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REVIEW

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A comprehensive decade review and analysis on designs and performance parameters of passive solar still

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Abstract

The simplest and easily accessible type of solar distillation is passive solar still which utilizes freely and abundantly available sun energy for removal of salinity/impurity from saline/brackish water. The main drawback of passive solar still is its lower efficiency and distillation output. Different designs of passive solar stills are fabricated and tested by various researchers to meet water demand economically. Concave wick basin pyramidal-shaped solar still was observed to produce 4.0 l/m^2/day average distillate with a cost of 0.065$/l. Double basin solar still showed an average of 85 % higher yield than single basin still. Stepped type, inclined, tubular, pyramidal, spherical, and hemispherical shapes were considered an efficient designs of passive solar still. Numbers of parameters such as water depth, solar radiation, ambient conditions, condensing cover material, its cooling and direction, internal and external reflectors, sun tracking system, wicks, thermal and energy storage materials were outlined which highly affect the performance of solar still. Water depth of 0.04 m and condensing cover inclination to latitude of the place were observed optimum operational parameters. A distillate output of 4.3 l/m^2 was collected with cotton gauge top cover cooling to V-type solar still. Increase of 75 % in productivity and 56 % in daily efficiency was observed with internal reflector stepped solar still. An improvement of 380 % was observed in stepwise basin solar still integrated with sun tracking system. Despite large efforts carried out on passive solar distillation, there are some challenges like bulkiness, high initial cost, and optimization of spacing between condensing cover and water surface of inclined still, thermophysical properties of basin material, flow rate, insulation material and its thickness, which need to be improved to make this technique efficient in practical utilization. This review paper mainly presents the results of previous work carried out on the designs, operational and process parameters affecting distillation, cost analysis, further scope of improvement in preceding work along with their limitations. The decade reviews on solar stills based on different context authored by many researchers have also been summarized. Moreover, this review paper will help the researchers to understand the basics of solar still with the need, developments and challenges in passive solar distillation to improve its thermal performance.

Keywords: Distillation, Solar energy, Solar still, Passive solar still, Solar still design

Background

With the growing demand of energy, environmental concern and fast run out of non-renewable energy sources, it becomes necessary to use the renewable energy sources for various applications. Solar energy is one of the renewable energy sources necessary to be utilized for the socioeconomic development of a nation. Solar energy is clean, eco-friendly, inexhaustible, abundantly available and has the greatest potential of all the sources of renewable energy.

The sun radiates the energy uniformly in all directions in the form of electromagnetic waves. Approximately, 3.8×10^{24} J per year solar radiation is absorbed by the earth and the atmosphere. The energy radiated by the sun on a bright sunny day varies from 4 to 7 kWh/m^2 in different regions (Arjunan et al. 2009). Use of renewable solar

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energy makes a significant reduction in the dependence towards non-renewable sources. The utilization of solar energy is of great importance to the countries where sunlight is abundant for a major part of the year (Tiwari 2013).

Along with energy, pure water is also one of the major concerns of today. More than 70 % of Earth's surface is covered with water. About 97.5 % of all water on earth is salt water, leaving only 2.5 % as fresh water. Nearly, 70 % of that fresh water is frozen in the icebergs in polar regions and the remaining present as soil moisture, or lies in deep underground aquifers as groundwater not accessible to human use. Only 1 % of the world's fresh water is accessible for direct human uses which is regularly renewed by rain and snowfall, and is therefore available on a sustainable basis (Postel et al. 1996). Worldwide, many problems are associated with lack of clean and fresh water. Millions of peoples die annually from the diseases related to impure water. Globally, problem for the pure water increases at a fast rate. Many methods and processes are used for water purification, most of which are costly and energy expensive. New methods of purifying water at a lower cost and with less energy consumption are needed along with environmental concern (Shannon et al. 2008).

Solar distillation is one of the techniques in which low-grade solar energy is used for converting brackish/saline water into potable water. This technology is not only capable to remove a wide variety of contaminants in just one step, but is simple, cost effective, and environmentally friendly. Solar distillation is a technology which operates directly with the help of solar radiation. Solar energy could provide a sustainable alternative to drive the distillation plants, especially in the countries which lie on the solar belt such as Africa, The Middle East, South Asian countries like India (Muftah et al. 2014).

Solar stills are the device used to make potable water from the impure water with the help of solar energy. It uses natural evaporation and condensation processes by which many impurities ranging from salts to microorganisms can be effectively removed from sea water to obtain potable water. Solar still can be broadly classified into two categories, namely, active solar still and passive solar still. Depending on the way of harnessing the solar energy, these can be further classified as given in Fig. 1. Active solar stills use thermal collectors, photovoltaic panels, and concentrator along with distillation unit. Passive solar stills directly use solar radiation in the distillation process (Tiwari and Tiwari 2007).

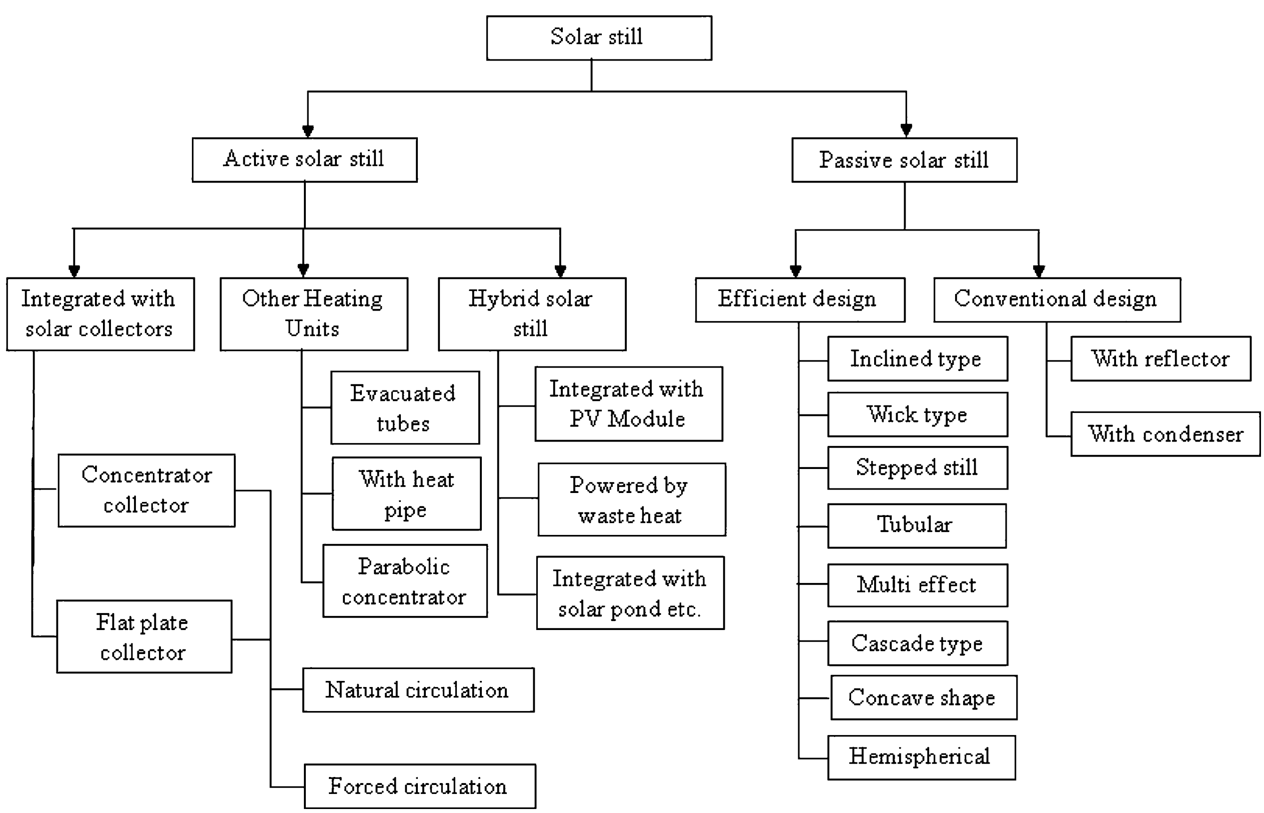

Fig. 1 Classification of solar still

Passive solar stills are simple in construction, operation, usually smaller in size, and less costly. Passive solar stills only utilize exorbitant available solar energy to remove the impurity in contaminated water, thus it is safe, clean, eco-friendly, and energy saving process. In this review paper, various designs, climatic and operational parameters affecting the performance of passive solar stills and their cost analysis have been described. Moreover, this review paper discusses developments, challenges; limitation and scope of improvement in passive solar stills. The decade review papers available in the literature have also been summarized.

Passive solar still

The basic passive solar still structure consists of an air-tight basin usually made of concrete, cement, or galvanized iron sheet containing contaminated or saline water. Upper side of the still is covered with a transparent material like glass, plastic, etc. The inner surface of the basin is black coated for maximum absorption of the solar radiation. The system is well insulated to prevent the heat losses. When the sun rays enter into the closed basin, heat is generated. After absorbing the adequate heat, temperature of water increases which causes its evaporation. The evaporated water vapor condenses on the inclined glass plate and gets collected in the collection chamber (Saidur et al. 2011). Thus, passive solar still effectively purifies seawater, raw sewage and thus removes salts/minerals, bacteria, parasites, heavy metals, etc. This distillation process occurring inside the passive solar still is just similar to natural hydrological cycle. Basic arrangement of a passive solar still is shown in Fig. 2.

There are a number of advantages of passive solar distillers. Some of them are (1) unutilized solar energy can be well utilized, thus the use of fossil fuels reduced to a great extent, (2) passive solar still does not involve any moving part, thus no electricity is required, (3) solar energy source is pollution free and eco-friendly, (4) distilled water can be generated in house with a small investment for domestic and commercial purposes, and (5) low maintenance cost.

Some of the disadvantages of solar stills are (1) the output affects during winter days, (2) it needs to be inclined towards the sun's orientation, and (3) need to be protected during adverse conditions like rain, high wind blowing, etc.

In the next section, some of the important reviews on solar stills along with studies carried out on different designs and performance parameters of passive solar stills by various researchers have been discussed.

Reviews on solar still

Solar stills provide an easy solution of fresh water to most of the earth's region. Different solar stills with different designs and combination have been developed and tested over an age. Various researchers studied and reviewed different designs, performance factors, status and progress in solar stills. Some important reviews on solar still are summarized in Table 1.

Literature review on passive solar stills

The efficiency and distillate output of passive solar stills is very less. There are numerous designs and operational parameters along with climatic conditions that affect the performance of a passive solar still. Due to the large scope of improvement in passive solar stills and for fulfilling the requirement of fresh potable water in an economical and environment friendly way, it has been studied intensively by various researchers. In this section, some of the important researches carried out on the design and

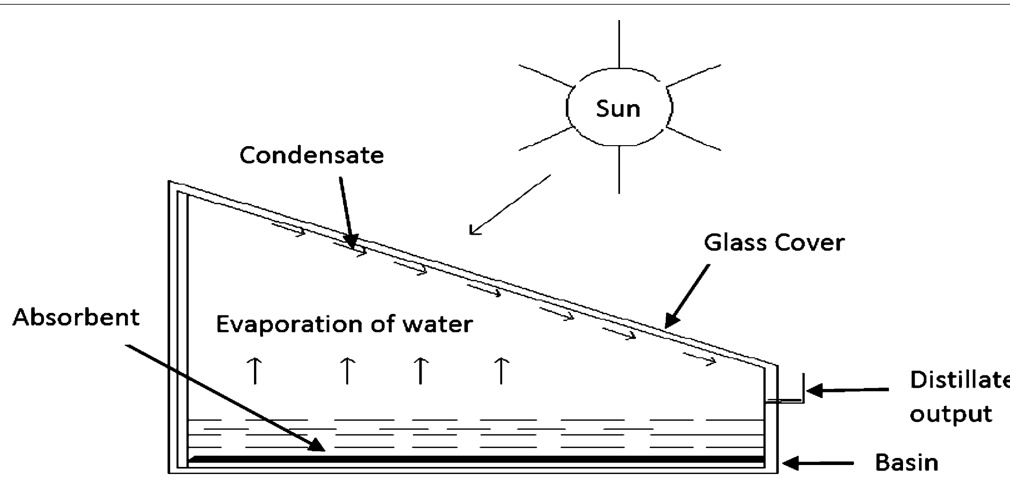

Fig. 2 Basic structure of a passive solar still

Table 1 Reviews on solar still

S. no.	Researcher	Context	Conclusion/remarks
1.	Tiwari et al. (2003)	Present status, past work, and future potential of solar still	From the economical view point, double slope fibre-reinforced plastic still was found efficient than others Passive solar stills were concluded more suitable for domestic purposes and active solar stills for commercial applications
2.	Aybar (2007)	Recent studies on solar still	Performance of solar still depends on various design, meteorological and water parameters. Multi-basin, multi-slop and solar still coupled with solar collector were suggested as improved and efficient designs
3.	Murugavel et al. (2008)	Methods to improve the performance of single basin passive solar stills	Orientation and inclination of condensing cover depend on the latitude of the place. Glass and rubber were found most efficient condensing and basin material Mirrors as reflectors were considered efficient for solar stills
4.	Aybar and Assefi (2009)	Direct and indirect type solar distillation systems	Indirect solar distillation gave higher distillate output but the system is complex, costly and needs high maintenance
5.	Arjunan et al. (2009)	Development techniques and status of solar desalination in India	Solar distillation is considered as the most attractive and reliable solution of fresh water for remote areas and small communities Cover cooling, lower water depth, absorbing materials, wick, multi basin and tubular still reported to give higher yield
6.	Sampathkumar et al. (2010)	Various types, technological development, modeling, and future scope of active solar still	Energy storing material in stepped solar sill coupled with solar pond results higher yield Kumar and Tiwari model was concluded the most suitable for evaluating internal heat transfer coefficients
7.	Kaushal and Varun (2010)	Types of solar still	Selection of solar still mainly depends on local and operating conditions
8.	Kabeel and El-Agouz (2011)	Researches and improvement parameters of solar still	Solar still productivity improves with lower water depth, condensing cover inclination equal to latitude of place, with energy storage materials, sun tracking system, reflectors, flat plate collector, and phase change material
9.	Balan et al. (2011)	Passive solar distillation along with design analysis	Wick type solar still was concluded an efficient solar still design Use of reflectors significantly improves the performance of solar still
10.	Velmurugan and Srithar (2011)	Productivity improvement factors analysis of solar still	Numerous operational parameters such as free surface area of water, water glass temperature difference, and inlet water temperature. Greatly affect the performance of solar still Use of sponges, fins, still with double glass, collectors, storage tank, wicks, reflectors, condenser, additives, etc. Improves the performance of solar still
11.	Ali et al. (2011)	Techno-economical review of various indirect solar desalination techniques	Indirect solar desalination could provide a solution to fulfill the demand of potable water in an economical way
12.	Ayoub and Malaeb (2012)	Critical review on developments in solar still desalination systems Cost analysis	Intensive research is needed in material optimization, system reliability, design sustainability of solar desalination system without affecting its basic advantages
13.	Compain (2012)	Different desalination technologies with solar energy	Combination of most common water desalination technologies with solar energy gives low cost, cleaner, efficient and fuel energy replacement techniques
14.	Shatat et al. (2013)	Need, challenges and various techniques of water desalination process Development and opportunity of solar water desalination technology	Low cost, inexhaustible and clean solar energy combined with different water desalination technologies provides a better alternative for water desalination in economics and environmental aspects

Table 1 continued

S. no.	Researcher	Context	Conclusion/remarks
15.	Sivakumar and Sundaram (2013)	Design, operational and meteorological parameters of solar still	Productivity of solar stills greatly enhances by energy storing materials, sun tracking systems, condensing cover cooling, reflectors, wick materials, stills with collectors, solar pond, and cooling tower Performance of still is highly dependent on location and experimental conditions
16.	Ranjan and Kaushik (2013)	Energy, exergy and thermo-economic analysis of solar distillation system	Energy and exergy efficiency of the conventional solar system was observed to be in the range of 20–46 and 4–5 % and can be increased up to 62 and 8.5 %, respectively. Per liter cost of distilled water was estimated in the range of US $ 0.014–0.237 For higher productivity, efficiency and economical point the solar distillation system must be integrated with other solar devices
17.	Murugavel et al. (2013)	Development and efficiency improvement methods of inclined type solar still	Reflectors, water flowing over condensing surface; phase change materials and wick greatly enhance the productivity of the inclined still
18.	Manikandan et al. (2013)	Status and analysis of various wick type solar stills	Use of wick in the still is considered as an efficient and economic technique to improve the productivity
19.	Xiao et al. (2013a)	Design developments, analysis and heat and mass transfer models for solar still	Under different climatic conditions, different design guidelines provided for yield improvement of solar stills Dunkle's relation was preferred for Grashof number less than 2.51×10^5 and for greater values Adhikari's correlation was recommended Future research was suggested for the development in solar still
20.	Khayet (2013)	Economics, energy consumption and water production cost analysis	Development and optimization of solar desalination by membrane distillation can reduce energy consumption and water production cost
21.	Muftah et al. (2014)	Study of performance parameters and cost analysis of solar still	Distillation productivity can be enhanced for a particular location through the operating and design conditions Almost all parameters which affect the productivity of basin type solar stills were reviewed except some important parameters like effect of vacuum technology and use of nanoparticles
22.	Sharon and Reddy (2015)	Various solar energy integrated desalination technologies	Solar desalination was considered as an efficient, environment friendly fresh water solution Present and future work related to development in solar desalination technologies was suggested along with their pros and cons, problems and remedies, economic and environmental impact
23.	Kabeel (2015)	Performance improvement techniques of stepped solar still	Stepped solar still was concluded as an effective and efficient solar still device Use of reflectors, thermal storage medium, glass cover cooling, sun tracking, wicks with stepped solar still highly improve its efficiency Tray/step depth, width, shape and design significantly affect the performance of stepped solar still
24.	Yadav and Sudhakar (2015)	Different domestic solar still designs along with performance and economic analysis	Solar still with their different designs was considered as an attractive solution to fulfill domestic fresh water demand but still needs efficient and optimized domestic designs to make the technology commercialized
25.	Gugulothu et al. (2015)	Thermal energy storage in solar distillation system	Latent heat storage was considered efficient than sensible heat storage. Combination of sun tracking system and energy storage with solar stills is recommended for future work

Table 1 continued

S. no.	Researcher	Context	Conclusion/remarks
26.	Durkaieswaran and Murugavel (2015)	Special designs of single basin passive solar still	Higher surface area of solar collector can increase the productivity of solar still. It is concluded that there is a scope of improvement in the existing designs to make the system efficient and economical
27.	El-Sebaii and El-Bialy (2015)	Advanced designs of solar desalination systems with cost analysis	Double basin, triple basin and stepped solar stills with reflectors gave higher distillate output with lowest production cost
28.	Kumar et al. (2015)	Single and multi-effect passive and active solar stills system with their merits and demerits	Solar radiation intensity, ambient conditions, condensing cover cooling, flat plate external reflector, and salinity were considered important parameters of solar still Research work on multi-effect and multi-stage evacuated stills was suggested for future scope of improvement

performance parameters of passive solar stills during the last decade have been highlighted.

Research conducted on various designs of passive solar still

Al-hayek and Badran (2004) investigated the performance of two designs of a solar still: asymmetrical greenhouse type (ASGHT) with mirrors and symmetrical greenhouse type (SGHT) shown in Fig. 3a, b, respectively. Productivity of ASGHT still was observed 20 % higher than that of the SGHT still due to adoption of mirrors on the inside walls. Addition of dyes and lowering the water depth also showed improvement in the distillate output of still.

Ayber et al. (2005) designed and studied an inclined solar water distillation system (ISWD) which produced a high amount of fresh distilled water along with hot water. The design was studied with absorber plate alone, with black wick cloth on absorber plate and with black fleece (Fig. 4). Distillate output was observed to be increased by 2–3 times using black wick in comparison to the bare plate alone. Hardness of distilled water was found to be lower in the bare plate than others. From their findings, it is suggested that the bare plate ISWD system is more suitable for high salinity/impurity in feed water.

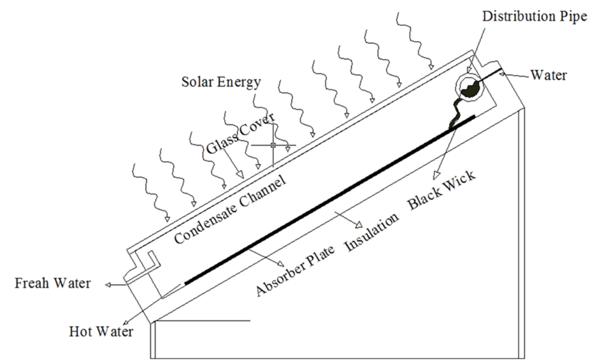

Fig. 4 Inclined solar water distillation system with wick (Ayber et al. 2005)

Kabeel (2009) investigated the performance and cost analysis of concave wick basin pyramidal-shaped solar still. The average distillate output of the still was observed to be 4.0 l/m^2/day with a cost of 0.065$/l. The proposed still shown in Fig. 5 was analyzed for data of only 4 days and for the month of high solar isolation.

Ahsan and Fukuhara (2010) developed a mass and heat transfer model of tubular solar still (TSS). The developed system is shown in Fig. 6. The proposed model considered humid air properties inside the still to calculate heat and mass transfer coefficients. Heat balance of humid air and mass balance of water vapor in humid air were also formulated. Field experimental results showed good agreement with the proposed model. Proposed mass and heat transfer model should be tested for distillate output with varying depth in TSS.

Tabrizi et al. (2010) designed a weir type cascade solar still (CSS) and studied the effect of water flow rate on its performance. The water flow path on the absorber plate of CSS is shown in Fig. 7. The internal heat and mass transfer and daily productivity of the CSS were reported to decrease with the increase of water flow rate. A distillate output of 7.4 kg/m^2/day was collected at a minimum flow rate of 0.065 kg/min. However, at lower flow rates large deviations are observed between the experimental hourly distillate output and the predicted values from the proposed model (shown in Fig. 8).

Wassouf et al. (2011) designed and constructed a low cost, light weight pyramidal and triangular prism-shaped solar stills made of polyvinyl chloride (PVC) material. Stills were designed considering several design parameters. Different tests were performed to measure temperature, solar radiation, turbidity, pH, density, and economic viability of the stills. Pyramidal still shows better efficiency than triangular prism solar still. However, there

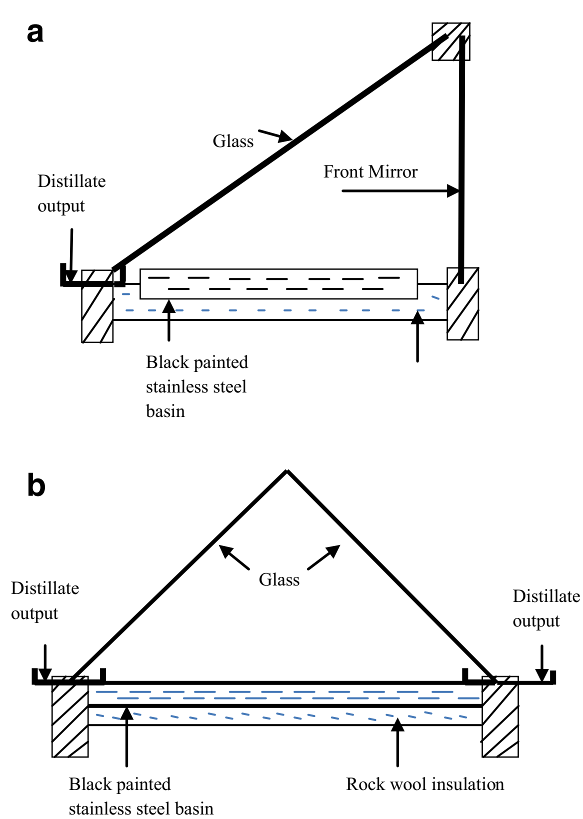

Fig. 3 **a** Asymmetrical green house type solar still (Al-hayek and Badran 2004). **b** Symmetrical green house type solar still (Al-hayek and Badran 2004)

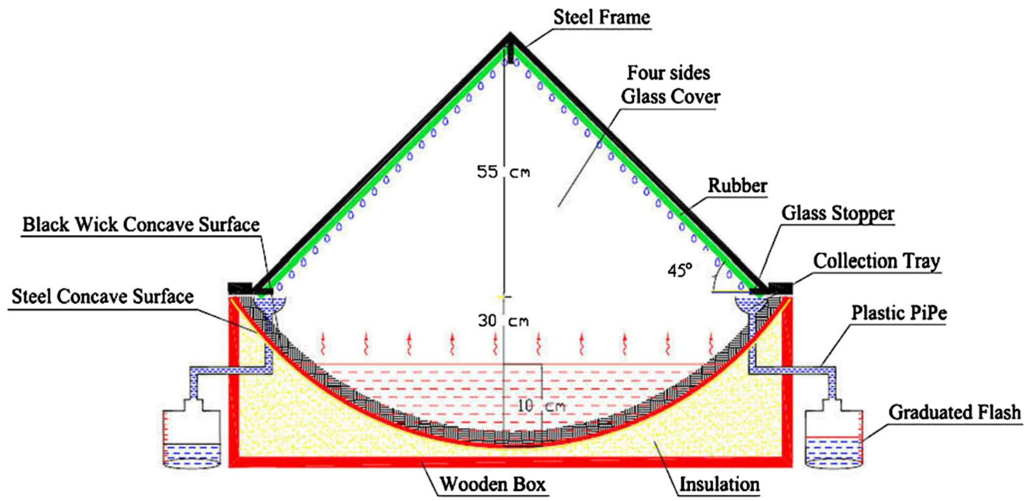

Fig. 5 Schematic view of concave wick basin pyramidal-shaped solar still (Kabeel 2009)

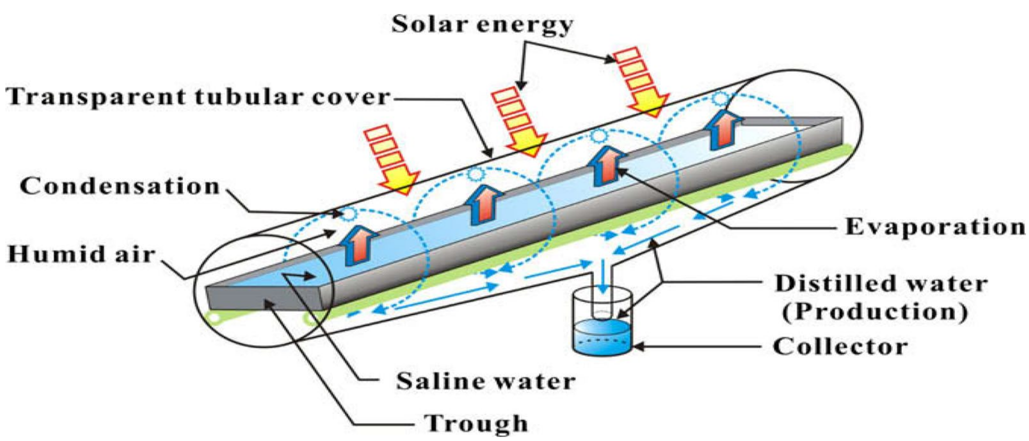

Fig. 6 Tubular solar still by Ahsan and Fukuhara (2010)

are possibilities of improvement in design and manufacturing techniques of these stills which may give a higher distillate output at lower cost. Taamneh and Taamneh (2012) experimentally investigated the effect of forced convection on the performance of pyramid-shaped solar still. A fan was mounted on one side of the glass for circulating the air inside the solar still. Distillate output was increased up to 25 % with this cost-effective modification. Ayoub et al. (2013, 2015) modified a conventional solar still design by introducing a hollow rotating cylinder/drum on it (Fig. 9). Several critical parameters (drum material, drum speed, condensing cover shape and cooling, brine depth, and weather conditions) were optimized for the new system. Proposed still was concluded cost effective and efficient design with an increase of more than 200 % in productivity. Brine depth was observed to be an important factor, while the air cover cooling showed minimal effect on the performance of modified still. Water cover cooling could be tested with the proposed still for better results.

Heat and mass transfer model of trapezoidal solar distiller based on a stagnant zone was formulated by Maalem et al. (2014) which was stated to help in the study of solar units like distillation, driers and greenhouse. Recently, El-Agouz et al. (2015) theoretically evaluated the performance of continuous flow inclined solar still. Performance of three type of models (inclined solar still, inclined solar still without and with makeup water) was studied considering the effect of water mass, water flow thickness, water film velocity and air wind velocity.

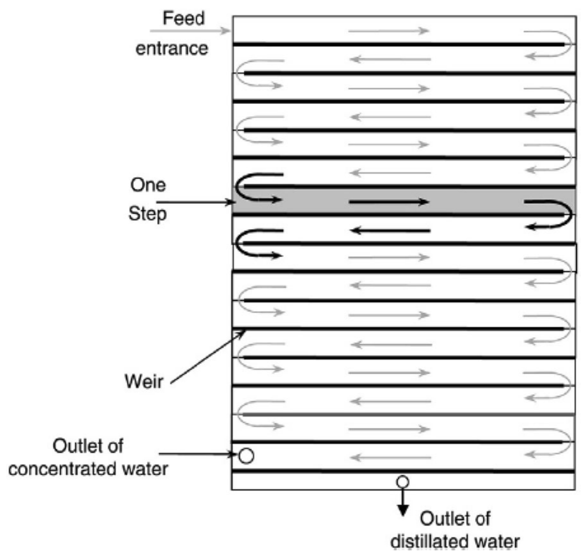

Fig. 7 *Top view* of water flow path on the absorber plate (Tabrizi et al. 2010)

Minimum value for water film thickness and moderate value for water film velocity were suggested for improvement in practical application of modified still.

Some more recent designs of passive solar stills along with different parameters studied by various researchers are summarized in Table 2.

Research conducted on performance parameters of passive solar still

A number of performance parameters such as water depth, cover tilt angle, condensing cover cooling, dyes, wicks, reflectors, sun tracking system, thermal and energy storing materials, etc. greatly affect the output of the passive solar still. Proper combination and utilization of these parameters meet the water demand effectively and economically. Some of the important researches available in the literature on the performance of passive solar still considering the above-mentioned parameters are discussed in this section.

Effect of water depth and condensing cover

Singh and Tiwari (2004) evaluated the monthly and annual performance of passive and active solar stills for five different Indian climatic conditions. It was concluded from numerical computation that the maximum yield of solar stills was obtained with lower water depth and by placing the condensing cover to the latitude of the place. Tiwari and Tiwari (2005) evaluated internal

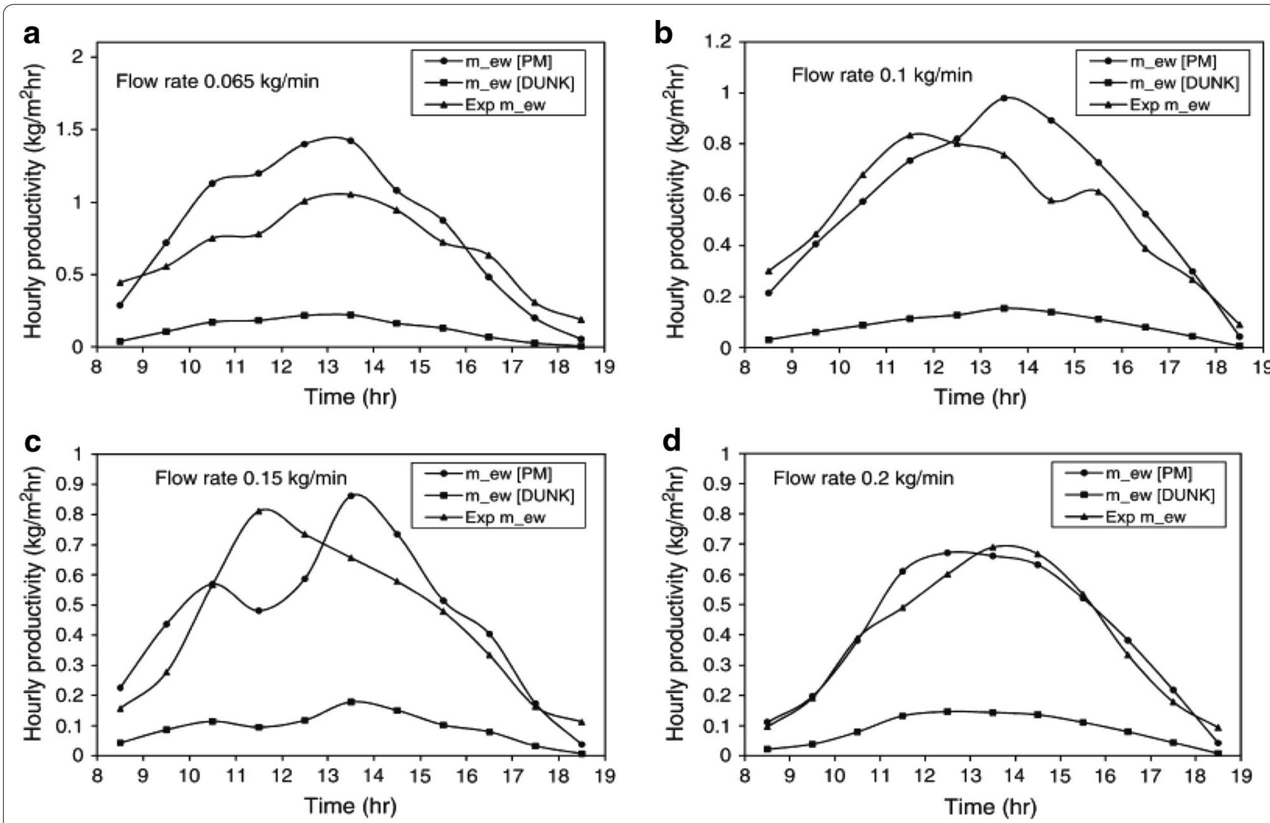

Fig. 8 Experimental and predicted hourly distillate values for CSS (Tabrizi et al. 2010)

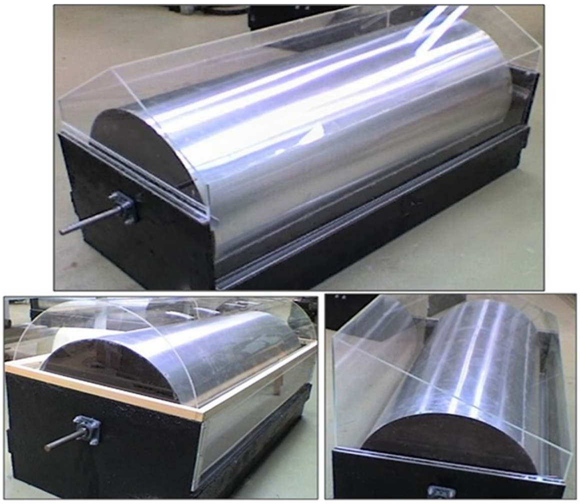

Fig. 9 Rotating hollow drum inside the solar still with different condensing cover shape (Ayoub et al. 2013)

heat and mass transfer coefficients for different condensing cover inclination of the solar still in indoor conditions. Glass cover inclination of 30° resulted in higher yield and high value of heat transfer coefficients. However, for evaluating the values of heat transfer coefficients, the effect of condensing cover material and water depth may also be considered. Tiwari and Tiwari (2006) evaluated the optimum water depth for a passive solar still in summer climatic conditions and also studied the effect of water depth (0.04–0.18 m) on internal heat and mass transfer coefficients. High yield and high efficiency were observed at lower water depth of 0.04 m. Large fluctuation in heat transfer coefficients was reported at lower water depth which was observed to reduce with increase in water depth. However, overall efficiency and productivity of the system are observed to be very low which need to be improved for better performance of passive solar still. Daily output and overall efficiency of the system at different water depth are shown in Fig. 14a, b, respectively.

Tripathi and Tiwari (2006) used the concept of solar fraction in thermal analysis of passive and active solar stills for different water depth. It was concluded that with an increase in water depth, internal convective heat transfer decreases. Also solar fraction significantly affects the thermal modeling of solar stills. The concept of solar fraction may also be applied and analyzed for double slope solar still. Alvarado-Juarez et al. (2015) numerically analyzed the performance of inclined solar still by considering the effect of glass cover, aspect ratio and tilt angle. The distillate output of the still was reported to increase with increase of tilt angle and at a lower aspect ratio. Recently, El-Maghlany (2015) optimized the glass cover inclination angle of double slope solar still and concluded that optimum cover tilt angle depends on the direction of each surface to the south direction.

Effect of wicking and dyes

Ayber (2006) mathematically modeled and simulate an inclined solar water distillation system. The effect of feed water flow rate and solar intensity on the productivity of the system was investigated. System generated 5.4 kg/m^2 of distillate with an input feed water flow rate of 3.6 kg/h as per simulation. Effect of glass cover cooling and hot water recirculation could also be investigated for the ISWD system. Janarthanan et al. (2006) examined the performance of the tilted wick type solar still with water flow over the glass cover (Fig. 15). It was concluded from the results that productivity significantly improves with glass cover cooling and the optimum water flow rate was observed to be 1.5 m/s.

Hansen et al. (2015) analyzed the performance of inclined solar still with different wick materials considering their various characteristics. Water coral fleece wick with wire-mesh stepped absorber plate gave maximum distillate (4.28 l/day). Performance of wick material also depends on mass flow rate and salinity/impurity present in water, thus their effects could also be studied. The correlations developed for the performance of basin type solar still by Khalifa and Hamood (2009) showed that efficiency of the system increases by lowering water depth, increasing solar intensity, and using dyes with brine. The results also showed that maximum distillate can be obtained at a cover tilt angle of about 30°. However, the factor of water purity which significantly affects the distillate output has not been considered for the formulation of their correlations.

Effect of sun tracking system

Abdallah and Badran (2008) implemented a sun tracking system in a solar still which increases the productivity and overall efficiency of the system by 22 and 2 %, respectively, in comparison to a fixed still. Productivity and performance of solar still are not so improved using sun tracking system and need further improvement. Abdallah et al. (2008) improve the performance of a single slope solar still by installing internal reflectors, stepwise basin (Fig. 16) and sun tracking system in solar still. A high improvement of 380 % was observed in stepwise basin type solar still integrated with sun tracking system. Productivity of modified still with sun tracking system can also be improved by integrating a flat plate external reflector with it. The distillate output of fixed and stepped basin sun tracking solar system is illustrated in Fig. 17.

Table 2 Researches on designs of passive solar still

S. no.	Researchers	Still type and geometry	Parameters studied	Modification/methods/ analysis	Results/achievements	Conclusions/remarks
1.	Abderachid and Abdencer (2013)	Double slope symmetrical (DSS), and single slope double effect asymmetrical still (SSDAS), basin area—1 m^2, condensing cover inclination—10°, 30°, and 45° (Fig. 10)	Effect of orientation, tilt angle, and water depth	Simulation study to compare the effect of DSS and SSDAS with different orientations and design parameters	Asymmetrical double effect solar still gives higher distillate output than symmetrical double slope still	South-North orientation of still, 10° tilt angle and 0.02 m water depth gives higher yield. However, these results are concluded only for one day data
2.	Omara et al. (2013)	Stepped solar still (SS), basin area—1.16 m^2, cover inclination—30° (Fig. 11)	Effect of internal reflectors	SS with internal reflectors	Increase of 75 and 57 % in productivity and 56 and 53 % in daily efficiency was observed in stepped solar still with and without internal reflectors, respectively	SS with and without internal reflectors shows better output than conventional stills. However, daily efficiency of SS with and without reflectors is not increased significantly (3 %)
3.	Rajaseenivasan and Murugavel (2013)	Double slope single and double basin still, basin area—0.63 m^2, cover inclination—30°	Water depth, and solar radiation	Theoretical and experimental validation of double slope single and double basin still	Maximum production of 4.75 l/m^2/day (85 % higher) with double basin still	At lower water depth lower basin production is higher than upper basin Cost and maintenance for double basin still are concluded higher than single basin still
4.	Arunkumar et al. (2013b)	Tubular solar still with rectangular basin, basin capacity—2 × 0.03 × 0.025 m	Condensing cover cooling with water and air, cost analysis	Compound parabolic concentrator concentric tubular solar still	Distillate output of 1.5 kg/m^2 day and 2.5 kg/m^2 day with a cost of approximately \$0.018 and \$0.015 per kg water was observed with air and water cooling, respectively	Water flow cooling gives more output than air flow cooling Cost estimation of solar still in their study not includes maintenance, labor and other service charges
5.	Ziabri et al. (2013)	Cascade-type inclined solar still, basin area—1.16 m^2, condensing cover inclination—20°	Weir dimensions	Weirs were constructed on each step of absorbing plate of inclined type of solar still	6.7 l/m^2/day distillate was collected with modified cascade solar still	Weir of appropriate size helps to improve the productivity of solar still. However, saline water flow rate can be optimized for better distillate output for the proposed still
6.	Anubraj et al. (2013)	Inclined solar still, basin size—1 × 0.75 × 0.157 m condensing cover inclination—25°, 30°, 35°	Inclination angle (25°, 30°, 35°), wick materials (black cotton cloth, jute cloth, waste cotton pieces), energy storage and permeable materials (mild steel pieces, clay pot)	Modification in design of inclined solar still with rectangular grooves and ridges on absorber plate	30° inclination angle facing south yield maximum of 3.77 l/day Increase of 12 % productivity was observed using black cotton cloth in basin liner	Energy storage and wicks improve the performance of a solar still at low cost. However, thickness of the wick materials needs to be optimized for future work

Table 2 continued

S. no.	Researchers	Still type and geometry	Parameters studied	Modification/methods/analysis	Results/achievements	Conclusions/remarks
7.	Ahsan et al. (2014)	Triangular solar still (TrSS), length, height, and width of TrSS—1, 0.44, and 0.5 m, respectively	Water depth, solar radiation intensity, and ambient temperature	TrSS fabricated with low, light-weight, and locally available materials	Correlation formulated between water depth (d_w) and distillate output (P_d) as: $P_d = 3.84 - 0.47\, d_w$, for $1 \leq d_w \geq 6$ cm	Inverse relationship between daily productivity and water depth, and direct relationship with solar radiation. However, the suggested correlation has been formulated by collecting the data for 3 months only
8.	Suneesh et al. (2014)	V-type solar still, basin area—1.5 m^2 (Fig. 12)	Condensing cover cooling	Cotton gauge top cover cooling (CGTCC) with and without air flow	4.3 l/m^2 distillate with CGTCC and 4.6 l/m^2 with air flow along with CGTCC	CGTCC without air flow is cost-effective modification. However, hot water supply inside the still with CGTCC may be taken as an objective for increased distillate output
9.	Sathyamurthy et al. (2014)	Triangular pyramid solar still, basin area—1 m^2	Energy storage material	Paraffin wax in heat reservoir integrated with the still	20 % (4.3 l/day) increase in distillate using phase change material (PCM)	Distillate output of solar still is improved using PCM, but it mainly depends on the specific heat capacity, latent heat of fusion, thermal conductivity and proper utilization of storage material
10.	Arunkumar et al. (2012)	Hemispherical solar still, basin diameter—0.95 m (Fig. 13)	Cover cooling	Hemispherical top cover, water quality and cost analysis	4.2 and 3.6 l/m^2/day of distillate were observed with and without condensing cover cooling	Condensing cover cooling improves the performance of solar still, but there are some vapor losses from the flowing water

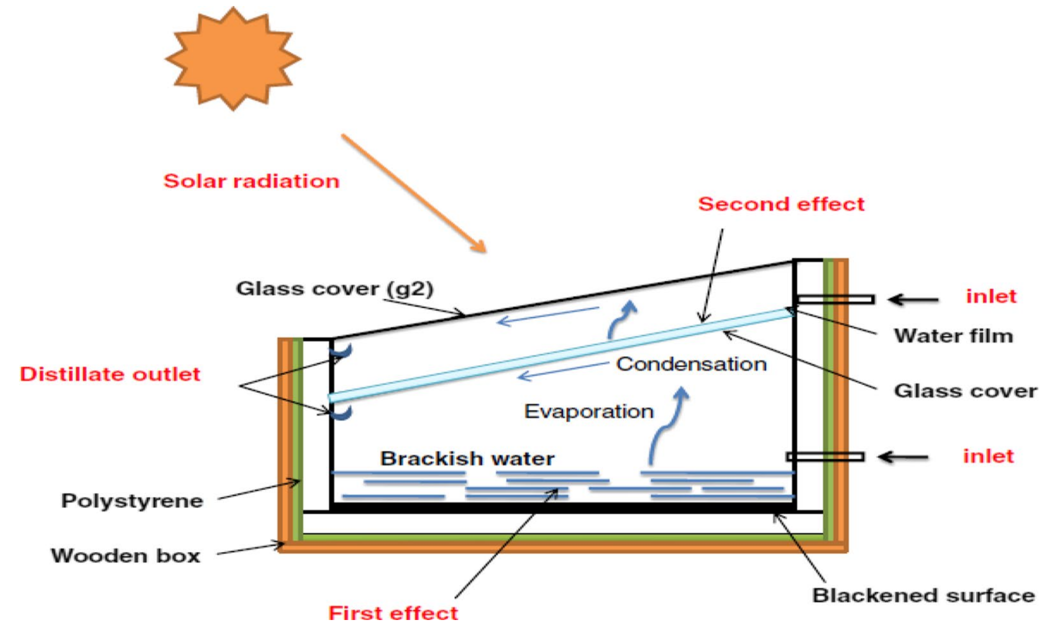

Fig. 10 Double effect asymmetrical solar still (Adberachid and Abdenacer 2013)

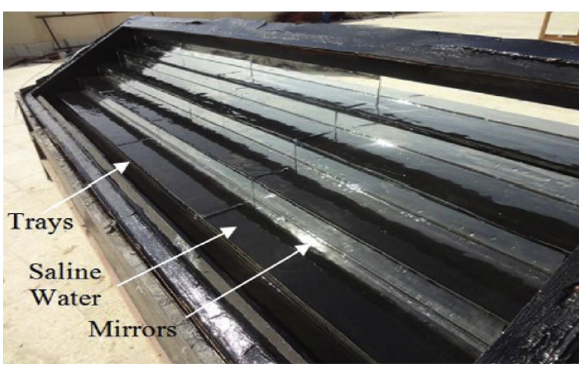

Fig. 11 Stepped solar still with internal reflectors (Omara et al. 2013)

Fig. 12 V-type solar still with cotton gauge top cover cooling (Suneesh et al. 2014)

Effect of internal and external reflectors

Tanaka and Nakatake (2009a) theoretically analyzed the distillate productivity of a tilted wick solar still (Fig. 18) for the winter season with an inclined flat plate external reflector. Still daily productivity was predicted to be improved by 15 or 27 % when reflector length is half or same as still length at 15° reflector inclination. With further improvement, they (Tanaka and Nakatake 2009b) numerically analyzed the effect of flat plate reflector and orientation (one step azimuth tracking) on the productivity of the tilted wick still. Average 41 % increase in distillate was observed from rotating still with reflector. Tanaka (2009a) theoretically analyzed the optimum inclination angle of still as well as of external flat plate reflector for a tilted wick solar still. An average increase of 21 % in distillate output can be proposed by adjusting the inclination angle of both still (10°–45°) and reflector (0°–25°) throughout the year.

Tanaka (2009b) evaluated the effect of internal and external reflectors on the productivity of basin type solar still in winter season. Daily productivity of still with reflectors was observed to be increased up to 70–100 % in comparison to conventional still.

Effect of energy storage and phase change materials

Velmurugan et al. (2008) developed a setup to distill the affluent water and introduced additional surfaces in the basin in the form of fins, saw dust, black rubber, sand, pebble and sponges. The additional surfaces resulted in an increased evaporation rate by 53 % in comparison to the conventional single slope solar still. Sakthivel and Shanmugasundaram (2008) studied the effect of different quantity but of the same size (6 mm) black granite gravel as an energy storage medium on the performance

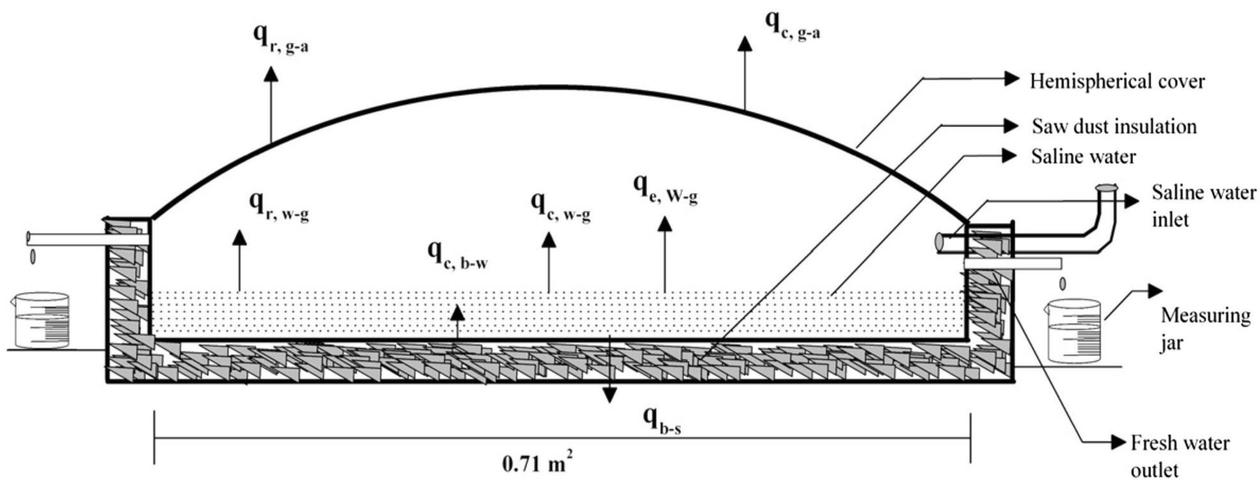

Fig. 13 Hemispherical solar still (Arunkumar et al. 2012)

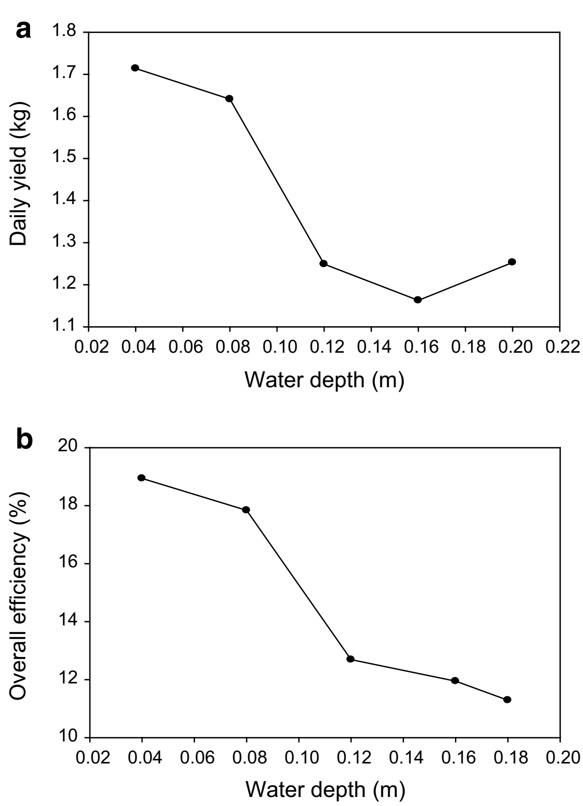

Fig. 14 **a** Variation of daily yield at all water depth (Tiwari and Tiwari 2006). **b**. Variation of overall efficiency at all water depth (Tiwari and Tiwari 2006)

of single basin solar still. System showed higher performance with large depth of storage medium. Daily yield was observed to be increased by 17–20 % and maximum efficiency by 8 % with the use of the low cost storage medium. Abdallah et al. (2009) experimentally investigated the performance of solar stills using different absorbing materials (coated and uncoated wirey sponges, and black volcanic rocks). The overall efficiency of the system was increased with the use of these absorbing materials in the still. Still containing black volcanic rocks showed an overall gain of 60 % in distillate output with no adverse effect, but it made the system bulky. El-Sebaii et al. (2009) studied the thermal performance of single slope-single basin solar still with and without phase change material (PCM). A mathematical model for the proposed still was formed. Computer simulation was used to investigate the performance of still with different mass of PCM. It was observed that daytime productivity of still was decreased with the increased mass of PCM but the overall productivity was increased. Tabrizi and Sharak (2010) experimentally studied the performance of basin solar still integrated with sandy heat reservoir. With the use of heat reservoir, overnight productivity of the still was increased and hence the total yield. It was also noted that wind velocity and solar intensity directly affect the performance of still. However, for more improvement in distillate output the inclination of condensing cover could have been taken equal to the latitude angle (i.e., optimum angle) of the place. Tabrizi et al. (2010) investigated the performance of weir type cascade solar still with and without PCM. Effect of flow rate on system performance was also studied experimentally. Solar still performance without PCM was observed higher than the still with PCM in sunny days and reverse was observed in cloudy days. In sunny days, maximum production of 4.85 and 5.14 kg/m^2 was observed at a minimum flow rate of 0.055 kg/min for still with and without PCM, respectively. The use of PCM as storage material will make

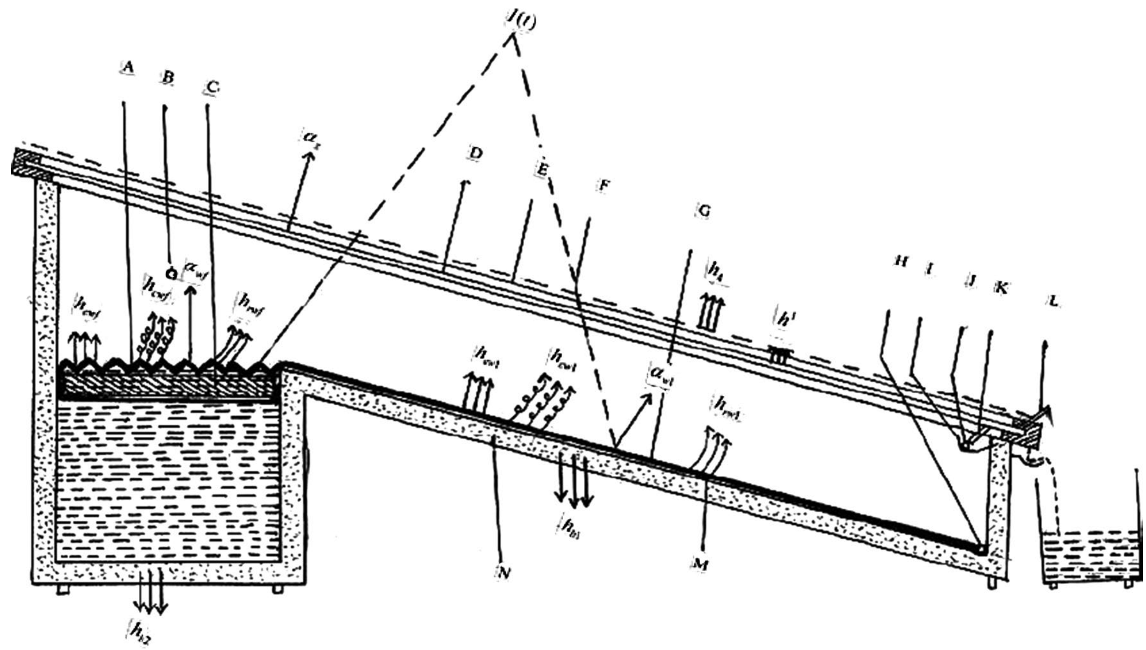

Fig. 15 Tilted wick type solar still (Janarthanan et al. 2006)

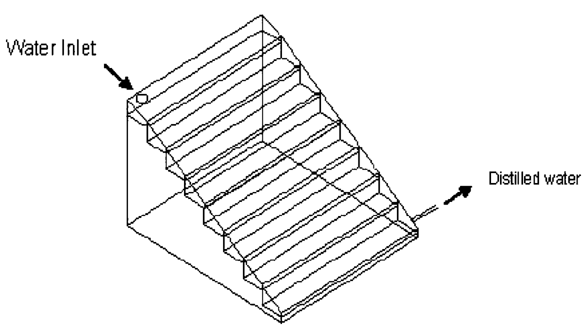

Fig. 16 Step wise water basin solar still (Abdallah et al. 2008)

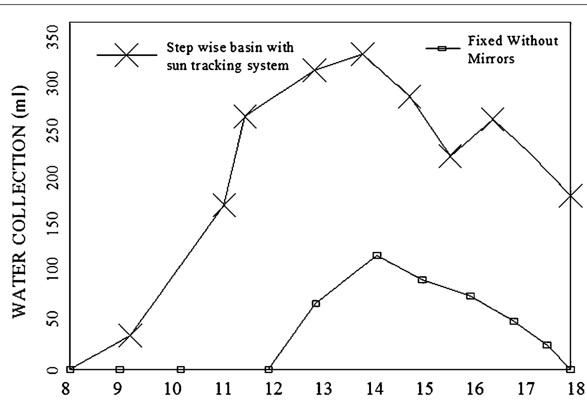

Fig. 17 Distillate output of fixed and stepped basin sun tracking solar still (Abdallah et al. 2008)

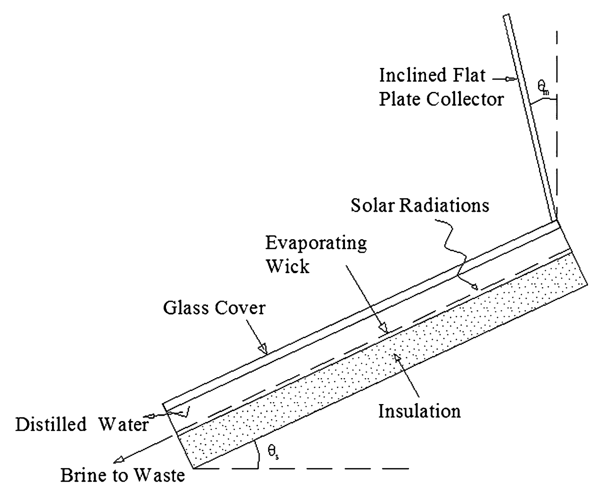

Fig. 18 Tilted wick solar still with external flat plate reflector (Tanaka and Nakatake 2009a, b; Tanaka 2009a)

the system bulky and costly. Moreover, from the findings of these researches, it is observed that use of PCM in inclined solar still is beneficial only for cloudy days. Dashtban and Tabrizi (2011) studied the performance of weir type cascade solar still with and without PCM. Thermal model for the designed still was developed. Effect of water level on the absorber plate and distillate between water and glass surface on the performance of the still was investigated. It was concluded that the productivity of the still was increased by reducing the water level and air gap in the still. With the use of PCM, still gave 31 % higher yield than the still without PCM. However, in the earlier work when the same experimental setup was analyzed and tested by researchers, the use of PCM in sunny days resulted in decreased distillate output. If the constant flow rate (0.07 kg/min) maintained during the operation could have been adjusted in accordance with the availability of solar intensity, then distillate output may have been improved. Arunkumar et al. (2013a) improve the yield of hemispherical basin solar still coupled with conical concentrator. Performance of the system was studied with and without PCM-filled metallic balls in the basin. Effect of PCM was observed more at lower water depth and during low sunshine hours. Productivity of the system was observed to be increased by 26 % with the use of thermal storage material. However, researchers have not provided any data related to water depth in the basin which could be tested for the said system. Figure 19 shows concentrator coupled with hemispherical basin solar still.

Effect of salinity and flow rate

Dev et al. (2011) studied the effect of water depth and total dissolved solid (TDS) on the performance of inverted absorber solar still (IASS) and single slope solar still (SS). The productivity of IASS and SS was observed to decrease with the increase of TDS in water. The optimum water depth for IASS system was reported to be 0.03 m in Oman conditions. Experimental view of IASS is shown in Fig. 20.

Mahdi et al. (2011) studied the effect of water flow rate and salinity on the performance of a tilted wick solar still. Charcoal cloth was used as a wick material which makes the system costlier. From the indoor and outdoor experiments, it was concluded that efficiency reduces with an increase of the input water flow rate and of salinity. Xiao et al. (2013b) evaluated the performance of the simulated brine flowing type solar still under indoor conditions and found that thermal efficiency increases with the decrease of feed water flow rate and increase of heat flux input. However, under outdoor conditions, wind velocity and ambient temperature changes, which affect the performance of solar still, have not been considered.

Fig. 20 Experimental view of inverted absorber solar still (Dev et al. 2011)

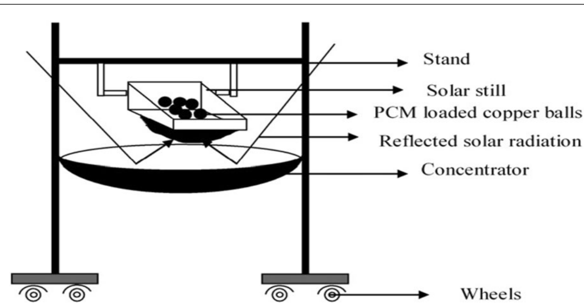

Fig. 19 Concentrator coupled hemispherical basin solar still (Arunkumar et al. 2013a)

Effect of condensing cover cooling

Khudhur and Rai (2014) studied the effect of fan on tubular solar still productivity. Daytime productivity was found to be increased by 8.56 % with the use of fan in still which is not significantly higher than conventional still. Ayoub and Malaeb (2014) modified a solar still by introducing a slowly rotating hollow cylinder to increase the evaporating surface area. Cost per unit water produced was compared with renewable-based desalination and fuel-based desalination technologies. The analysis showed that the economic feasibility of a solar still desalination system becomes more justified, if environment degradation costs associated with fuel-based desalination are acknowledged. However, the modified solar still is complex, costly and has limitation during off-sunshine hours. Somwanshi and Tiwari (2014) attempted to enhance the performance of a single basin solar still numerically with flow of water on the glass cover from an air cooler (Fig. 21). They computed and compared the yield and efficiency of a still with and without water flow on condensing cover for different Indian climatic conditions. The distillate output was observed to increase with the increase of mass flow rate from air cooler and the reverse result was reported with flow of water at ambient conditions. Maximum distillate was recorded with air cooler at lower water depth in hot and dry climatic conditions. However, the results could

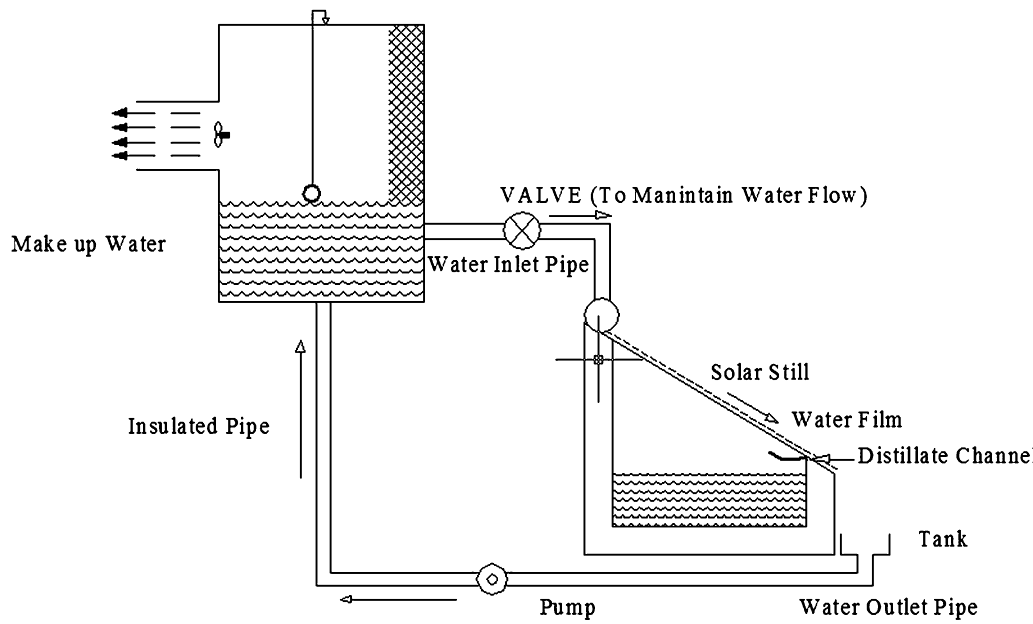

Fig. 21 Solar still coupled to an air cooler (Somwanshi and Tiwari 2014)

also be checked experimentally for obtaining optimized mass flow rate of water under different climatic conditions.

Effect of external condensation and nanofluids

Kumar and Bai (2008) enhanced the condensation surface of the solar still by providing water circulation to the side walls of the still. The performance of the system was studied for tap water, sea water and dairy industry effluent in the basin with and without condensation on the side walls. The efficiency of the system was found to be high using tap water and with water circulation on the side walls of the still. However, the distillate output of the proposed still is observed more or less equal to conventional solar still. Kabeel et al. (2014) integrated an external condenser with single basin single slope solar still along with nanofluids in basin surface. Productivity of still was increased up to 116 %, but cost per unit distillate output is observed to be higher for modified still. Elango et al. (2015) studied the performance of single slope solar still with and without nanofluids. Stills were tested with different nanofluids (Al_2O_3, ZnO, SnO_2) with their varying concentrations. Use of Al_2O_3 water nanofluid (0.1 % concentration) in still gave 29.95 % more distillate output due to its higher thermal conductivity which is concluded as an important property of nanofluids in the performance of a solar still. However, preparation of nanofluids to be used for distillation is a costly and time-consuming technique.

Effect of insulation

Badran and Abu-Khader (2007) studied the effect of insulation thickness and other effective parameters like water depth, solar intensity, overall heat loss coefficient, effective absorbitivity and transmissivity, ambient, water and vapor temperature on thermal performance of a single slope solar still. The efficiency of the system was observed directly related with insulation thickness and solar intensity and inversely with water depth. Optimization of insulation thickness can be made for the proposed model for better performance. Sahoo et al. (2008) experimentally investigated the performance (removal of fluoride contaminants from drinking water) and efficiency of solar still using blackened basin surface and thermocol insulation. A reduction of 92–96 % fluoride from sample water and an increase of 4.69 and 6.05 % in efficiency were observed using blackened basin liner and blackened basin liner with bottom and side thermocol insulation. Elango and Murugavel (2015) experimentally investigated the performance of single and double glass basin double slope solar stills. Stills were investigated at different water depth (1–5 cm) under insulated and uninsulated conditions. Insulated double basin still gave higher distillate output at lower water depth (1 cm). Water depth in the upper basin of double basin solar still may affect the distillate output, thus its effect can be studied in the future.

Some more researches carried out on different parameters affecting the performance of passive solar still are summarized in Table 3.

Cost analysis

Cost analysis of an energy system is essential to know the success of a system economically and to reduce the risk of project failure. Cost analysis of a solar distillation system

Table 3 Studies on parameters affecting the performance of passive solar still

S. no.	Researchers	Still type and geometry	Parameters study	Modification/methods/analysis	Results/achievements	Conclusions/remarks
1.	Khalifa (2011)	Single slope and double slope	Cover tilt angle	Relation between cover tilt angle and productivity, and between optimum tilt angle and latitude angle	(a) Optimum cover tilt angle should be near to the latitude angle (b) Productivity increases with increase in cover tilt angle throughout the year	In winter, higher cover tilt angle gives better results and opposite in summer season. However, similar type of results in regard of cover tilt angle has already been published in (Murugavel et al. 2008)
2.	Tanaka (2011)	Single slope still, glass cover inclination—20°	Effect of inclination angle of the external reflector	External bottom reflector to the front wall of solar still	Optimum inclination angle of external reflector was found to be 40°, 55°, and 25° for spring, summer and winter seasons, respectively	Effect of external reflector is greatest in summer season and minimum in winter. However, this work can also be carried out at different latitudes
3.	Rajamanickam and Ragupathy (2012)	Double slope solar still basin area—1 m^2	Solar intensity, ambient temperature, wind speed, water depth, orientation	Effect of water depth on internal heat and mass transfer and economic analysis	Maximum distillate of 3.07 l/m^2 at a water depth of 0.01 m and higher distillate was recorded in north south orientation	Increase in water depth decreases output and evaporative heat transfer coefficients
4.	Ahsan et al. (2012)	Tubular solar still (TSS)	Condensing cover material	Polythene film as cover of TSS, rectangular trough, heat and mass transfer coefficients, cost analysis	Fabrication cost and weight of new TSS were reduced to 92 and 61 %. Distillate output was found to be proportional to temperature difference inside the still	Cost of water production highly reduced with the new design
5.	Ansari et al. (2013)	Single slope still, surface area—1 m^2	Influence of PCM	Numerical computation for three kinds of PCM of different melting point	Productivity and efficiency of the system was greatly enhanced using PCM	Melting point of PCM chosen is nearly to the maximum of basin water temperature for better distillate Productivity of the still can also be checked for varying water depth in basin
6.	Srivastava and Agrawal (2013)	Single slope, basin area—0.5 m^2, condensing cover inclination—24°	Water depth, base and side insulation	Blackened cotton cloth porous fin	7.5 kg/m^2/day distillate collected in the month of May	Still gives better performance at lower water depth and with insulation
7.	Zoori et al. (2013)	Weir type cascade solar still, evaporative area—0.45 m^2, still inclination—30°	Flow rate, water layer over absorber plate, solar intensity, ambient temperature	Analyzed energy and exergy efficiency	Maximum energy and exergy efficiency of 83.3 and 10.5 % were observed at 0.065 kg/min of brine flow rate	Low brine flow rate and small water thickness over absorber plate improve the efficiency of the system
8.	Bhardwaz et al. (2013)	Single slope, basin area—0.27 × 0.27 m^2 cover inclination—30° to 90°	Cover inclination, material, contact angle	Sponges, hot water bath, temperature controller	Low contact angle, glass as condensing surface, high transmittance of solar radiation from surface produces higher yield	Contact angle, cover material, reflection are considered as important parameters affecting water production
9.	Rajaseenivasan et al. (2013)	Double slope single (DSS) and double basin still (DBS), basin area—0.63 m^2 cover inclination—30°	Water depth, wick, porous, absorbing and storing material	Additional upper basin with different wick, porous, energy absorbing and storing material at lower basin	(a) 85 % higher distillate was collected in double basin still with maximum of 5.68 l/m^2/day at lower water depth and using mild steel as energy storing material	Providing a double basin, lower water depth in lower basin with different storing materials highly increases the distillate, but DBS is bulky and needs more cleaning and maintenance than DSS

Table 3 continued

S. no.	Researchers	Still type and geometry	Parameters study	Modification/methods/analysis	Results/achievements	Conclusions/remarks
10.	Srivastava and Agrawal (2013)	Single slope, basin area—0.52 m^2, condensing cover Inclination—24°	Effect of external reflectors, porous absorber, water depth	Blackened jute cloth floated in basin water, external reflectors on side walls	Distillate gain of 68 % with the modified still, and of 79 % over modified still with the use of twin reflectors	Absorber and two-side reflectors significantly increase the productivity However, impurities (high salt concentration) in basin water and ambient conditions (non-clear days) significantly affect the performance of the proposed still
11.	Omara et al. (2014)	Single slope and stepped solar still of basin area—1 and 1.16 m^2, cover inclination—30°	Effect of internal and external reflectors	Internal and external (top and bottom) reflectors, cost analysis	Internal and external reflector increases the productivity to 125 % than conventional solar still	Use of reflectors greatly enhances the yield. However, the basin water depth has been maintained approximately constant throughout the working period which is difficult to maintain
12.	El-Agouz (2014)	Conventional and stepped solar still, absorber area—1 m^2, cover angle—30°	Storage tank, flow rate, cotton absorber	Stepped solar still with layer of cotton cloth and continuous water circulation using storage tank	Modified still shows 43 and 48 % increase in distillate for sea and salt water using black absorber, while 53 and 47 % using cotton absorber	Maximum output is obtained at lower flow rate
13.	Boodhan and Haraksingh (2015)	Double slope cascade solar still, effective collector area—1.995 m^2 glass cover inclination—10.5°	Varying glass cover thickness and still orientations	Double sided cascade-type solar still with varying cover thickness (3.18, 4.76, 6.35 mm)	Glass cover thickness of 4.76 mm facing south resulted highest yield with average daily efficiency of 29.28 %	Thickness of condensing cover should be selected which allows maximum solar radiation to enter the solar still and minimizing losses
14.	El-Samadony and Kabeel (2014)	Stepped solar still, basin area—1.16 m^2	Cover cooling and film thickness, flow rate, wind speed, feed water temperature	Theoretically performance evaluation of stepped solar still using water film cooling over the glass cover	Optimum conditions: film thickness from 2.5×10^{-4} to 5.5×10^{-4} m, flow rate 4×10^{-5} to 8.5×10^{-5} m^3/s, glass cover length from 2 to 2.8 m	Performance of the stepped solar still increases with low water film cooling thickness and with high water film cooling volumetric flow rate over glass cover
15.	Arjunan et al. (2014)	Single slope single basin solar still, basin area—0.5 m^2 cover inclination—10°	Effect of different energy storage materials	Cheap, simple, and easily available energy storage materials (blue metal stone, black granite gravels, pebbles, paraffin wax) effect on solar still performance	Black granite gravel were observed more efficient storage medium and showed 9.69 % higher yield than conventional solar still	Use of energy storage material is low cost improved modification, but the system becomes bulky with it

depends on several key factors. The main important factors on which economy of solar still depends are initial setup cost, interest rate, operational and maintenance cost, number of sunny days, solar radiation, system life, annual distillate yield, selling price of distillate, and salvage value (Kumar and Tiwari 2009). Although some of these factors vary considerably from one location to another. Kumar and Tiwari (2009) concluded the cost of distilled water of passive solar still approximately 2.8 times lower than hybrid PV/T active solar still. Ahsan et al. (2013) estimated the fabrication cost, water production cost, and cost payback period of tubular solar still and concluded that the water production cost greatly depends on the solar radiation intensity and reduces with increase in sunny days and by the decrease of operational and maintenance cost. Cost analyses of different type of solar stills are tabulated in Table 4. Cost per liter of solar still is obtained based on the following formulae (Yadav and Sudhakar 2015).

$$\text{Average daily productivity} = m.$$

$$\text{Yearly productivity} = m \times \text{operating days}.$$

$$\text{Cost per liter} = \text{total cost/yearly productivity}.$$

Operating day may assume as 300 sunny days in a year.

Scope and future improvements

Passive solar distillation is a naturally operated process to make potable water from contaminated water utilizing abundantly and freely available solar energy. Due to various harmful effects of impure water and energy scarcity, there is an urgent need to make pure water. From the future perspective of utilizing renewable energy and providing clean water to mankind, passive solar distillation is considered as an efficient method. The main disadvantage of passive solar distillation system is its lower distillate output (average 2–4 l/m^2) and efficiency. Energy and exergy efficiency of conventional solar distillation system is found to be in the range of 20–46 and 5–7 %. So there is large work needed in the existing designs of passive solar still to improve its performance at reasonable cost. Numbers of different combination of parameters have to be tested with conventional solar still to increase the distillate output. Some of them are,

- For better improvement in performance of inclined solar water distillation (ISWD), the system flow rate should be adjusted in accordance with the ambient conditions mainly with solar radiation.
- There are various factors which affect the performance of solar still, but it is difficult to optimize all

Table 4 Cost analysis of different solar stills

S. no.	References	Type of still	Productivity	Water production cost per liter
1.	Samee et al. (2007)	Single slope single basin solar still	1.7 l/day/0.54 m^2	0.196 $/l
2.	Kabeel (2009)	Concave wick basin pyramidal-shaped solar still	4.0 l/m^2/day	0.065 $/l
3.	Wassouf et al. (2011)	Pyramidal and triangular prism-shaped solar still	Average 1.8 l/m^2/day	0.046 and 0.063 $/l for pyramidal and triangular prism-shaped solar still
4.	Rajamanickam and Ragupathy (2012)	Double slope solar still	3.07 l/m^2/day	0.217 $/l
5.	Arunkumar et al. (2012)	Hemispherical solar still	4.2 l/m^2/day	0.017 $/l
6.	Ahsan et al. (2014)	Triangular solar still	1.6 l/m^2/day	0.072 $/l
7.	Rajaseenivasan and Murugavel (2013)	Single and double basin double slope solar still	4.75 and 2.56 l/m^2/day for double basin and single basin still	0.088 and 0.11 $/l for double basin and single basin still
8.	Arunkumar et al. (2013b)	Compound parabolic concentrator concentric tubular solar still with water cooling	2.5 l/m^2/day	0.015 $/l
9.	Suneesh et al. (2014)	Cotton gauge top cover cooling V-type solar still	4.3 l/m^2/day	0.170 $/l
10.	Velmurugan et al. (2008)	Fin type solar still	2.77 l/m^2/day	0.192 $/l
11.	Dev et al. (2011)	Inverted absorber solar still	Average 4.0 l/m^2/day	0.11 $/l
12.	Somwanshi and Tiwari (2014)	Single basin, water cooled cover solar still	Average 2.17 l/m^2/day	0.06 $/l
13.	Elango et al. (2015)	Single basin single slope solar still with nanofluids	3.8 l/m^2/day	0.095 $/l
14.	Omara et al. (2014)	Stepped solar still with reflectors	Average 6.0 l/m^2/day	0.088 $/l
15.	El-Algouz (2014)	Stepped solar still with water circulation	5.23 l/m^2/day	0.19 $/l

these factors, but there are some factors like spacing between condensing cover and water surface of inclined still, thermo physical properties of basin material, flow rate, insulation material and its thickness can be optimized in accordance with the available conditions.
- To harness the large solar radiation concentrators/reflectors should be tested with different designs of solar stills.
- Integration of solar distillation technologies with other system (multi-effect systems) can improve the energy efficiency of the system.
- Thickness of wick materials needs to be optimized for future work.
- The sun tracking system has to be tested along with external reflectors.
- To increase the solar collected area for improvement in the system.
- Water cover cooling and hot water circulation can be tested in inclined wick type solar still for higher distillate output.

From future view point, combination of different parameters with new simple and practical designs of passive solar still can make solar distillation technique highly efficient.

Conclusion

There are numerous designs, operational and environmental factors which affect the performance of a solar still. Large numbers of researches are carried out on passive solar still to improve its distillate output and efficiency. It was concluded from the study that inclined solar still design with wick and weir, lower water depth, still orientation, condensing cover cooling, and energy storage materials significantly improve the distillate output of the system. The water production cost of the conventional solar still is also comparable to other energy extensive water purification methods. The following conclusion has been made from the study related to passive solar still.

- ASGHT with mirrors, ISWD system, concave wick type, tubular, pyramidal, triangular, trapezoidal and hemispherical solar still are considered as an efficient solar still design.
- Weir type cascade solar still shows a maximum distillate output of 7.4 kg/m^2/day with a minimum flow rate of 0.065 kg/min.
- Humid air properties significantly affect the performance of solar system and need to be considered during their thermal modeling.
- Hollow rotating cylinder/drum inside a solar still is an effective design modification.
- Double basin solar still gives higher distillate output than single basin solar still.
- Stepped and weir type inclined solar still improves the yield by more than 50 %.
- V-type solar still is an improved design modification of double slope still and needs to be tested for future research.
- Lower water depth (0.04 m) and condensing cover inclination equal to the latitude of the place are optimum operational parameters.
- Flow rates need to be adjusted according to the solar intensity for inclined solar distillation system for better performance.
- Condensing cover cooling and use of wicks largely improve the distillate output of a solar still.
- Optimum cover tilt angle depends on the direction of condensing cover surface to the south direction.
- Thickness of condensing cover should be selected which allows maximum solar radiation to enter the solar still and minimizing losses.
- Sun tracking system, internal and external reflectors, extended surfaces (fins), energy storage and phase change materials are the efficient performance improvement modifications in the solar still.
- For better utilization of sun rays with external reflector, it should be adjusted slightly forward in winter and slightly backward in summer and its length should be equal to still length.
- Ambient conditions like solar radiation, temperature, and wind speed directly affect the distillate output.
- High amount of salinity/impurity in the feed water decreases the yield of a solar still.
- Use of nanofluids in the basin water highly improves the performance of a solar still.
- Condensing cover inclination, contact angle and aspect ratio are considered as an important performance parameters.
- Cost of distilled water of passive solar still approximately 2.8 times lower than hybrid PV/T active solar still.

Though passive solar stills are simple in design, fabrication and have low water production cost yet it has not been fully commercialized due to its low efficiency and productivity. Therefore, more efforts are required for the improvement in its existing designs and performance parameters to make this environmentally friendly technique more useful for humankind.

Authors' contributions
HM prepared the manuscript. MK reviewed and guided in preparing the manuscript. Both authors read and approved the final manuscript.

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