence on the lower basin the water mass should be maximum and on the other basin with a minimum water mass as the yield increases
Pyramid solar still (Kabeel, 2007; Taamneh and Taamneh, 2012; Nagarajan *et al*., 2014a; Sathyamurthy *et al*., 2014a, b)	Daily yield was increased up to 25% compared to free convection solar still	For a concave wick type the replacement of wick to be carried out in order to avoid salt deposition and smelling effect to maintain the quality of fresh water produced	Effect of tilt angle on the system performance has to be studied. This may increase the productivity
Thermo electric module and heat pipe (Rahbar and Esfahani, 2012)	Daily yield was 1.2 kg m^{-2}	It requires additional power source and refilling of heat pipe fluid is required	It is applicable for portable domestic use
Tubular solar still (Ahsan and Fukuhara, 2009, 2010; Ahsan *et al*., 2010, 2012; Ahsan and Fukuhara, 2010)	Total yield from still is 1.7 kg m^{-2}	Cover material has to be frequently changed as it is exposed to direct heat	Use of polyethylene films reduced the overall cost
Solar still with solar water heater (Sampathkumar and Senthilkumar, 2012)	Yield is increased by 4 time than conventional solar still	Requires additional insulation and the tubes of solar collectors are to be regularly cleaned for effective heat transfer	Initial investment cost is higher

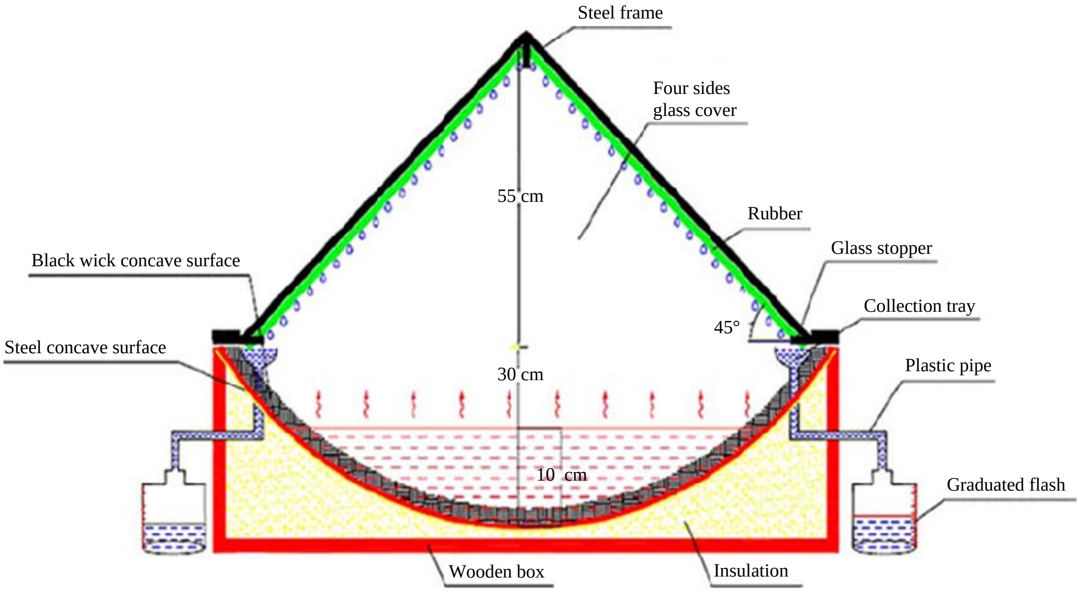


Fig. 4: Schematic diagram of a concave wick solar still (Kabeel, 2009)

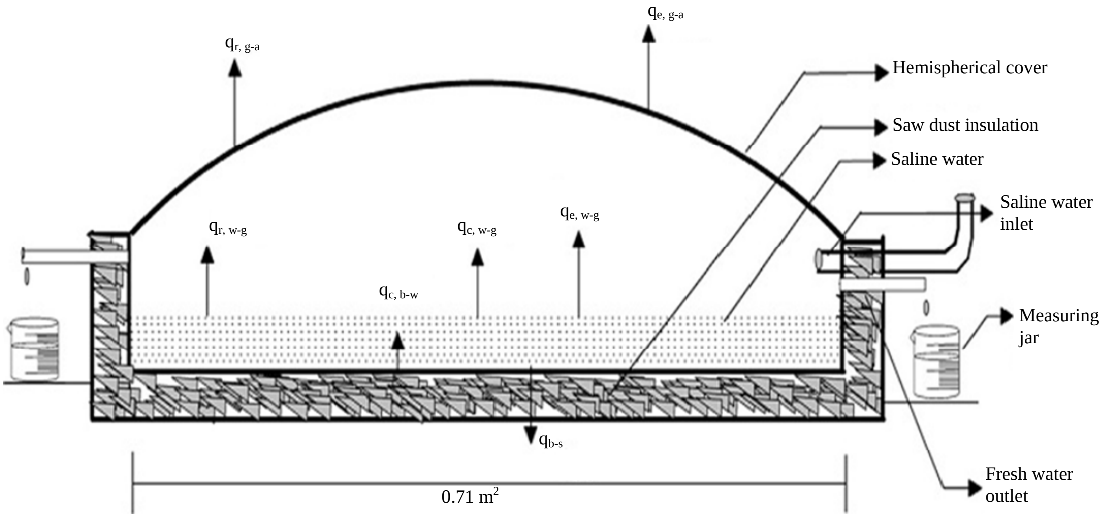


Fig. 5: Schematic diagram of hemispherical solar still (Arunkumar *et al*., 2012)

The average output with and without cooling is found as 4.2 and 3.5 L m^{-2} day^{-1}, respectively. The improvement in yield is due to dome shaped cover instead of flat plate cover. Also, the area of aperture area is more for incident radiation, whereas from conventional still shadow effect is more.

Inverted absorber solar still: Figure 6 shows a single basin inverted absorber solar still. In either way heat input to the solar still can be given which was proposed by G.N. Tiwari. Tiwari and Suneja (1998) and Dev *et al*. (2011) experimentally investigated the effect of reflecting the solar radiation through the bottom of the absorber. The yield of inverted absorber increases by two times than conventional solar still yield. Other parameters such as multiple basins, water

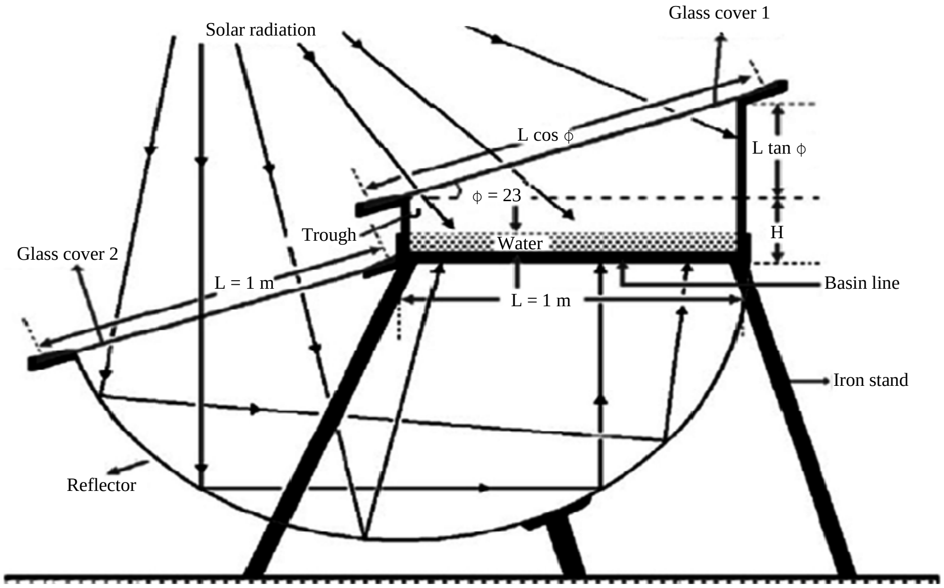


Fig. 6: Schematic diagram of an inverted absorber solar still (Dev and Tiwari, 2011)

depth and effect of wind velocity are also discussed. While analyzing different water mass the evaporative heat transfer is higher at minimum water mass. Due to the higher water depth inside the basin, water could not able to heat up to a higher temperature. The yield of solar still drops from 5.2-3.5 kg m^{-2} day^{-1} for 0.01-0.1 m, respectively. Dev and Tiwari (2011) theoretically and experimentally derived the characteristics of an inverted absorber and single slope conventional solar still. The results showed that the instantaneous gain and loss in efficiency and distillate are similar to the previous model while the depth of water maintained at 0.01 m. It is also reported that the increase in depth of water decreases the gain efficiency and increases the loss efficiency from the still, due to the effect of thermal energy storage by water.

Tiwari and Suneja (1998) investigated the performance of solar still and arrived to a conclusion that there is an increase in temperature of water in the absorber due to the reduction of heat loss from absorber and increased value of absorptivity. The depth of water is an important parameter for the water temperature and it is increased by decreasing the water depth in the basin which simultaneously increases the evaporative heat transfer. As the water depth increase from 0.08-0.1 m there was no significant improvement in the convective and radiative heat transfer coefficient.

Pyramid single basin solar still: Taamneh and Taamneh (2012) experimentally studied a pyramid solar still under forced and natural convection. Experiments are carried out in Tafila city (Jordan) and performance of solar still with and without fan show that the reduced temperature of glass increases the condensation with larger temperature difference. The solar still yield during mid noon on experimental day with and without fan found to be 0.4 and 0.35 kg m^{-2} h^{-1}, respectively and the maximum efficiency of the solar still was increased from 40-50% with fan as cooling source. This is due to that the water evaporated from the surface of water reaching the apex on all the surface area getting accumulated by releasing its heat through the glass surface and some vapor cannot get condensed. Hence, with the help of a solar PV assisted fan cools the surface areas of the glass for better condensation of vapor.

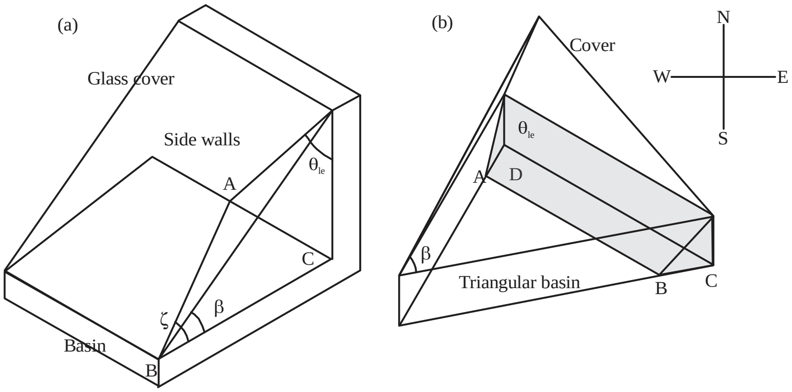


Fig. 7(a-b): Schematic diagram of a triangular pyramid solar still (Sathyamurthy *et al*., 2014c)

Nagarajan *et al*. (2014b) conducted a detailed review about the solar collectors using nano fluids in solar thermal applications. Nagarajan *et al*. (2014a) and Sathyamurthy *et al*. (2014a) investigated the performance of a triangular pyramid solar still as shown in Fig. 7. The results showed that the yield from solar still is higher and for a least water mass of $d_w = 2$ cm it was found as 4.2 kg m^{-2} day^{-1}. The convective and evaporative heat transfer from the solar still is equal to the Duckle's prediction and the solar radiation follows the similar curve of water temperature. This proves that the water temperature is directly proportional to solar radiation. The water temperature throughout the basin is equally maintained and this is due to the reduction of shadow of side walls falling in the solar still. On the economic and space constraints the new model is more efficient for 75 and 50%, respectively than a conventional solar still.

Sathyamurthy *et al*. (2014a, b) and Ravishankara *et al*. (2013) investigated a triangular pyramid solar still with latent heat energy storage. The results showed that the use of latent heat energy storage improved the fresh water production by 35% than the solar still without any storage. Also, further investigation are made to see the performance of solar still during summer and winter conditions. Water temperature of solar still without any energy storage, during the sunshine hours is more than the still with energy storage. This is due to some of the heat stored in energy storage during the charging mode. The temperature of basin and water are very close and temperature difference for both still is higher than the conventional solar still. Similarly during the winter conditions the yield is reduced by 20.9% than summer conditions with energy storage.

Solar still integrated with heater: Voropoulos *et al*. (2003a, b, 2004) investigated the effect of integrating a solar still with storage tank and electric heater as shown in Fig. 8. The existence of driving force of solar still ensures the continuous process of solar desalination process. Coupling of solar still with solar heater is the best way to increase the basin water temperature. Fresh water output of the system has been found to be rather constant for the whole 24 h.

Spherical solar still: A schematic diagram of a spherical solar still is shown in Fig. 9. Saline water from the storage tank is fed into the absorber which is placed inside the spherical shaped cover through which the solar radiation is transmitted to evaporate the saline water. The major advantage of the solar still is from all the direction the radiation is transmitted and the thermal equilibrium of water is maintained for evaporation. Dhiman (1988) analysed a spherical solar still on the thermal performance and results have showed that the efficiency of solar still is increased by 30% than the conventional solar still.

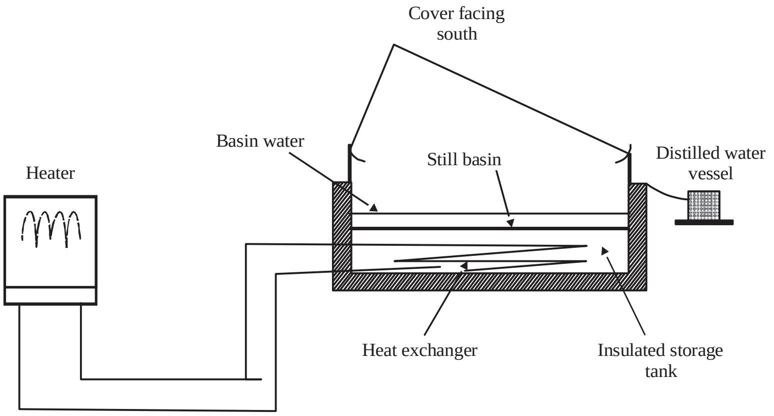


Fig. 8: Schematic diagram of solar still integrated with a heater (Voropoulos *et al*., 2003b)

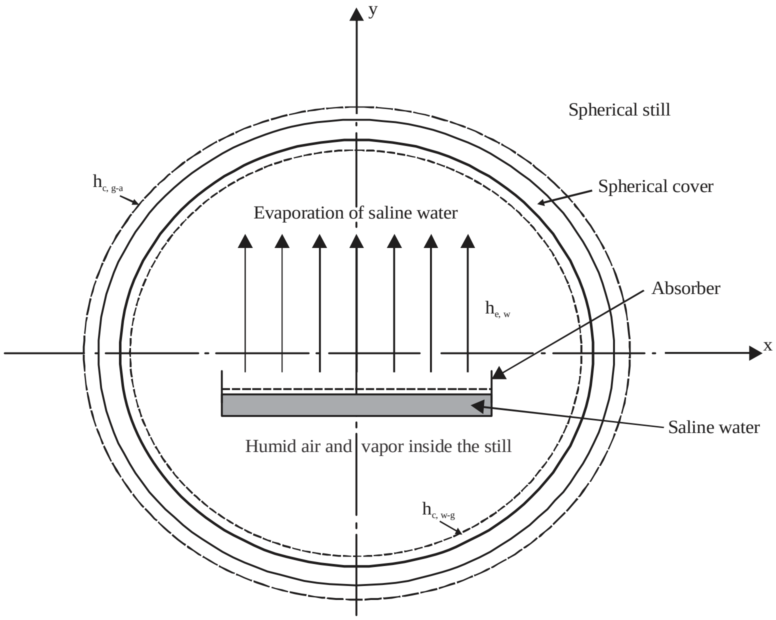


Fig. 9: Schematic diagram of spherical solar still

Transportable hemispherical solar still: Ismail (2009) reported that a transportable hemispherical solar still typically produces between 2.8-5.7 L m^{-2} day. The average efficiency of solar still reached a maximum of 33%, further there is a efficiency decreased by 8% when the depth of water increased by 50%. Figure 10 shows a simple transportable hemispherical solar still. Also, the daily efficiency decreased linearly as the depth of water increased.

Tubular solar still: A simple mechanism of a tubular solar still is shown in the Fig. 11, where it usually consisting of transparent cylindrical tube in which a rectangular absorber is placed. The solar intensity is transmitted through the cover reaching the absorber and heat up the water. The water evaporated in the inner surface forming a thin film and rejects its latent heat for condensing. Due to gravity, the condensed water slides through the inner surface of cover and get

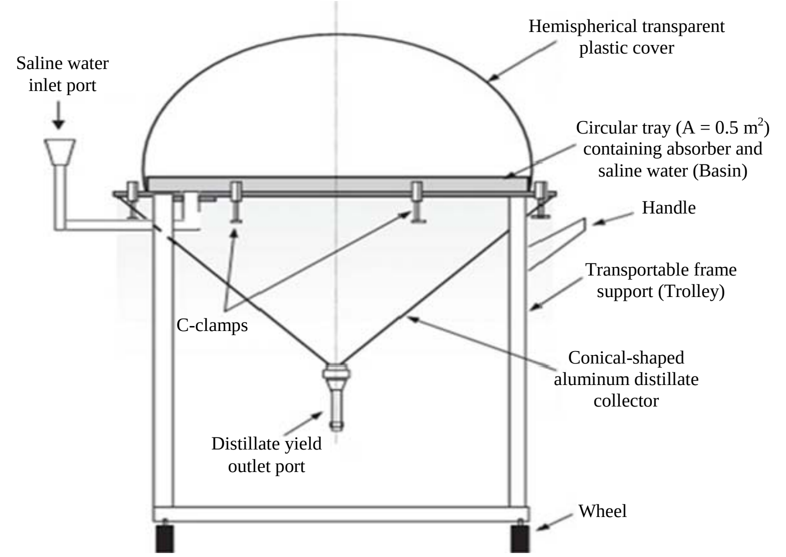


Fig. 10: Schematic diagram of transportable hemispherical solar still (Ismail, 2009)

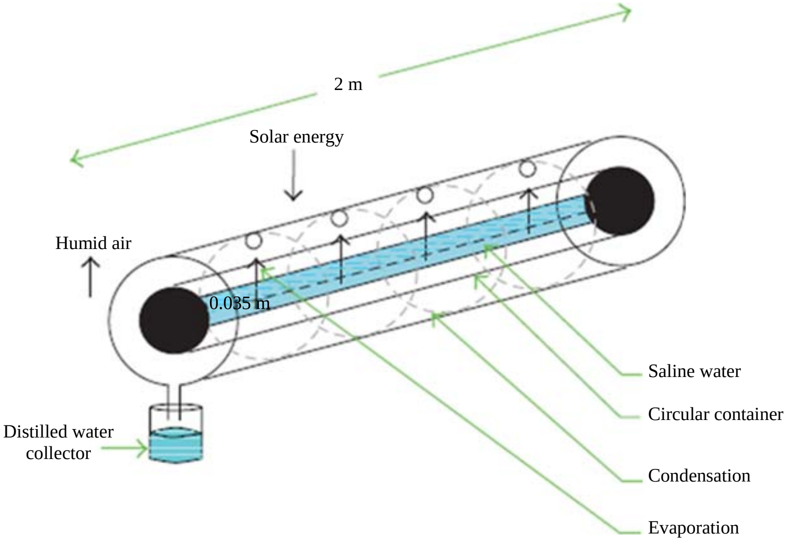


Fig. 11: Schematic diagram of tubular solar still

accumulated in the calibrated flask. A new model is created for the heat and mass transfer by Ahsan and Fukuhara (2009, 2010) and Ahsan *et al.* (2010, 2012) by taking all the parameters such as vapor density, surface tension, relative humidity to estimate the heat transfer coefficient and the proposed model is validated using experimental values. The validation of the model is verified using field experimental values. The economic viability of the new tubular solar still has reduced from 92-61% (Ahsan and Fukuhara, 2010). Evaporation and heat transfer co-efficient are much higher than those of condensation and a linear relation between temperature difference and hourly production was found to be $p = 0.0052 (T_w - T_c)$ where P, T_w and T_c are productivity, water temperature and cover temperature, respectively.

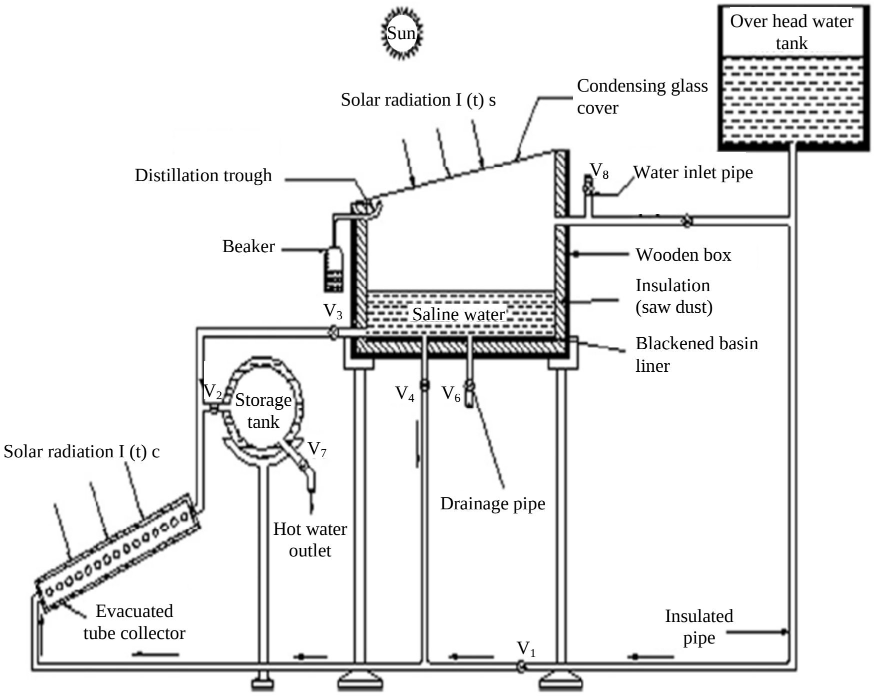


Fig. 12: Sketch of a solar still connected to solar water heater Sampathkumar and Senthilkumar (2012)

Table 2: Position of valve during experiment and comparison of thermal and yield from active and passive solar still (Sampathkumar and Senthilkumar, 2012)

	Valve positions		Thermal efficiency		Yield from solar still	
Cases	V1 and V2 (kept in closed position)	V3 and V4 (kept in open position)	Active SS (%)	Passive SS (%)	Active SS (kg m^{-2} day^{-2})	Passive SS (kg m^{-2} day^{-2})
A	24 h	24 h	20.2	28.8	7.00	3.1
B	8-12 h (opened thereafter)					
	8-12 h	Thereafter closed	12.8	27.6	5.60	3.2
C	12-17 h (opened thereafter)	12-17 h (thereafter closed)	14.4	29.2	5.92	3.0
D	12-17 h (opened thereafter)	8-17 h (thereafter closed)	19.1	27.3	6.80	3.2
E	Till water temperature reaching 60°C valve is opened		11.4	28.0	5.33	3.1
F	8-17 h	8-17 h (thereafter closed)	21.0	30.1	6.93	2.9

Solar water heater: The integration of single slope solar still evacuated tube collectors and storage tank is shown in Fig. 12. The heated brine solution from the Evacuated Tube Collector (ETC) is fed into the solar still as well as to the storage tank. Water temperature on evaporation and depth of water maintained in the solar still are the important parameter in increasing the yield of solar still. Totally six cases are considered for the experimental studies conducted by Sampathkumar and Senthilkumar (2012). The cases are as tabulated in Table 2 and the yield from the solar still under case A, case D and case F are found to be the same whereas from case B, C and E the yield is similar. On the same for a passive solar still the accumulated yield are same for any case.

The lower layer from the basin is continuously fed into the ETC for increasing the temperature of water furthermore. Condensed water is collected from the distillate trough and the water is collected in a measuring jar. The pipelines of the solar still are insulated to avoid the heat loss to the ambient. The results showed that there is an increase of 77% in the yield of solar still under active conditions, than passive conditions. The average productivity during the night and day time of passive solar still is found as 0.42 and 2.5 kg m^{-2}, which are lower than the active solar still which is found as 1.2 and 5.7 kg m^{-2}, respectively for summer conditions. The average water temperature in the hot water storage tank is found as 60°C, which is sufficient enough to evaporate and condense water during off shine period.

Multi basin solar still: The performance of conventional solar still is very low due to lower dissipation of heat through the inner surface of glass and enormous fluctuations such of wind velocity over the glass surface. Although enough cooling on the surface for improving the yield and condensing rate using various fluid medium (air, water) are used and glass temperature is reduced to increase the temperature difference between glass and water. In the multibasin solar still, the number of effects is increased to utilize the latent heat from vapor (1st effect) to heat up the water (2nd effect). The basin additionally added usually made of glass which allows the solar radiation to reach the lower basin (Tiwari *et al*., 1993).

Double basin solar still: Figure 13 shows a schematic diagram of a double basin solar still. Cappelletti (2002) experimentally investigated a double basin solar still. In the shape of "V" the second basin is separated from the lower basin through which the horizontal trays are kept inside. The water evaporated in the lower part of the basin gets condensed in the "V" basin. The condensed water trickles down to the centre were the distillate collector placed. Due to the lower temperature in the bottom basin the maximum efficiency of the still is found as 16%. Al-Hinai *et al.* (2002) experimentally investigated a shallow water solar basin with asphalt as coating material. A

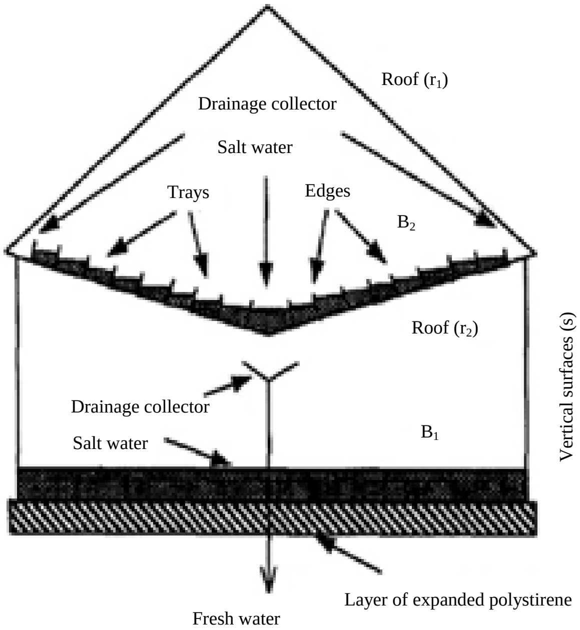


Fig. 13: Schematic diagram of double basin solar still (Cappelletti, 2002)

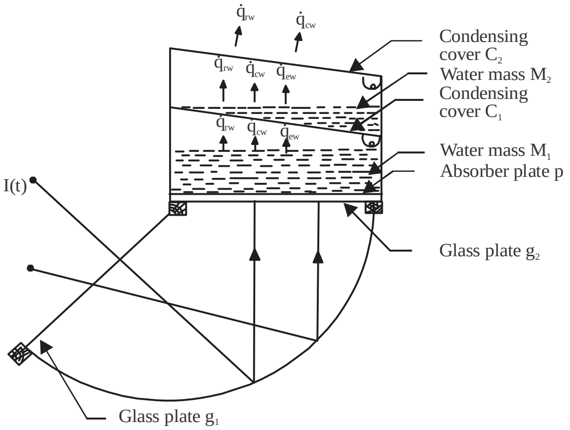


Fig. 14: Schematic diagram of inverted absorber double basin solar still (Suneja and Tiwari, 1999b)

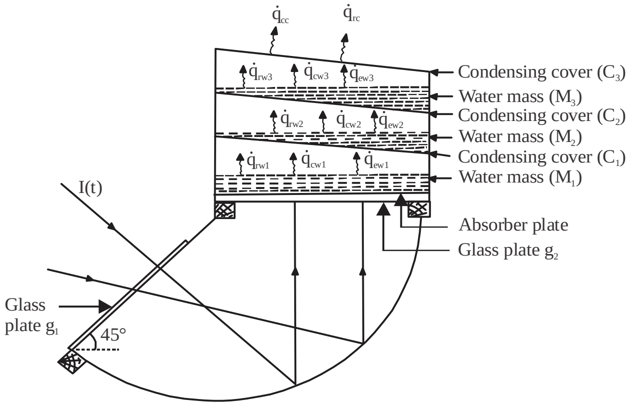


Fig. 15: Schematic diagram of inverted absorber triple basin solar still (Suneja and Tiwari, 1999a)

comparative analysis has been carried out to analyse the performance of single and double effect. Results shows that an average yield of 4.15 and 6 kg m^{-1} day^{-1} for single effect and double effect solar still respectively.

Inverted absorber double and triple basin solar still: The effect of number of basin and water depth in multi basin inverted absorber still (Fig. 14) was theoretically and experimentally determined by Suneja and Tiwari (1999a). The results agree that, the increase in water depth on the lower basin increase the daily yield of fresh water. Figure 15 shows the simple inverted absorber triple basin solar still. The daily yield of inverted absorber triple basin solar still is higher while comparing it with conventional still and increase in depth of water in the basin yield is lower. At a water depth of 0.02 m the yield was 11.5 kg m^{-2} and keeps on decreasing when the depth of water increased.

Pyramid multi basin solar still: Figure 16 showing the schematic diagram of a triple basin pyramid solar still. Hamdan *et al.* (1999) experimentally carried out the performance of triple basin pyramid solar still. It was found that the yield of solar still is improved by 24% which is higher than

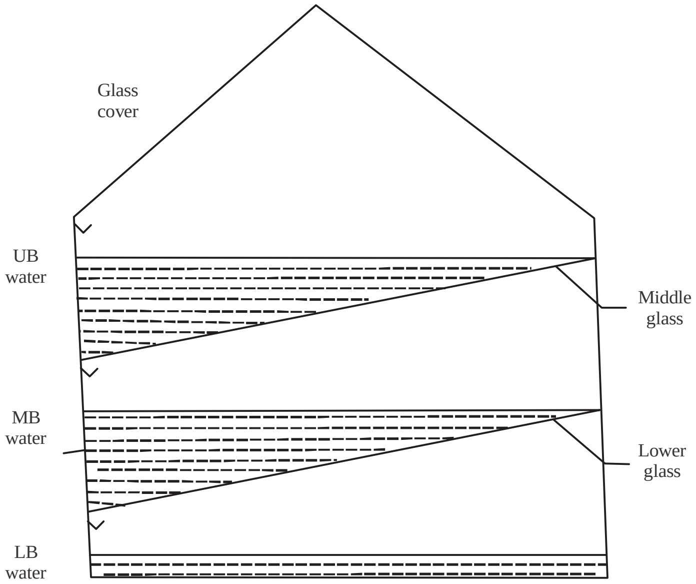


Fig. 16: Schematic diagram of pyramid triple basin solar still (Hamdan *et al*., 1999)

that of single basin. Furthermore, the solar still efficiency was 44% in the case of triple basin still and 42% in the case of double basin (Sodha *et al*., 1981), while it for a single basin is 32% (Murugavel *et al*., 2008).

Pyramidal solar still are the next evolutionary solar still, which is discussed by Kabeel (2007). A multi shelve pyramidal solar still is shown in Fig. 17. Two identical solar still with distance between each shelves 30 cm are fabricated. Each solar still with bed material as saw wood and cloth material are placed in the shelves. The glass can be opened and during the night hours the moisture can be absorbed by the absorbing materials. The results showed that the area of the upper basin is lesser than the lower consecutive shelves and hence the temperature from the upper layer is higher and gradually decreasing. Also, it reports that the use of cloth as absorbing material increases the productivity by 3.2% than wood saw and the maximum productivity during the mid noon found to be 0.45 and 0.38 kg m^{-2} h^{-1} for cloth bed and saw wood respectively. This is due to that cloth material evaporates and absorbs the solution and porosity level is higher in the case than saw wood. Recommendations discuss that the better absorbing material and distance between each shelves improves the productivity of fresh water.

Portable solar still utilizing heat pipe and thermoelectric cooler: Figure 18a shows the schematic diagram of a portable solar still with thermo electric module and heat pipe. Normally condensation of vapor either depends on material of cover used for a reduced cover temperature and environmental parameters. Due to the inconsistency of wind velocity over the cover, the temperature is invariant. Also, a fact that all evaporated water is not being condensed. To enhance the condensation of vapor a novel method is being introduced by integrating thermo electric module with aluminium plate at the end of cold side and a heat pipe is used to take away the heat from the hot side of Thermo Electric Module (TEM). The aluminium plate is kept on one side the top surface in the plexiglas to reduce the temperature of vapor to get condensed and droplets are being formed for the saturated vapor in the still. The condensed vapor tends to fall due to gravity in the

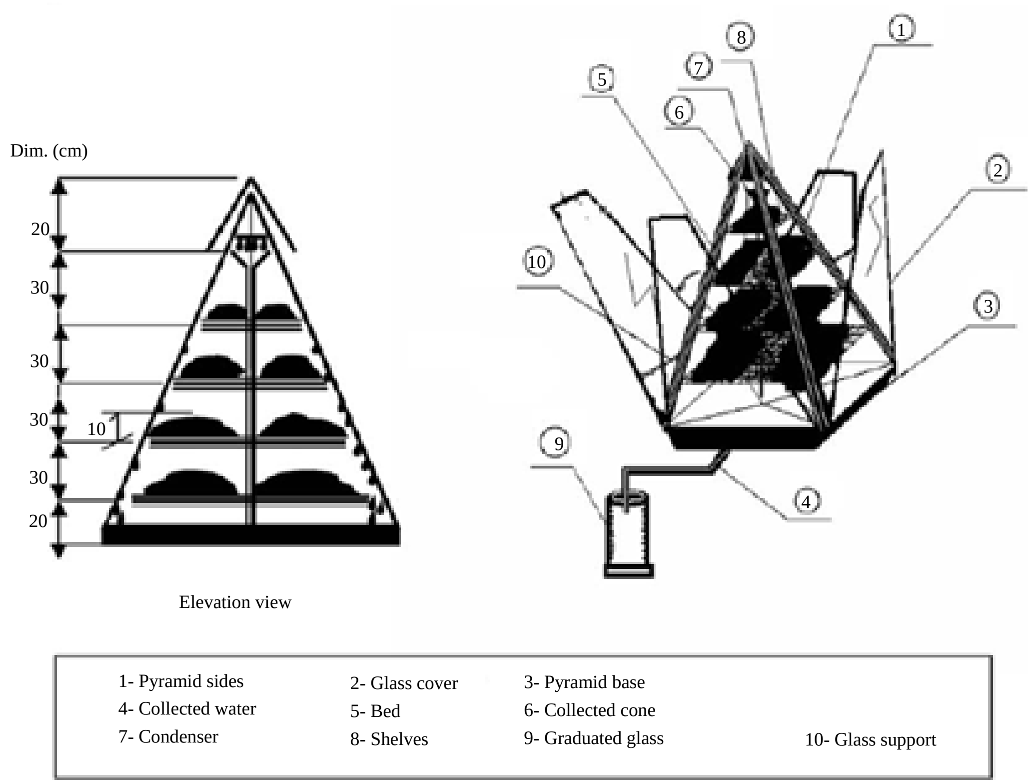
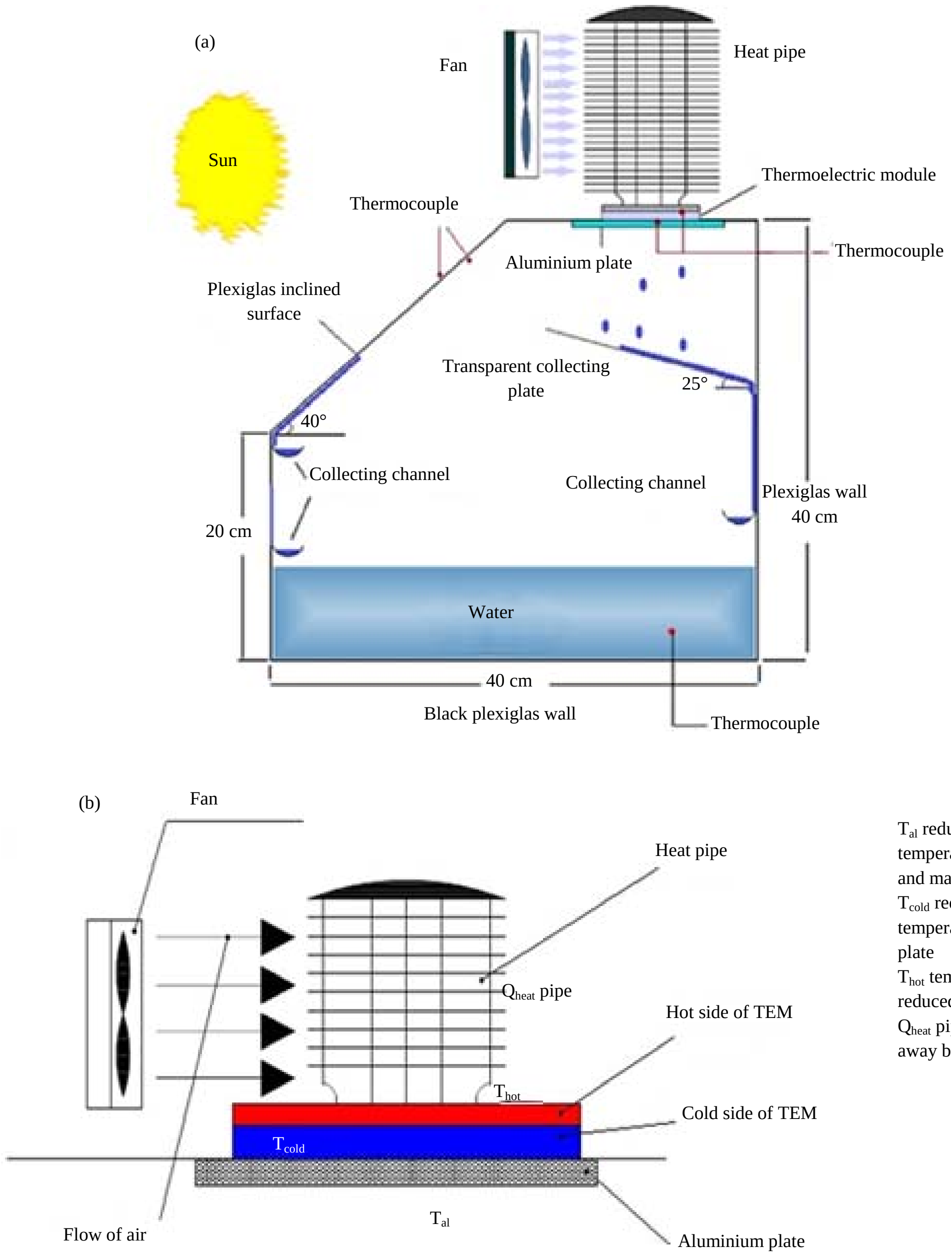


Fig. 17: Schematic diagram of pyramidal multi shelve solar still (Kabeel, 2007)

still is collected in the transparent collecting tray kept inclined as shown in Fig. 18a. Rahbar and Esfahani (2012) experimentally investigated the portable solar still with TEM and heat pipe. The results showed that the efficiency of solar still is depending on the solar radiation throughout the day. The average efficiency using TEM in the solar still is 6.75%, since the evaporation is depends on solar intensity. Also, it is observed that with higher wind velocity the efficiency and yield is decreased. This shows that efficiency and yield are inversely proportional to the wind velocity. During the experimentations average water temperature found to be 55°C and the TEM cold side temperature is 23.7°C. The rate of condensation in vapor is due to that heat can be transferred from hot body to cold body to attain thermal equilibrium condition for formation of droplets. Since the plate placed inside the still, water droplets will be formed on both the sides of the plate. Also, the reduction in temperature of the walls of the still decreases the temperature using the TEM a larger temperature difference between water and glass is achieved. As temperature difference acts as driving force a novel method is incorporated in the solar still with a thermoelectric cooler between evaporating and condensing zone. A heat pipe is a device which takes away the heat from the hot surface of a thermoelectric cooler for improving the cooling effect on the surface of condensing zone. Some suggestions were made that the use of plexiglas reduces heat loss and the use of PCM as a heat absorbing material enhance the productivity of water during the absence of solar radiance.

Single slope double basin solar still: The yield of solar still depends on water mass and glass temperature. On the other aspect in a multi basin solar still depends on the water temperature in



T_{al} reduces the vapor temperature in the still and making it condense
T_{cold} reduces the temperature of aluminium plate
T_{hot} temperature is reduced using heat pipe
Q_{heat} pipe heat taken away by the flowing air

Fig. 18(a-b): (a) Schematic diagram of novel portable solar still with thermo electric module and heat pipe (Rahbar and Esfahani, 2012) and (b) Flow of heat from different elements of solar still for condensation

the upper basin and lower basin. Tiwari *et al.* (1985) investigated a double effect single slope solar still as shown in Fig. 19. It is concluded that the yield of fresh water depends on the lower basin water mass and the decrease in the water mass yield is more while during the absence of solar radiation the effect is reduced. For an higher water mass the yield is lower and during the absence of solar radiation the energy stored in the salt water is released and hence there is no discontinuous distillation.

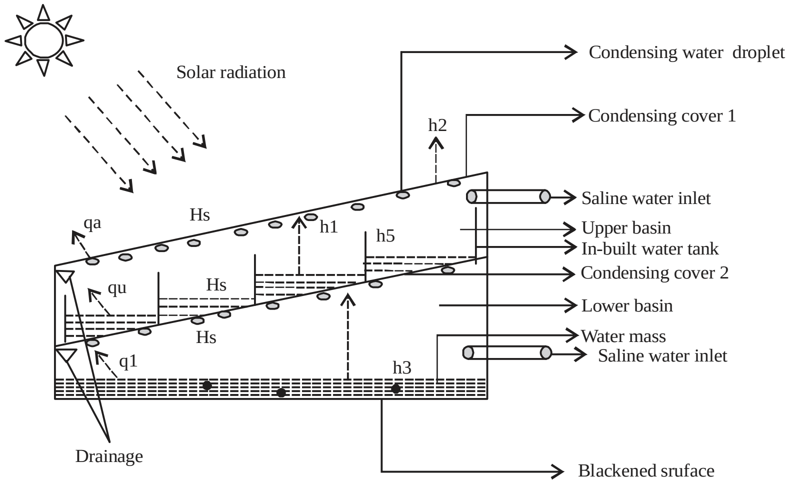


Fig. 19: Schematic diagram of single slope double basin solar still

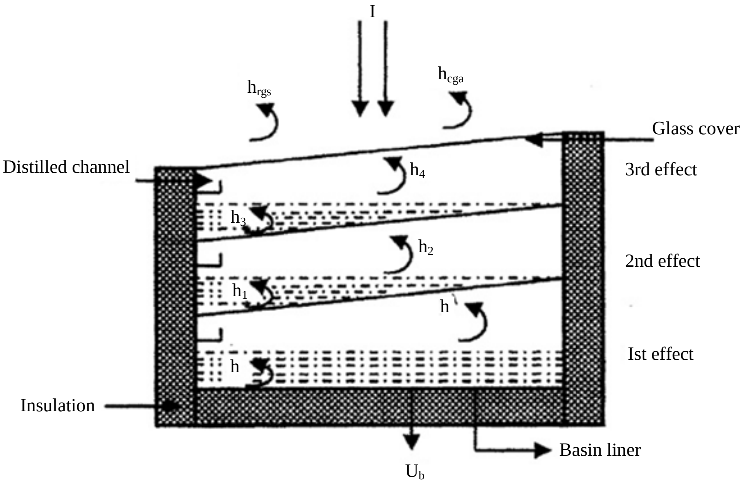


Fig. 20: Schematic diagram of triple basin solar still (El-Sebaii, 2005)

Continuous or intermittent flow of water on the glass surface is another method of improving the yield, which creates a larger driving force by taking away the heat from the vapor in the internal surface. The water takes away the heat from the surface by gaining the heat and water is restored in the basin by regenerating the heat. The results of Abu-Hijleh and Mousa (1997), Abu-Arabi *et al.* (2002) and Abu-Hijleh (1996) show that the flow of water over the cover increases the production rate by 20%. The utilization of flowing heat energy from the cover increases the productivity and produces an additional effect. Regenerative still with minimum water depth increase the productivity.

Triple basin solar still: El-Sebaii (2005) analytically studied the thermal performance of triple basin solar still. Balancing of energy is analytically solved using elimination technique. The results showed that, for a triple basin solar still the productivity of water is higher in the lower basin than that of the middle and upper basin as shown in Fig. 20. Daily yield of water is maximum with least

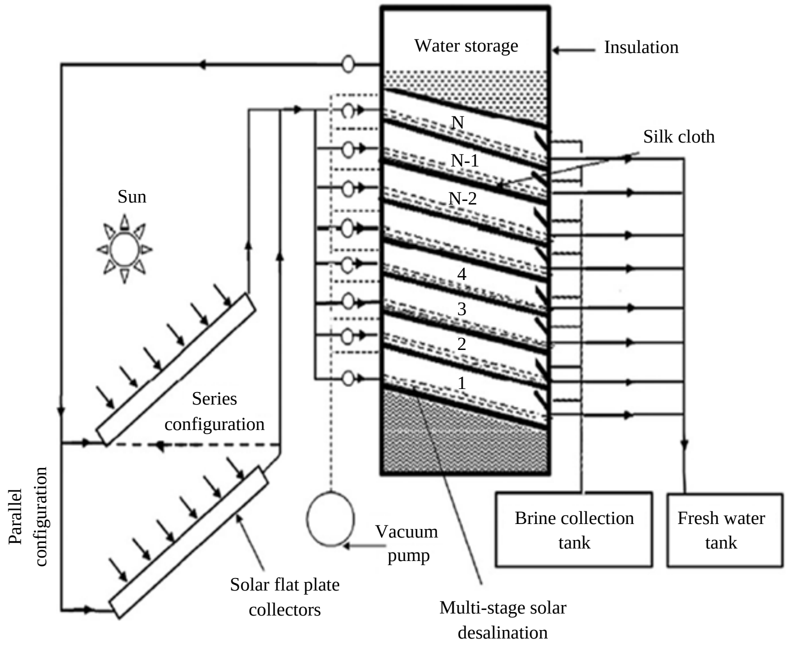


Fig. 21: Schematic diagram of a multi stage evacuated solar still (Reddy *et al*., 2012)

water depth in the middle and upper basin. The depth of water in the lower basin is higher in order to store the energy. As the depth of water increases the yield from the solar still becomes less dependent on specific heat capacities of water. The daily productivity of water increases with an increase in the velocity of wind. For a triple basin the results indicate daily yield from solar still is 12.635 kg m^{-1} day^{-1} with an average intensity of 651 W m^{-2}.

Evacuated multi stage: Figure 21 shows a multistage evacuated solar still. Flat plate collectors in the configuration of parallel and series are made to see the effect of fresh water yield from the solar still. Water storage is kept for feeding saline water into the stages and the saline water is preheated using the flat plate collectors. More over in parallel configuration the saline water is fed to both the inlet of collectors, whereas in the case of series configuration the fed water is given to the inlet of collector1 and the outlet of collector1 is connected to the collector 2. Vacuum pressure is maintained in the evacuated stages using a vacuum pump. Flow control valve is provided that the water flows through the collector to each stage at control volume. From each stage the fresh water is taken out and the remaining brine solution is collected and stored in a separate tank. As we know that pressure is directly proportional to temperature, water evaporates even at room temperature. Reddy *et al*. (2012) experimentally investigated a multistage evacuated solar still. The results indicate that the fresh water in multistage depends on parameters such as gap between stages, mass of water supplied into each stage and working pressure. It is also reported that for a year around analysis the optimum flow rate and number of stages are 55 kg m^{-2} day^{-1} and 4, respectively. The gap between each stage varied from 50-250 mm and the yield of solar still is higher in the case of least gap. Moreover the gap cannot be further reduced due to the thickness of water flowing and spacing of evaporated water volume increase inside the chamber and possible of the expanded volume occurs to leak through the weaker portions of the chamber. The optimum gap between each stage is found to be 100 mm, which simultaneously increases the temperature difference for better evaporation and condensation. Vacuum pressure inside the still is varied from 0.01-1 bar and results show that increase in pressure decreases the cumulative output from the still by 20% from 0.2-1 bar pressure. It has been concluded that for better performance the optimum conditions are set to 100 mm gap between each stage, 0.03 bar working pressure and 55 kg m^{-2} day^{-1} flow rate.

CONCLUSION

Table 1 summarises the performance, maintenance and operational aspects of different solar stills. From the above discussions, the following conclusions were arrived:

- By flowing water or air as cooling medium over the glass surface the yield of solar still increases. Also, it is identified that the heat extracted from the cover can be used as feed water into the basin as it gains some amount of energy
- On multi basin solar still the optimized number of basins is three and there was no further increase in yield as the number of basin is increased
- Use of any other heat source such as solar collectors, electricity and other conventional sources improves the yield and efficiency
- The use of flat plate collector, parabolic trough collector, concentrating trough collector, point focus and solar pond leads to increase in inlet temperature of saline water for better evaporation and continuous usage of these leads to scaling effect on the inner surface of tubes as it uses saline water. Nano fluids can be used in flat plate collectors and parabolic trough collectors as it may be utilized as continuous heat supply to the system by heat exchange
- For a multi basin solar still, the yield depends on minimum water depth in lower and middle basin
- The effect of tilt angle on the system performance of triangular pyramid solar still has to be studied. As the tilt angle increased the area of glass surface increases and this may increase the yield of fresh water
- The yield of solar still depends on colleting area and this is directly proportional to the yield
- The continuous circulation of water in the flat plate collector has to be disconnected during off shine period as there will be heat loss with the surroundings
- The increase in condensing area like separate condensing chamber or inbuilt condensing chamber on other side of single slope solar still increases the yield

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