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REVIEW ARTICLE

Factors affecting the performance of a solar still and productivity enhancement methods: A review

Mohit Bhargva[1] · Avadhesh Yadav[2]

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Abstract

Good-quality drinking water is an essential requirement for a healthy and sustainable future. In the current scenario, people living in remote areas of the world are deficient of potable water, especially in developing nations. Desalination technologies available today are energy intensive and aggravate carbon emissions as most energy requirements are fulfilled by using fossil fuels. Solar still is a simple and direct solar desalination device used for water distillation. The major problem associated with a solar still is its low productivity. The main aim of this review paper is to discuss various modifications in a solar still which resulted in productivity enhancement. Different parameters affecting a passive solar still performance and their optimum values for maximum productivity are also thoroughly analysed in this paper. Water depth is an important operating parameter that influences still productivity, and various results showed that maximum productivity is achieved mostly at minimum water depths.

Keywords Solar still · Productivity · Efficiency · Water depth

Introduction

Amongst all water resources available on planet earth, only 3% are fresh water resources (Durkaieswaran and Murugavel 2015). Majority of fresh water is found in icecaps and glaciers which are not physically accessible. Only a small amount is present in rivers, lakes and underground that are used by the people for drinking. In the present scenario, the large-scale consumption of fresh water has resulted in plummeting fresh water resources. Moreover, the disposal of industrial effluents in the rivers and underground is contaminating the freshwater resources (Kumari and Rani 2014). This makes a large amount of potable water unfit for drinking and sanitation purposes (Kumari and Rani 2014). Therefore, desalination of seawater and brackish water becomes imperative for the availability of safe drinking water. The potable water produced from desalination methods like membrane process, nano-filteration, multi stage flash distillation and ion exchange process is costly. These methods are energy intensive and most of the energy requirements are fulfilled by using fossil fuels which aggravates environmental pollution. Solar still is a simple and affordable water treatment device used for distillation and desalinating water. It is simple in design and easily fabricated from locally available materials (Omara et al. 2013a; Rajaseenivasan et al. 2017). Solar still consists of three main components, namely, basin liner, saline water mass and a glass cover inclined at the latitude of still location. The still basin is painted matt black in order to absorb maximum solar radiations. Solar radiations transmitting through glass cover are absorbed by basin water, basin liner and inner walls of still. Water evaporates and gets condensed on relatively cooler inner surface of the glass cover. Condensed droplets glides down the glass surface and collected in a channel inside the still. They are further collected in a container located outside the still. Storage tank is used to maintain desired water depth in still basin.

The main limitation of solar still is its low productivity. Recent experimental studies conducted shows an average water output of 2–3 L/m^{2}day from a conventional still (Bhargva

Responsible Editor: Philippe Garrigues

✉ Mohit Bhargva
bhargvam@gmail.com

Avadhesh Yadav
avadheshyadava@gmail.com

[1] Mechanical Engineering Department, Maharishi Markandeshwar (Deemed to be University), Mullana, India

[2] Mechanical Engineering Department, National Institute of Technology, Kurukshetra, India

and Yadav 2019a, b) (Velmurugan and Srithar 2011; Nagarajan et al. 2017). A review of various efficient methods to increase the productivity of a solar still is suggested and analysed by Rahim (2001), Arunkumar et al. (2019b) and Katekar and Deshmukh (2020a, b). The various modifications in solar still design are done by previous researchers for improving the water output. The water output is increased by 20% when a single-slope solar still with internal reflectors is experimentally compared with a double-slope solar still (Al-Hayeka and Badran 2004). The blackened layers of sponge placed in still basin increased the distillate output by 58% (Sellami et al. 2017). When a porous rectangular black sponge is placed in the still basin, the water output is improved by 17% in comparison to simple basin type still (Rashidi et al. 2018d) and a volume of fluid simulation method showed 39% rise in still output when the porosity of sponge is 0.4 (Rashidi et al. 2018b, c). The partitioning of still absorber resulted in enhancing the still output by 4.8% (Rashidi et al. 2016; Rashidi et al. 2017) (Rashidi et al. 2017). The experiments performed on a single-slope solar still proved it more economical and efficient than a pyramid solar still (Fath et al. 2003). A rise in water output is observed by using quartzite rock (Murugavel et al. 2010), sand reservoir (Tabrizi and Sharak 2010) (Dumka et al. 2019) and pumice stones in still basin (Bilal et al. 2019) as sensible heat storage materials. Due to high heat storage capacity, the use of blue metal stones sized 12mm (Nithyanandam et al. 2017) and asphalt basin liner (Badran 2007) also increased the still productivity. The effect of using internal and external reflectors on still performance is experimentally studied in the winter season (Tanaka 2009a, b). Results showed a remarkable rise of about 100% in still productivity. It is concluded that using an inclined external reflector is less beneficial in summers than in winters (Tanaka 2009a, b) (Khalifa and Ibrahim 2009). The still efficiency is improved by 29% with internal reflectors and fins (Bataineh and Abbas 2020). The effect of using different wick materials, namely, light cotton cloth, sponge sheet, coir mate, and waste cotton pieces in the still basin is experimentally studied (Murugavel and Srithar 2011) and maximum productivity is achieved with light cotton cloth. The still output is improved by 9% using woollen wick (Saravanan and Murugan 2020) and by 16.9% with bamboo cotton wick (Bhargva and Yadav 2019a, b) in comparison to jute wick. A linen wick used with carbon black nanoparticles improved the still output by 80.5% (Sharshir et al. 2020). Phase change materials are used to expedite the evening time water output from the still. An exhaustive review of the applications of various phase change materials in solar still is presented by Katekar and Deshmukh (2020a, b). The application of a corrugated wick absorber and phase change material resulted in 87.4% increment in still productivity (Kabeel et al. 2017). The efficient condensation of vapours in still basin is important to improve the still output. A review of different methods used to improve the condensation rate is presented comprehensively (Patel and Modi 2020). A water-cooled glass is used and experiments were performed for distinct cooling water flow rates (Abu-Arabi et al. 2020). The results showed improvement in water output with the increase in flow rate of cooling water. Silicon based nanoparticles are used on various condensing surfaces to boost the film condensation (Zanganeh et al. 2020). The application of forced water and air cooling of glass is experimentally studied and an improved water output of 8.6l and 8.0l is obtained from the still respectively (Hassan et al. 2020a, b). The still productivity is improved by 3% using a solar powered cooling fan for glass cover (Bani-Hani et al. 2017). Various heat-absorbing materials like charcoal (Naim and El Kawi 2003), black dye mixed in brackish water (Layek 2018) and black volcanic rock (Abdallah et al. 2009) improved the still productivity significantly. The use of fin absorber plate in still basin enhanced still productivity by 15.5% due to increase in surface area and rate of heat transfer (Ayuthaya et al. 2013). The square and solid circular shaped fins (Jani and Modi 2019) and hollow circular fins (Kabeel et al. 2020b) placed in still basin also improved the still output. The application of nanoparticles in a solar still is gaining momentum due to high still output achieved in recent studies. A review on the role of nanoparticles in improving the still water output is conducted exhaustively (Rashidi et al. 2019). The use of copper oxide (CuO) and flake graphite nano-particles (Sharshir et al. 2017a, b) in still basin resulted in increasing the still output to a considerable extent. The coating TiO_2 nanoparticles (Shanmugan et al. 2020) and Al_2O_3-H_2O nanofluid (Rashidi et al. 2018b) (Subhedar et al. 2020) improved the water output from solar still. A simulative study on the Al_2O_3-H_2O nanofluid induced solar still showed a rise in entropy generation with an increase of solid volume fraction (Rashidi et al. 2018a). The effect of various climatic conditions on the performance of a simple basin type solar still is studied (Boukar and Harmim 2001; Subhedar et al. 2020). Different design parameters and their impact on still output are studied (Keshtkar et al. 2020) to understand the most influencing parameters. It was observed that still productivity was strongly influenced by solar intensity and ambient temperature. Tiwari and Tiwari (2006) studied the effect of water depth on heat transfer in a passive solar still. Results showed high daytime productivity at lower water depths and high night time productivity at higher water depths. The water output from solar still is decreased when the water flow rate is increased (Modi et al. 2020) (Kabeel et al. 2019c). The water output from still is increased to high values by integrating with solar collectors. The still output is enhanced with a parabolic trough (Kumar et al. 2020) (Hassan et al. 2020a, b) (Madiouli et al. 2020) (Elashmawy and Alshammari 2020), Parabolic trough concentrator and an evacuated tube collector which are coupled to a still to increase the water output by 34% (Dawood et al. 2020). The application of Fresnel lens (Mu et al. 2019), evacuated tube collector (Shehata et al. 2020), parabolic dish (Kabeel et al. 2019a) and thermoelectric modules (Rahbar et al. 2017) in a solar still resulted in the enhancement of still output.

In this study, the experimental and theoretical research conducted on a single-slope solar still in the last one decade has been discussed in a detailed manner. Different design modifications in a solar still along with the effect of various parameters on still performance are highlighted and reviewed comprehensively in this study. On the basis of experimental and theoretical results, the most influencing parameters which affect the still performance are also identified and highlighted. The most recent research studies conducted on solar still for improvement in water output are analysed and represented in this study. This article encapsulates the latest advancements in solar still along with the most influential parameters for enhancement in water output.

Factors affecting solar still performance

Productivity of solar still is greatly influenced by various design, operating and climatic parameters. These parameters include collector area, water depth, glass cover temperature, water temperature, wind velocity, ambient temperature, glass cover thickness and inclination. Numerous researchers have worked on these parameter variations to understand their optimum value at which maximum productivity is obtained. The design and operating parameters can be varied during experiment to obtain maximum distillate output. But climate-related parameters are uncontrolled and cannot be varied. Some of the important design and operating parameters and their influence on the still output are mentioned below.

Water depth

Water depth influences the freshwater productivity to a considerable extent. Reduced water depth results in increasing evaporation rate of basin water as small quantity of water mass at lower depths quickens evaporation rate and enhances still productivity (Rajaseenivasan et al. 2014). The water output of 3.27 kg is achieved for a double-slope solar still operating at a saline depth of 1 cm (Manokar et al. 2020). The results from the experiments conducted on a pyramid still (Kabeel et al. 2019c) indicated a decrease in water output when water depth is increased from 1 to 3.5 cm. An experimental investigation of a tubular still at distinct water depths showed maximum output (4.5 kg/sq.m) at 0.5 cm depth and minimum output (3 kg/sq.m) at 3 cm depth (Kabeel et al. 2019b). The overall performance of an active solar still improved surprisingly with increased water depth when tested for 10 days continuously (Taghvaei, Taghvaei et al. 2014). It is observed that for all solar–collecting areas, as water depth decreases, the still productivity and efficiency increase (Taghvaei et al. 2015). Khalifa and Hamood (2009b) analysed various research studies concerning the effect of water depth on still performance. An overall decreasing trend of productivity is observed as the water depth increases. Elango and Murugavel (2015) varied water depth from 1 to 5cm and achieved maximum hourly and daily productivity at 1-cm water depth.

Glass thickness and inclination

The transmittance effect of glass cover with thickness 4mm, 5mm and 6mm is experimentally investigated by Panchal (2016). Results showed maximum productivity increase of 27% and 12% for 4-mm thick glass cover in comparison to 5mm and 6mm, respectively. The water output of still is improved by 3.5% when the glass thickness is reduced to 2 mm from 4 mm (Keshtkar et al. 2020). The glass cover inclination also influences the performance of solar still. In summers, at 10°inclination, solar still receives maximum solar radiations which results in 24.45% increase in productivity. In winters, at 45° inclination, the productivity increased by 34.28% (El-Samadony et al. 2016). The maximum productivity of a passive slope still is achieved when it is oriented in south-facing direction (Rajamanickam and Ragupathy 2012). The north-south orientation of still resulted in higher water output in comparison to east-west orientation (Modi et al. 2021). The glass cover of thickness 4 mm and 30° inclination is used in a double slope still to attain maximum productivity of 4.9 kg/sq.m (Salem, Salem et al. 2020). The difference in daily water output of experimental and numerical studies conducted on a pyramid still is minimum for a glass inclination of 40° (El-Sebaii and Khallaf 2020).

Temperature difference between basin water and inner glass cover surface

Evaporation rate of basin water is greatly influenced by the temperature difference between water and inner surface of glass cover. Glass cover absorbs latent heat of condensation of vapours which increases its temperature. This decreases the temperature difference, further decreasing the still productivity (Eltawil and Omara 2014). Solar still integrated with flat plate collector has higher temperature difference of water and inner glass surface than a conventional still (Morad et al. 2015). Abdenacer and Nafila (2007) theoretically calculated that the maximum still productivity and efficiency are achieved at maximum temperature difference between basin water and inner surface of glass cover. The difference in temperatures of glass and water is observed to be higher for water-cooled glass cover than air-cooled glass cover (Shoeibi et al. 2021).

Wind velocity

Sathyamurthy et al. (2015) studied the effect of wind velocity on still performance. Increased wind velocity decreases the temperature of glass cover and increases the condensation rate. Castillo-Téllez et al. (2015) investigated the effect of different wind velocities 2.5 m/s, 3.5 m/s, 5.5 m/s and 6.9 m/s on the performance of solar still. The results indicated performance enhancement up to 5.5 m/s wind velocity. When the velocity increases beyond 5.5 m/s, the still performance decreases. El-Sebaii (2011) performed a theoretical analysis on a passive solar still and calculated critical water depth. It was concluded that still productivity increases with wind velocity beyond critical water depth. For water depth less than critical water depth still productivity decreases as wind velocity increases. An approximate rise of 14% in water output is reported when velocity of outside air is increased to 6 m/s from 1 m/s (Keshtkar et al. 2020).

Solar intensity and ambient temperature

On a bright sunny day, solar intensity increases and reaches its maximum value at noon (Essa et al. 2020b) and then decreases afterwards till the evening. Ambient temperature is dependent on the amount of solar radiations entering earth's atmosphere. As solar intensity increases, the temperature of various parts of still also increases. This temperature increase is higher for a stepped still than a conventional still (Abdullah 2013). The maximum solar radiations are observed at 1 P.M and maximum ambient temperature at 3 P.M (Rashidi et al. 2017). This time difference is due to thermal capacity, moisture content and density of surrounding air. The water output of still directly depends on solar intensity of the region. The water output increase with a rise in solar intensity (Narayanan et al. 2020).

Insulation material and thickness

The experiments conducted on a cascaded solar still with insulations, namely, glass wool, cellular glass, phenolic foam, and fibre glass resulted in highest water output with phenolic foam (Khanmohammadi and Khanmohammadi 2019). The optimum value of insulation thickness is theoretically calculated as 0.1m for an active solar still operating at a water depth of 0.03m (Tiwari et al. 2009). The application of thermocol insulation (Elango et al. 2015) (Karthikeyan et al. 2020) used in a passive solar still resulted in improving the water output. Glass wool insulation of 5cm thickness (Kabeel 2009) and saw dust insulation (Velmurugan et al. 2009) are also utilized in solar stills to minimise the heat losses. Khalifa and Hamood (2009a, b) studied the effect of insulation thickness on still productivity. Styrofoam sheet of thicknesses 30mm, 60mm and 100mm are used in the experiment. It was observed that operating water temperature and productivity increase with insulation thickness up to 60mm. Sahoo et al. (2008) conducted experiments in a passive solar still and achieved 6% increase in productivity by using thermocol insulation. The experiments performed on a pyramid still with insulation resulted in an approximate rise of 19% in comparison to a conventional still (Manokar et al. 2020).

Productivity enhancement methods

The still productivity is enhanced by applying various design modifications. These modifications expedite the rate of heat transfer occurring inside and outside the still. Solar still augmented with different wick materials, fins and glass cover cooling improves the evaporation and condensation rate. The use of sensible and latent heat storage materials boosts night time productivity of the still (Fig. 1).

Fins

Fins increase the heat transfer area and enhance the convection heat transfer between basin liner and basin water. The convective heat transfer coefficient also increases due to an additional fin surface. This increases overall performance of the still. Alaian et al. (2016) enhanced the solar still performance by using a pin-finned wick absorber at the still basin. This increases the evaporation surface and also increases productivity by 23%. Rajaseenivasan and Srithar (2016) experimentally investigated the effect of using square and circular fins in the still basin. Fins are covered with wick and the system is tested at distinct water depths from 1 to 4cm. The maximum productivity of 4.55 kg/m^2 day is achieved with square fins at 1-cm water depth. The use of square fins and circular fins increases the productivity by 36.7 and 26.3% in comparison to a conventional still. The economic analysis

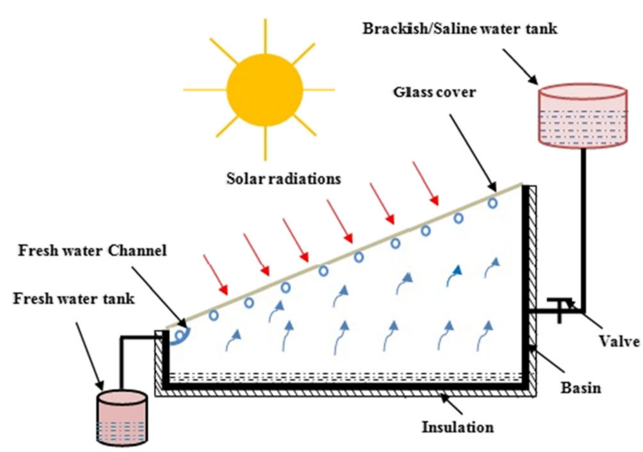

Fig. 1 Schematic diagram of a simple basin type solar still

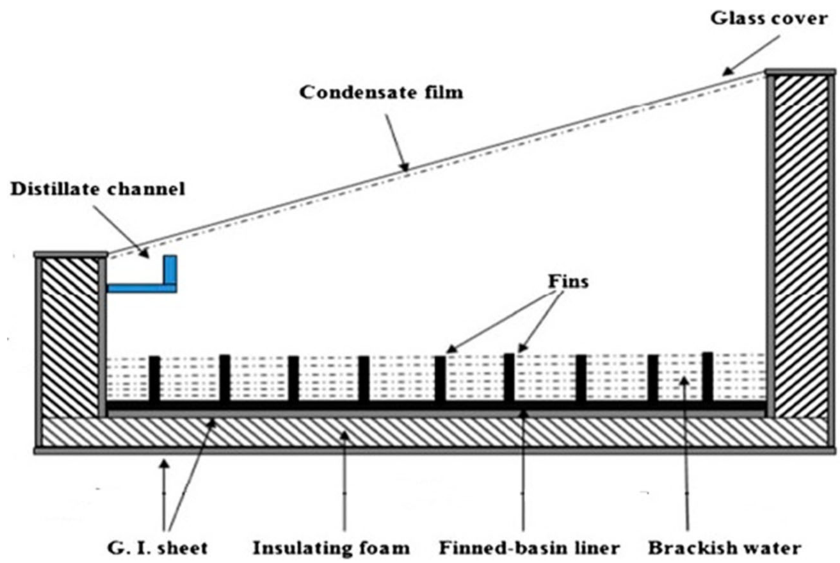

Fig. 2 Schematic diagram of solar still with fin absorber (El-Naggar et al. 2016)

showed a payback time of less than a year. Panomwan Na Ayuthaya et al. (2013) utilized a pin fin absorber plate in still basin to enhance the still productivity. An increase of 12% is achieved in comparison to the conventional still. El-Naggar et al. (2016) integrated metallic fins to the basin liner and experimentally investigated the effect on still performance. The schematic diagram is shown in Fig. 2. The maximum daily productivity and efficiency of 4.8 kg/m^2 and 55.37% are obtained.

Panchal and Sathyamurthi (2017) experimentally compared the performance of still with and without porous fins. Still with porous fins enhances the productivity by 42.3% in comparison to the still without porous fins. Some other research works using different types of fins for improving the still output are shown in Table.1.

Wick materials

Wick increases effective area of evaporation and improves the heat transfer rate. Also basin water heats up quickly because of slow movement of water in a wick. A wick has higher heat storage capacity and enhances thermal performance of a still. The impact of various wick materials on still output is reviewed by Abdullah et al. (2021a, b). Omara et al. (2016) experimentally investigated corrugated absorber solar still integrated with wick and internal reflectors. A double-layer wick is used over the corrugated absorber. A constant water depth of 1cm is maintained throughout the experiment. An increase of approximately 146% in still productivity is observed in comparison to a conventional still. Productivity is increased by 90% when corrugated absorber still is used with

Table 1 Effect of different types of fins on still output

Author(s)	Type of fins/material	Type of solar still	Water depth (mm)	Percentage rise in water output (%)
(Jani and Modi 2019)	Hollow square, hollow circular/steel	Double slope single basin	10	3.32, 17.51
(Kabeel et al. 2020b)	Hollow circular/copper	Double slope single basin	20	43
(Bataineh and Abbas 2020)	Rectangular	Single slope single basin	25	No significant improvement
(Panchal et al. 2020c)	Vertical, inclined	Single slope single basin	10	24.19, 26.77
(Suraparaju and Natarajan 2021a, 2021b)	Pin fins	Single slope single basin	20	24.26
(Abdelgaied et al. 2021)	Vertical pin, inclined pin	Tubular	-	18, 27.6
(Suraparaju and Natarajan 2021a, 2021b)	Hollow pin, solid pin	Single slope single basin	-	41.5, 20.8
(Panchal et al. 2020b)	Solid fins/mild steel	Double slope single basin	25	25
(Kateshia and Lakhera 2021)	Pin fins	Single slope single basin	-	30
(Shmroukh and Ookawara 2020)	Square/copper	Stepped	30	129

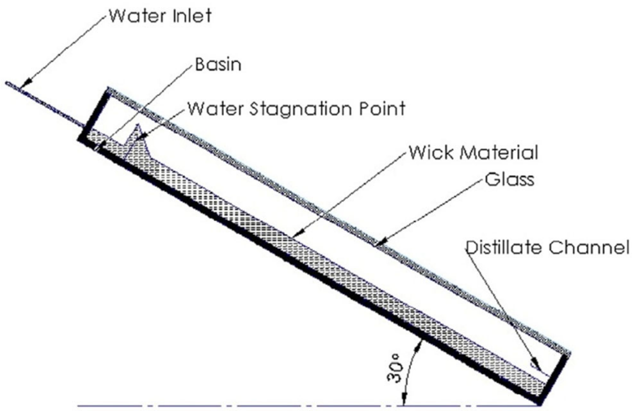

Fig. 3 Schematic diagram of tilted wick solar still (Karthick Munisamy et al. 2017)

wick only. Haddad et al. (2017) Abdullah et al. (2019) designed a basin type solar still with a vertically rotating wick integrated at back side of the wall in order to increase the evaporation area. This system is driven by a 25 W electric motor. The vertically rotating wick provides a fillip to the productivity by 14.72% in comparison to the solar still without wick. Hansen et al. (2015) examined the effect of water coral fleece fabric, wood pulp paper wick and polystyrene sponge wick materials on still performance. Due to better porosity, absorbency and capillary rise water coral fleece wick material with productivity 4.28 kg/m^2 performed better in comparison to others. Pal et al. (2017) conducted experimental analysis of a single-basin double-slope solar still using black cotton and jute wicks. The use of black cotton wick enhances the still productivity by 28% in comparison to jute wick. Karthick Munisamy et al. (2017) used terrycloth, jute, polyester cloth and fur fabric as wick materials in a tilted solar still. The maximum productivity of 3.63 L/day is obtained using fur fabric wick material. The schematic diagram tilted wick solar still is shown in Fig. 3.

The other studies conducted to understand the effect of different wick materials on still output are shown in Table.2.

Sponges

Sponge acts as a source of heat storage and keeps absorber temperature high enabling evening time productivity. Arjunan et al. (2011) performed theoretical and experimental analysis on the effect of using sponge liner of variable thickness in still basin. Still productivity increased by 35.2% using sponge liner of thickness 5mm than conventional still. The use of black-painted sponge layer of 5mm thickness as shown in Fig. 4 enhances the still productivity by 58% in comparison to conventional still (Sellami et al. 2017). Rababa'h (2003) conducted experiments to understand the effect of using sponge cubes in still basin. At higher water depths, the portion of sponge exposed above the water surface reduces. This resulted in an increased capillary rise which enhances the evaporation rate of water from the sponge. Increasing the sponge size exposed more surface of it above basin water level. This reduced the capillary rise of water in sponge and resulted in decreased evaporation rate and still productivity.

Thermal energy storage materials

Thermal energy storage materials have high heat storage capacity. The heat energy absorbed during sunshine hours is utilized in enhancing evening hour productivity. Sensible and latent heat storage materials are two types of thermal energy storage materials used to improve the still performance.

Sensible heat storage materials

Servotherm medium oil and sand were used in still basin by Deshmukh and Thombre (2017) as sensible heat storage materials as shown in Fig. 5. The water depth is kept constant at 0.6cm, and the heat storage material depth is varied during the experiment. The maximum productivity of still is obtained at 5mm storage depth using servotherm oil.

Table 2 Effect of different types of wick materials on still output

Author(s)	Wick material	Type of solar still	Water depth (mm)	Percentage rise in water output (%)
(Modi and Modi 2020)	Jute	Double basin single slope	10	23.71
(Abdallah et al. 2009)	Jute	Single basin single slope/rotating wick	10	300
(Sharshir et al. 2020)	linen	Stepped double slope	10	35.8
(Saravanan and Murugan 2020)	Cotton, jute, polyester, wool	Square pyramid	20	7.2, 19.4, 30.9, 40.3
(Bhargva and Yadav 2019a, 2019b)	Bamboo cotton	Single basin single slope	10	51.9
(Abdullah et al. 2021b)	Jute	Single basin single slope/sliding wick	10	260
(Dumka et al. 2020)	Plastic balls wrapped in jute cloth	Single basin single slope	sensible	64

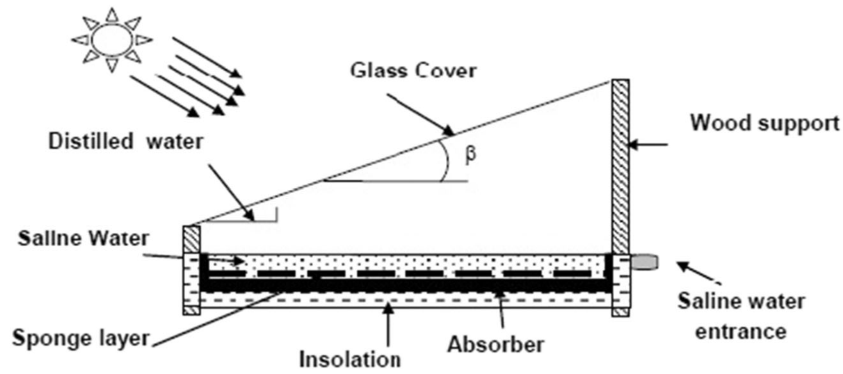

Fig. 4 Schematic diagram of solar still with sponge layer on basin liner (Sellami et al. 2017)

The use of pebbles as heat storage material enhances the still productivity by 9.5% in comparison to a conventional still (Arjunan et al. 2017).

Latent heat storage materials

A review study on the application of various phase change materials in solar stills (Katekar and Deshmukh 2020a, b) encapsulated their impact on still output. Latent heat storage materials change their phase by absorbing heat during daytime and again change phase by releasing heat during night time. This heat release is utilized for evaporating basin water during night time. The use of paraffin wax as a phase change material enhanced the still productivity by approximately 68% (Kabeel and Abdelgaied 2016). Aluminium oxide (Al_2O_3) nanoparticles dispersed in paraffin wax phase change material are used by Rajasekhar and Eswaramoorthy (2015). The results showed 5% increase in productivity with nanoparticles than using PCM without nanoparticles. Shalaby et al. (2016) experimentally investigated the use of a v-corrugated copper absorber and paraffin wax as PCM as shown in Fig. 6.

To dispel the problem of air trapping in paraffin wax on solidification, copper tubes were inserted through the gaps drilled on one side of the storage tank. This allows proper exit of air bubbles from storage tank. The results showed an increase of 72.7% in overnight productivity and a decrease of 7.2% in daylight productivity with PCM. Al-harahsheh et al. (2018) used PCM filled tubes in still basin for heat storage during daytime. Sodium thiosulfate pentahydrate due to its high latent heat of fusion, small change in volume on phase change and easy availability at low cost is used as PCM. Results showed enhancement in night time productivity with the use of PCM. Kabeel et al. (2018) conducted experiments to test different PCM’s and analysed their effects on still performance. Capric palmatic an inorganic PCM and A48 an organic PCM were used in still basin. Application of both PCMs in still basin enhanced still performance, but organic PCM A48 is preferred due to its eco-friendliness. The results indicated that solar still productivity increased by 92% using A48 PCM. Govindaraj et al. (2017) studied the effect of different fin orientations on the heat transfer rate of paraffin wax PCM-filled spherical-shaped capsule. Paraffin wax was used as PCM. The results showed that the orthogonal orientation of fin reduced the total time for charging and discharging of PCM by 22 and 15% in comparison to circumferential orientation of fin respectively. Arunkumar et al. (2017) utilized PCM-filled vacant copper balls in the basin of single-slope solar still for performance enhancement. The effect of integrating compound parabolic concentrator and compound conical concentrator on the still performance was also studied.

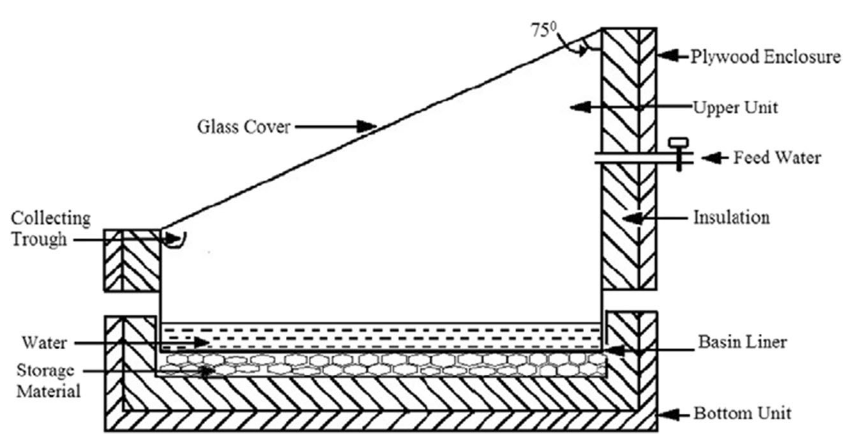

Fig. 5 Schematic diagram of solar still with sensible heat storage material in basin (Deshmukh and Thombre 2017)

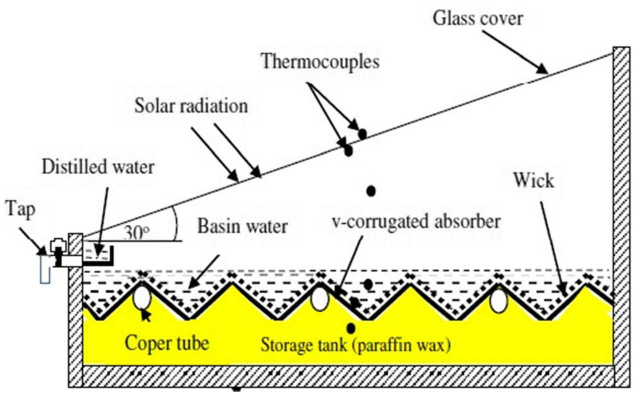

Fig. 6 Schematic diagram of solar still with corrugated absorber and PCM (Shalaby et al., 2016)

The results indicated that still productivity is increased using PCM by 20.8% (compound conical concentrator with single slope solar still) and 2.6% (compound parabolic concentrator with pyramid solar still), respectively. Arunkumar et al. (2013) analysed the effect of using paraffin wax PCM filled in empty copper balls situated in the hemispherical basin of a single-slope solar still. A parabolic dish concentrator was used to concentrate solar radiations at the bottom of hemispherical basin. The schematic diagram and photograph of experimental set-up and the photograph of PCM filled copper balls are shown in Fig.7.

The results indicated that due to thermal energy storage in PCM, the freshwater productivity of the still increased by 26.7% in comparison to still without PCM. Some of the recent studies conducted to know the effect of various heat storage materials on still output is shown in Table 3.

Internal and external reflectors

The productivity of still enhances with the application of reflectors inside and outside the still. Internal and external reflectors reflect solar radiations onto absorber and increase the basin water temperature. This results in expediting evaporation rate and increasing the distillate output from the still. The application of an external reflector in a double-slope still improved the still output to a good extent (Patel et al. 2020b). In winters, the application of internal reflectors in still basin proved more beneficial than summers in enhancing water output (Bataineh and Abbas 2020). A rise of 57% is achieved with the use of internal reflectors in still basin (Abdullah et al. 2020). Omara et al. (2013a, b) experimentally investigated the effect of using internal reflectors on inside vertical walls of the stepped still. The results showed 18% increase in productivity with the use of internal reflectors. This system when augmented with external reflectors further bolster productivity by 50% (Omara et al. 2014). An increase of 22 and 34% in annual efficiency and productivity is observed when internal reflectors are used in a passive solar still. This increase is higher in winters than in summers (Estahbanati et al. 2016). Tanaka (2011) theoretically calculated the effect of using internal and external reflectors on still performance. The schematic diagram is shown in Fig. 8. Total solar radiations reflected by external reflector and absorbed by basin liner are also calculated. The results showed 62% productivity increase in winters when internal and external reflectors are used.

Pearce and Denkenberger (2006) concluded that use of compound parabolic concentrator has a remarkable economic benefit in producing potable water. Fig.9 shows the different

Fig. 7 (**a**) schematic diagram of experiment set-up. (**b**) Photograph of PCM filled copper balls. (**c**) Photograph of parabolic concentrator integrated single slope solar still with hemispherical basin (Arunkumar et al., 2013)

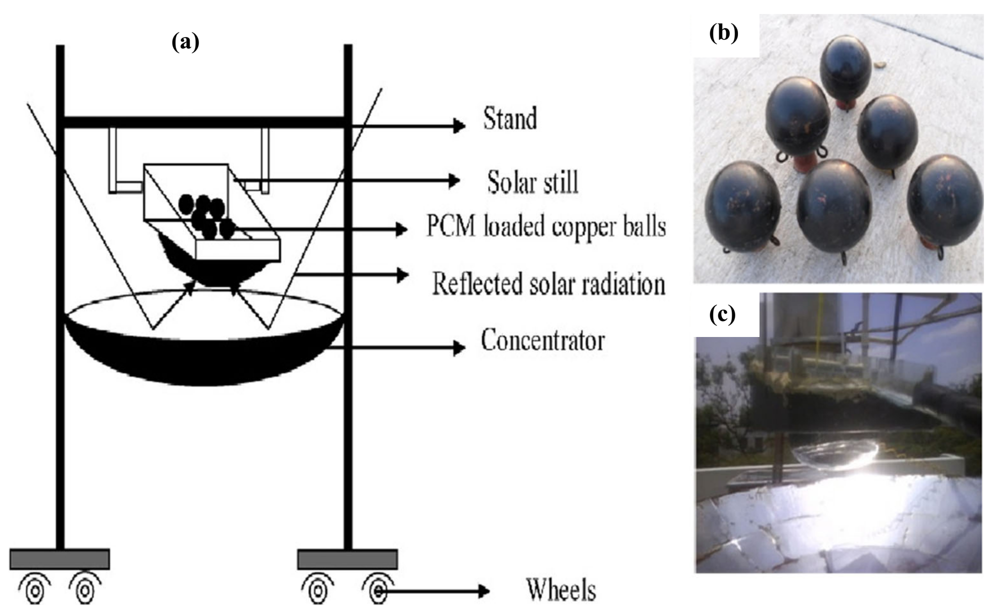

Table 3 Effect of different types of heat storage materials on still output

Author(s)	Type of solar still	Name of heat storage material	Type of heat storage (sensible/latent)	Percentage rise in water output during night time (%)
(Mohamed et al. 2019)	Single basin single slope	Black basalt (size- 2cm)	Sensible	33.37
(Kabeel et al. 2020a)	Tubular	Paraffin wax	Latent	110
(Bilal et al. 2019)	Single basin single slope	Pumice stones	Sensible	14.9
(Panchal et al. 2020a)	Evacuated tube integrated single slope	Calcium stones	Sensible	104.6
(Madiouli et al. 2020)	Parabolic trough collector+ flat plate collector coupled single slope	Glass balls	sensible	172
(Abu-Arabi et al. 2020)	Flat plate collector coupled single slope	Sodium acetate trihydrate	Latent	21
(Dumka et al. 2019)	Single basin single slope	Sand in cotton bags	sensible	28.5
(Arunkumar et al. 2020)	Single basin single slope	Polyvinyl alcohol sponges, pebbles, spherical clay balls	Sensible	18.7, 75, 62.5
(Vigneswaran et al. 2019)	Single basin single slope	Paraffin wax	Latent	19.6

heat and mass transfer processes occurring in the compound parabolic concentrator integrated solar still.

Arunkumar et al. (2016) used 5 sets of compound parabolic concentrator integrated tube solar still to preheat the saline water which was then directed to the basin of a single slope solar still. The photograph of experimental set-up is shown in Fig. 10

Experimental results indicated that the freshwater productivity increased by 74.1% using extracted heat. Arunkumar et al. (2015) integrated a parabolic dish concentrator to a single-slope solar still and examined the effect of PCM and glass cover cooling on the performance of still. A considerable improvement in still productivity is observed with the use of parabolic dish concentrator, glass cooling and PCM. Experimental results also indicated that the cost efficiency of the system decreased using glass cooling.

Nano-fluids

The nanoparticles expedite the heat transfer in the still basin, and their application is diverse in a solar still. Nano fluids have very high thermal conductivities, high heat absorption and high coefficient of heat transfer. The carbon black nanoparticles (1.5% concentration) are mixed in basin water to improve the evaporation rate of water (Sharshir et al. 2020). Kabeel et al. (2014) used cuprous oxide and aluminium oxide nanoparticles in still basin. The experimental results showed a productivity increase of 94% and 89% using cuprous and aluminium oxide nano particles respectively. Flake graphite nanoparticles due to their good absorbing properties also find application in solar stills. The still productivity is enhanced by approximately 51% with the use of flake graphite nanoparticles (Sharshir et al. 2017a, b). Arunkumar et al. (2019a, b) experimentally investigated the effect of using a stainless steel absorber plate coated with copper oxide nanoparticles on the still performance. The use of copper oxide nanoparticles resulted in the enhancement in productivity and efficiency of the still with maximum values attained at 2995 ml/m^2/day and 53%, respectively.

Glass cooling

The cooling of glass cover increases the temperature difference between basin water and inner glass cover. This

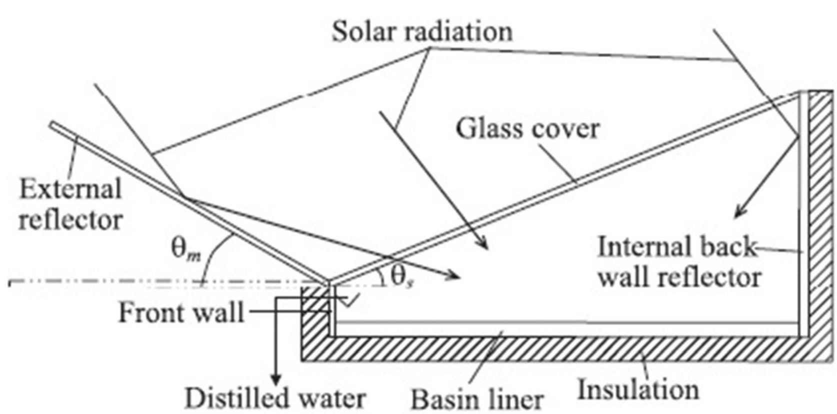

Fig. 8 Schematic diagram of solar still with internal and external reflector (Tanaka 2011)

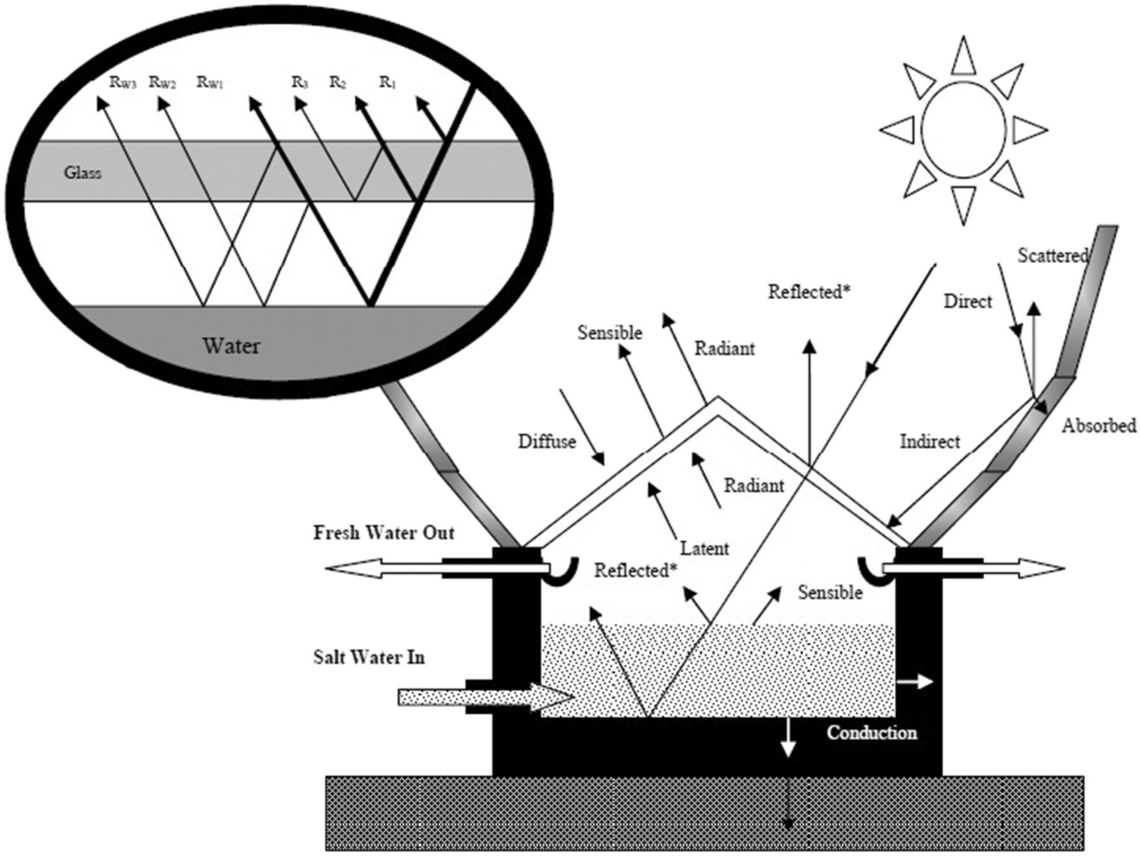

Fig. 9 Different heat and mass transfer processes happening in the compound parabolic concentrator integrated solar still (Pearce and Denkenberger 2006)

improves condensation rate of vapours and enhance still performance. Still performance increases at higher mass flow rates of cooling water (Abu-Arabi et al. 2020) (Shoeibi et al. 2020). (Sharshir et al. 2017a, b). It is also recommended not to increase flow rate further due to slow rise of cooling rate and increase in operating cost. For evenly distribution of cooling water over glass cover, cotton gauze cooling is used by Suneesh et al. (2014). The productivity of 4.3 L/m^{2}d is achieved which is further enhanced to 4.6 L/m^{2}d with the air flow over the cooling cover. The use of external fan for glass cover cooling in winters decreases the productivity of a double-slope solar still (Al-Garni 2012). This is due to the increased heat transfer between basin water and glass surface which reduces the evaporation rate.

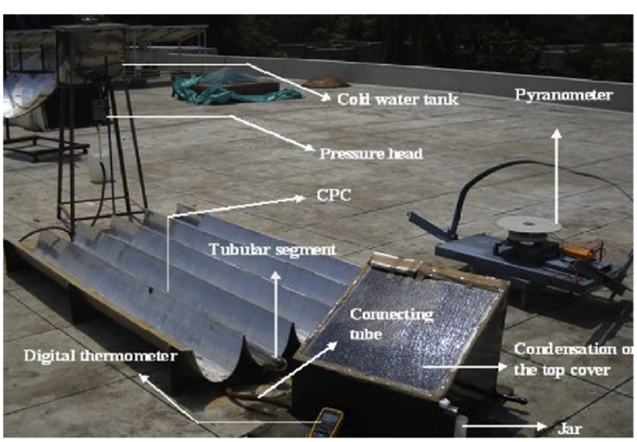

Fig. 10 Experiment set-up photograph (Arunkumar et al. 2016)

Various absorber configurations

The main aim of using distinct absorber configurations is to increase the exposed surface area to enhance the heat transfer rate inside the still. Omara et al. (2011) compared the experimental performances of finned absorber and corrugated absorber used in a solar still. Water depth is maintained constant at 5cm and saline water quantities of 30L and 50L are used. The results showed 19% increase in productivity of finned absorber still in comparison to corrugated absorber still. Moreover, the use of v-corrugated absorber and PCM in a pyramid still enhanced the productivity to 6.6 kg/m^{2}d (Kabeel et al. 2017). Abdelal and Taamneh (2017) used an absorber plate made up of carbon nanotube-modified epoxy composites. The carbon nanotube weight of 5 and 2.5% is utilized in making the absorber plate. The experimental results showed 109 and 65% increase in productivity, respectively. Hansen and Murugavel (2017) used different absorber

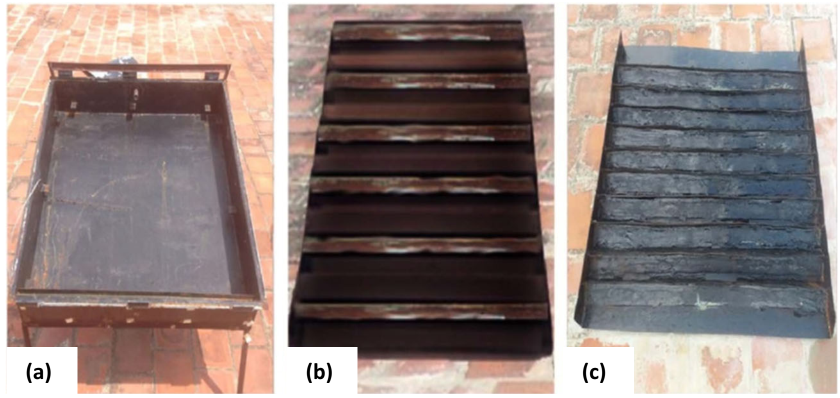

Fig. 11 Photographs of (**a**) flat plate absorber, (**b**) grooved absorber, (**c**) fin absorber (Hansen and Murugavel 2017)

configurations in solar still as shown in Fig.11 and experimentally investigated their effect on still performance.

The use of fin absorber resulted in better productivity and efficiency in comparison to grooved and flat absorber.

Other modifications

Some other modifications includes using of wind turbine powered water fan and PV panel operated water stirrers in still basin to enhance heat transfer rate. The use of co-axial pipes, preheated water supply and vapour adsorption basin in a passive solar still also resulted in productivity enhancement.

Wind turbine powered propeller

Omara et al. (2017) investigated the effect of using a wind turbine powered propeller on still productivity. A small wind turbine is designed and attached to a propeller which is installed in still basin as shown in Fig. 12.

Water fan enhances evaporation and condensation rate and increases productivity by 17% at 3-cm water depth and 30rpm rotational speed.

Glass basin with preheated water supply

Rajaseenivasan et al. (2016) fabricated and experimentally investigated a glass basin which is divided into evaporator section and preheating section as shown in Fig.13.

Saline water enters preheating section and gets evaporated in the evaporator section. Hollow fins are used in preheating section to increase the exposed heat transfer area. Fins are filled with heat storage materials like charcoal, river sand and metal scraps to increase heat capacity of the basin. The results showed productivity rise at low water depths. Also, the use of heat storage materials decreases daytime productivity but enhances night time productivity. Maximum productivity of 3.63 kg/day is achieved with the use of charcoal as heat storage material.

Water stirrer

Rajaseenivasan et al. (2017) investigated the effect of four stirrers in still basin operated by a solar PV panel of 40 W capacity as shown in Fig. 14.

Charcoal and paraffin wax are used as thermal energy storage materials. Water depth is maintained constant at 1 cm, and basin height is varied in the experiment. Performance of this modified still is compared with a conventional still. The results showed an increase in basin water temperature and productivity with decreased basin height. The distillate output is increased by 30% with highest value of 5.23 kg/m^2 day.

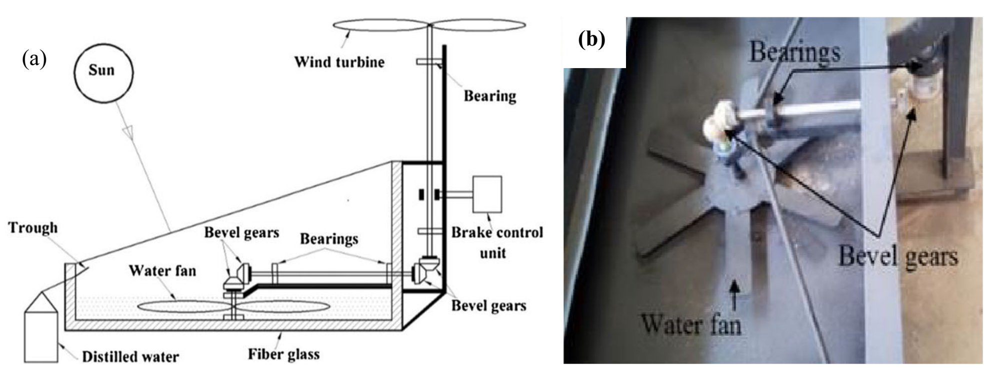

Fig. 12 (**a**) Schematic diagram of solar still with water propeller. (**b**) Picture of propeller, bevel gears and bearings (Omara et al., 2017)

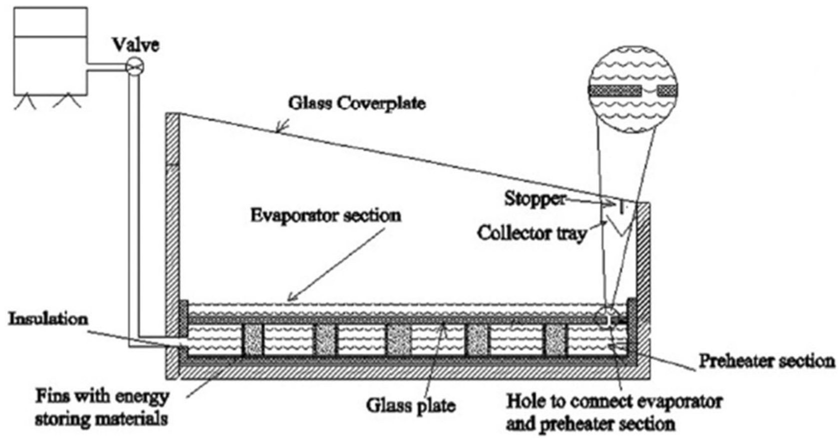

Fig. 13 Schematic diagram of solar still with preheated water supply (Rajaseenivasan et al. 2016)

Co-axial pipes in basin

Kabeel and Abdelgaied (2017) designed and tested a solar still consisting multi groups of two co-axial copper pipes. The higher surfaces of outer pipes have holes of 3-mm diameter with a distance of 1.5 mm between them. Saline water flows in the annular space of co-axial pipes as shown in Fig.15.

The still is customized with pipes of different inner diameter and annular space. Still using pipe with inner diameter 41.28 mm and annular space 5 mm resulted in maximum productivity rise of 98% in comparison to other combinations.

Solar still integrated with vapour adsorption basin

Kannan et al. (2014) investigated a solar still integrated with an adsorbent bed network of pipes as shown in Fig. 16.

Activated carbon and methanol are filled in the annular space of inner and outer pipes. Saline water gets preheated during its flow from inner pipes of adsorbent bed and is re-circulated to the storage tank. Still is also customized with the combination of sponge, gravels, sand and black rubber as heat storage material. The maximum productivity of 4.3 kg/m^{2}day is achieved with a combination of sponge, sand and black rubber used as heat storage materials.

Solar collectors

The integration of distinct solar collectors to the solar still is the most influencing modification to improve the still output. The extra heat supplied to basin water using solar collector increases the water temperature and the rate of evaporation. Figure 17 shows a single-slope still coupled to a parabolic trough collector and a heat exchanger in the still basin (Hassan et al. 2020a, b).

The heat transfer oil is pumped to heat exchanger before circulating from a tube placed at focal line of the parabolic trough. The external heat supplied to basin water resulted in improvement of still output by 102%. Figure 18 shows a Fresnel lens coupled to a single slope still (Mu et al. 2019). The application of a Fresnel lens expedites the phase change process and improves the still output to a very large extent.

The experimental results showed a formidable increase of 467% in water output with Fresnel lens. Many other solar external heat sources namely evacuated tube collector (Alwan et al. 2020; Bhargva and Yadav 2020; Patel et al.

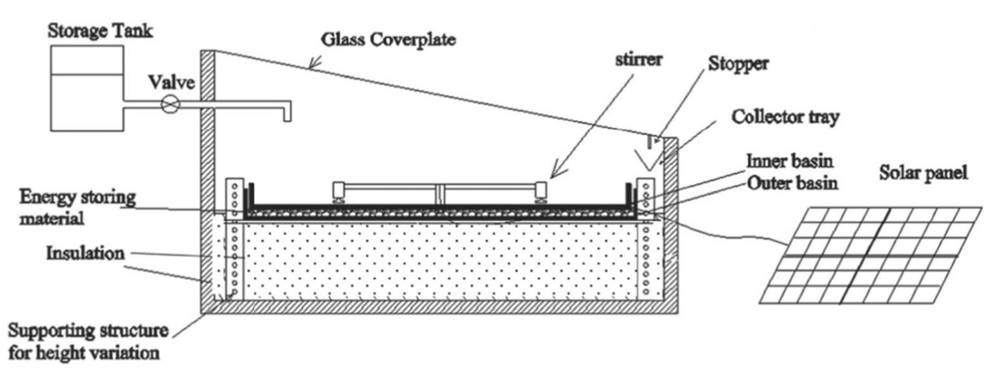

Fig. 14 Schematic diagram of solar still with water stirrers (Rajaseenivasan et al. 2017)

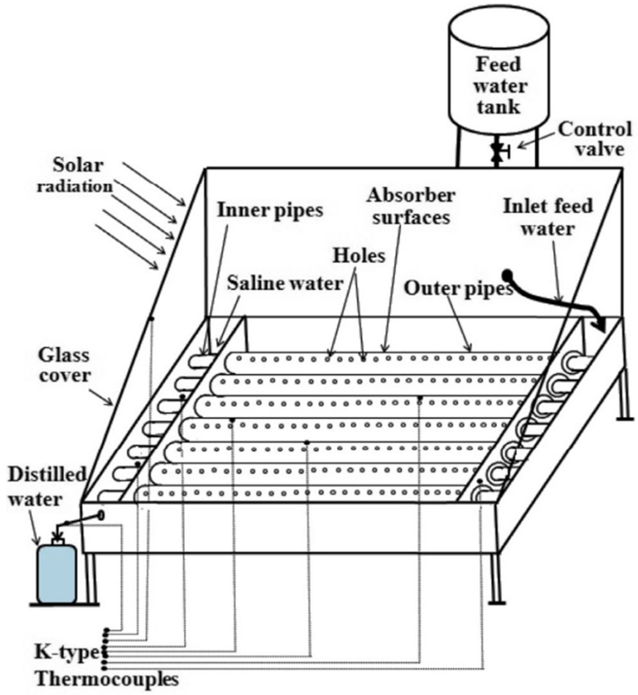

Fig. 15 Schematic diagram of solar still with coaxial pipes in basin (Kabeel and Abdelgaied 2017)

2020a, b), a flat plate collector (Eltawil and Omara 2014; Raju and Narayana 2018; Patel et al. 2020a, b; Alwan et al. 2021), hybrid photovoltaic thermal collector (Singh et al. 2016; Winston et al. 2018) and a solar pond (El-Sebaii et al. 2008; Appadurai and Velmurugan 2015; Bisht et al. 2020) resulted in the improvement in water output of the still. It is inferred from the review of recent articles that a multiple number of modifications in a solar still is prevalent to improve the still output. The most recent studies conducted on the solar still for the improvement in the water output are shown in Table 4.

Future prospects

Some of the future work and prospects pertaining to the solar still research are as follows:

- The arrangement for chemical treatment of water obtained from solar still could make it a complete device for extraction of potable water from brackish water.
- The active solar still could be made completely solar powered using PV panels for operating DC pumps

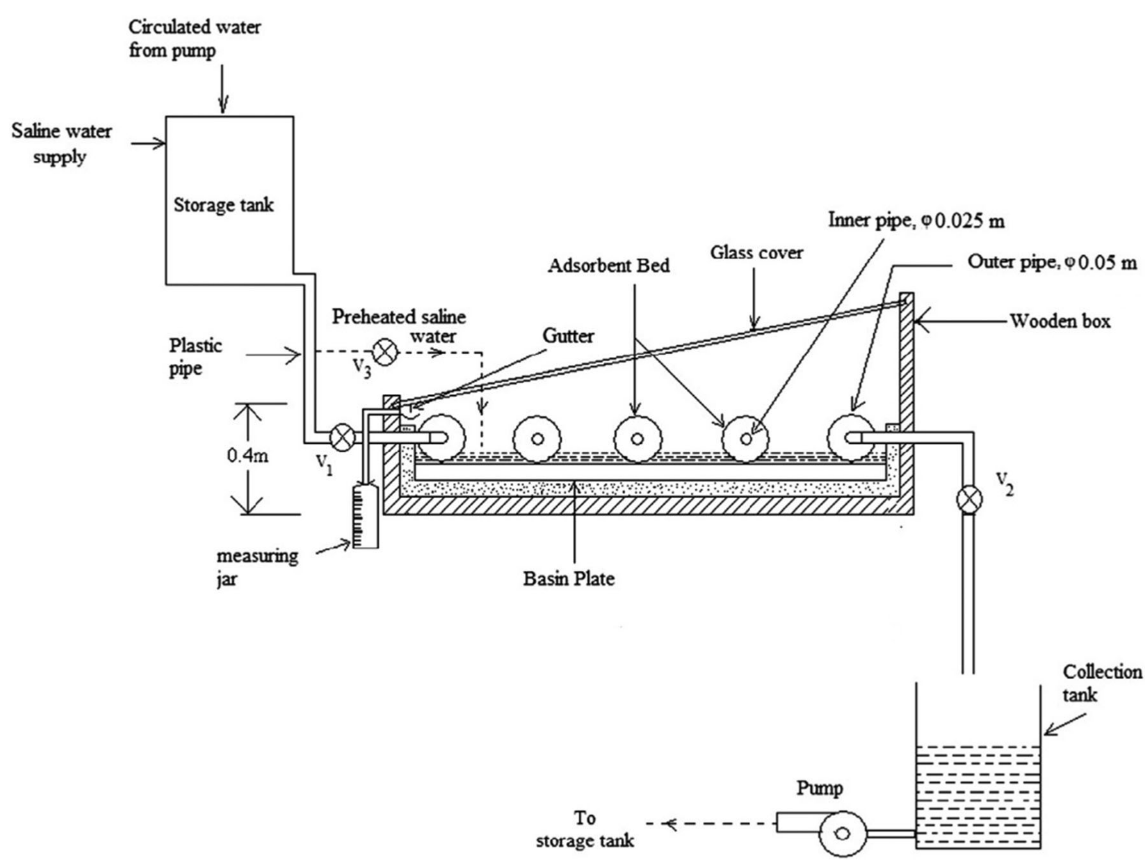

Fig. 16 Schematic diagram of solar still with vapor adsorption basin (Kannan et al. 2014)

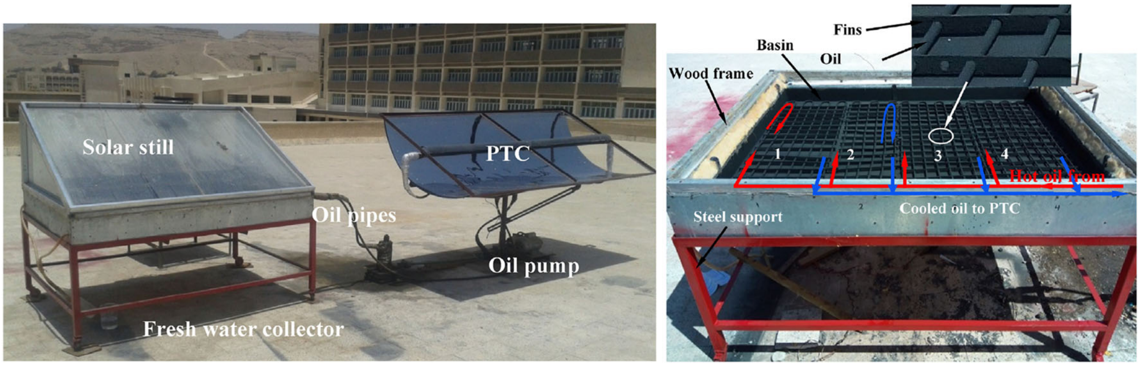

Fig. 17 Photograph of parabolic trough integrated to solar still and heat exchanger placed in still basin (Hassan et al. 2020a, b)

used for circulating heat transfer fluid to the heat exchanger.

- The application of various nanoparticles with different concentrations in the still basin should be explored further for improving the still output.
- The research on the use of different solar concentrators like parabolic dish and Scheffler reflector to improve the water output could be explored further.
- The different techniques used for increasing night time water output could be explored further by the application of various heat storage materials.
- The higher still water output during night time is attainable and more feasible for active solar stills using phase change materials because of faster charging rate. The use of solar concentrators namely parabolic trough, parabolic dish, and Scheffler concentrator for charging the PCM could be explored further for improving the night time water output from the still.

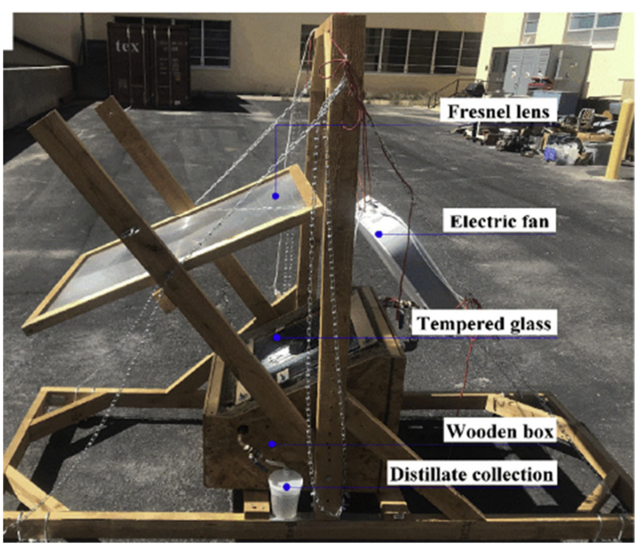

Fig. 18 Photograph of the Fresnel lens integrated single slope still (Mu et al. 2019)

Conclusions

A literature review is carried out on understanding different still modifications and various parameters affecting still performance. The main highlights of the study are as follows:

- Solar still productivity increases as the water depth decreases because of maximum heat absorption and quick evaporation rate at minimum water depths.
- The transmittance effect and productivity increases with the decrease in glass cover thickness. The maximum productivity is achieved when still is oriented in south facing direction and glass cover is inclined at latitude of the location.
- Increased temperature difference between basin water and inner surface of glass cover and moderate wind velocities enhanced the condensation rate. The still productivity decreases at very high wind velocities.
- Intensity of solar radiation increases up to afternoon and decreases after that. Water temperature and still productivity also follow the same trend.
- The use of pin fins, square fins, and metallic fins in basin liner increases the exposed heat transfer area and enhances the overall still performance.
- Use of Jute, black cotton and fur fabric wick materials slows down the movement of water in still basin and thus increases the evaporation rate and still productivity.
- Blackened sponge layer and sponge liner have high storage capacity and their use resulted in ensuring good evening time productivity.
- Sensible heat storage materials like servotherm oil and pebbles enhanced still performance by enabling off sunshine hour productivity. The use of paraffin wax also increases night productivity. It is the most widely used latent heat storage material due to low cost and easy availability.
- Using internal and external reflectors ensures maximum trapping of solar radiations inside the still. Productivity rise of around 50% is reported when both reflectors are used simultaneously in the still.

Table 4 Latest modifications and research trends in solar still

Author(s)	Modifications	Type of solar still	Advantages	Location	Water output (kg/m^2day)
(Essa et al. 2020b)	Coffee colloid mixed with basin water	Single slope	Low cost and eco-friendly nanofluid	Tanta city, Egypt	4.8
(Mohammadi et al. 2020)	PTC+ heat exchanger	Single slope	Enhancement in evaporation rate and water output	Shiraz, Iran	8.9
(Fallahzadeh et al. 2020a, 2020b)	Heat pipe+ water and ethanol as working fluid	Pyramid	Increased temperature difference between inside glass cover and water	Mashhad, Iran	6.9
(Kabeel et al. 2019b)	Glass cooling by water sprayer	Tubular	Enhanced condensation rate	Cairo, Egypt	4.5
(Modi et al. 2020)	Parabolic dish	Spherical basin	Higher water temperatures achieved, higher evaporation rate	Valsad, India	8.25
(Salarabadi and Rahimi 2020)	Olive oil layer	hemispherical	Reduces the reflection of solar radiations, increased water temperature	Kermanshah, Iran	1.99
(Madiouli et al. 2020)	PTC+ FPC+ glass ball heat storage	Single slope	Higher evaporation rates and night time water output	Abha city, Saudi Arabia	6.03
(Suresh and Shanmugan 2019)	PCM+ wick+ nanoparticles+ glass cooling	Single slope	Enhanced rate of heat exchange, increased water temperature and evaporation rates, higher condensation	Chennai, India	9.42
(Abu-Arabi et al. 2020)	FPC+ PCM+ glass cooling	Single slope	High night time output, higher condensation rates	Jordan	6.3
(Xinxin et al. 2019)	Hybrid photovoltaic thermal (PVT) solar collector+ compound parabolic concentrator (CPC)	Single slope	Increased heat transfer to basin water, higher evaporation rates	Beijing, China	7.26
(Beik et al. 2020)	Multiple steps	Square pyramid	Increased exposed area of heat transfer, higher water temperature and evaporation rates	Dezful, Iran	12.39
(Fallahzadeh et al. 2020a, 2020b)	Spiral collector	Single slope	Enhanced heat transfer area, higher evaporation	Mashhad, Iran	2.23
(Kumar et al. 2020)	Evacuated tube+ PTC	Single slope	Increased water temperature and evaporation rate considerably	Bhopal, India	4.1
(Arora et al. 2020)	CPC+ PVT+ carbon nanotube nanofluid	Double slope	Higher energy transfer to basin water, high distillate output	New Delhi, India	12.1
(Dawood et al. 2020)	Evacuated tube+ PTC+ heat exchanger+ PCM	Single slope	Basin water exposed to higher temperatures, higher day time output, enabled night time output	Ismailia, Egypt	11.14
(Essa et al. 2020a, 2020b)	Rotating discs in still basin	Single slope	Enhanced heat transfer rate to the basin water	Kafrelsheikh, Egypt	3.15
(Younis et al. 2020)	Rotating drums in still basin	Double slope	Enhanced heat transfer, higher evaporation rates	Lebanon	2.39
(Taamneh et al. 2020)	Spiral tube heater in still basin	Single slope	High rate of heat transfer, higher water temperature and evaporation rate	Chennai, India	8.3
(Kabeel et al. 2020a, 2020b)	Parabolic dish+ PV module+ cone receiver	Single slope	High heat absorption, high water temperature, high water output	Ismailia, Egypt	13.63
(Shehata et al. 2020)	ETC+ ultrasonic humidifier	Single slope	Increased frequency of evaporation using ultrasonic waves, higher water temperature	Alexandria, Egypt	7.4

- Cuprous oxide, aluminium oxide and flake graphite nanoparticles have very high thermal conductivities. The use of these nanoparticles expedites heat exchange rate in the still basin and resulted in a productivity enhancement of around 94%.
- Glass cover cooling using water and blowing air through external fan increased the temperature difference between basin water and glass cover. This resulted in enhancement of still productivity. Maximum performance is achieved at higher mass flow rates of cooling water over the glass cover.
- The use of water fan and stirrers in still basin also increased the heat transfer in still basin.

Author's contributions MB analyzed all the design, operating, and environmental parameters which influenced the performance of the solar still. AY identified different modifications in the design of solar still which resulted in productivity enhancement. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The author's declare that they have no competing interests

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