



Research Article

A study on heat and mass transfer analysis of solar distillation system

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ABSTRACT

The solar stills were developed to fulfil the freshwater need of the growing population. The paper presents the recent modifications made in still to improve their productivity like the application of phase change materials (PCM), connecting flat-plate collector (FPC), use of nanoparticles, stepped solar still, and attaching separate condenser in the still. Active solar stills are found more productive than passive ones and the thermal efficiency of active solar stills lie in the range of 50–70%, which is far better than passive still having 20–55% thermal efficiency. According to the literature studied in the paper, the maximum productivity of active solar still is 10 litres per day and in passive solar stills, it is 6 litres per day. The different approaches used to carry out the heat and mass transfer analysis of single and double slope active and passive solar stills are also discussed in the paper.

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INTRODUCTION

Freshwater is an essential requirement of human life. 97.5% of saline water on earth is present in the form of seawater and only 2.5% of water is fresh [1, 2]. Therefore, researchers are making such devices that can convert impure water to potable water by using renewable resources. Solar still (SS) is a sustainable device that uses solar thermal energy to transform saline and dirty water into freshwater [3, 4]. The solar stills are mainly categorised into two parts, passive SS and active SS. Passive SS completely relies on natural resources (Solar Energy) while external devices are used in active SS like flat-plate collectors, PVT, electric

water heaters, etc. These are economical and can provide adequate fresh water to remote villages. Passive and active solar stills are further classified as single and double slope SS [4]. Single slope solar still has only one glass cover while two glass covers are placed on the double slope solar still. As per the study, the detailed classification of solar still is shown in Figure 1. In the last few years, researches in solar distillation systems are focused on minimising energy consumption, fabrication price, environmental impact and maximising productivity and thermal efficiency.

Erfan et al. [5] constructed a double slope SS with PCM and PV/T collector. PV/T collector was used for preheating

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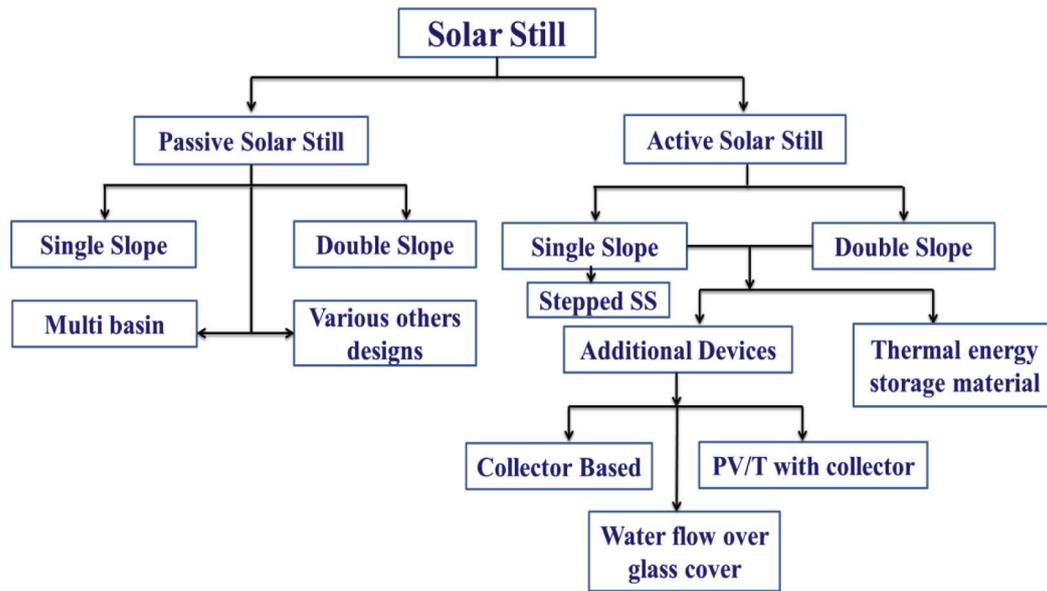


Figure 1. Classification of Solar still.

the basin water and the use of PCM makes it possible to operate still at night. PV/T collector had also been used for electricity generation. They study the effect of PCM and PV/T collector on the productivity of double-slope solar still.

The double step solar still is tested with four different modifications by Kalita et al. [6] The first modification is the designed single basin with double step, jute wick absorber plates as second, charcoaled jute wick absorber as third and the absorber with double glass cover as a fourth modification. Among all modifications, the maximum productivity still was 3.94 l/m² in the case of the double glass cover, as it increases the condensation area.

Stepped solar stills are another method to boost the productivity of stills as less quantity of water is evaporated in more areas, so a faster evaporation rate is obtained [7]. Muftah et al. [8] designed two different types of stepped SS, one is the conventional stepped SS and in another setup, an additional condenser is added in the solar basin. Due to large areas of condensation, the modified setup gives daily 2 kg/m² distilled water more than the simple stepped solar still.

The application of thermal energy storage materials inside the stills increases the daily operation period that helps in producing more water. Bilal et al. [9] had used the two different masses (5 and 10 kg) of pumice stones in a still basins to store thermal energy as heat storage material. In the case of 10 kg, the productivity was less than as in the case of 5 kg by 130ml for the same water depth in both cases. This showed that too much use of thermal storage material may result in a decrease in productivity.

A Peltier-based active solar still (ASS) with PV/T system was developed by Pounraj et al. [10] The efficiency of the developed still is 30% higher and produces 6.5 times more water than conventional SS. It was further suggested that the use of PCMs improves productivity and also helps

in the 2 or more hour's continuous operation of SS after sunset. Shalaby et al. [11] tested the single basin SS having v-corrugated basin liner filled with paraffin wax. Due to the use of PCM, productivity increases by 72.7% during the night as compared to conventional SS. To absorb more solar radiation, dyes [12], and charcoal pieces [13] are placed inside the basin. By increasing the absorption capacity of the basin surface, the extra energy can be absorbed which can be used during cloudy weather and night time and this will increase water productivity.

Wick, nanofluids, and various other types of energy-storing materials had been also utilised in still to increase its productivity. A pin fin wick-based solar still was made by Alaian et al. [14], in which 294 pin fin wick elements were placed on the surface of the basin. Due to the fins, the radiation absorption capacity of the basin surface is increased, causing heat absorption and heat release through a large area and the basin water evaporates rapidly due to the capillary action of the fin. Through this new modification, the productivity of solar still increased by 23%, compared to conventional still.

Six different types of heat-absorbing materials like quartzite rock, red brick pieces, cement concrete pieces, washed stones and iron scraps are used by Murugavel et al. [15] in solar still. They found that quartzite rock had the highest productivity. Because the size of the quartzite rock was larger than the rest of the absorber stones, so it can store a higher amount of energy. Also, Murugavel et al. [16] had done a compressive study of the performance of double-slope solar stills with different heat storage materials such as black cotton cloth, waste cotton pieces, sponge sheets, and coir mate at different water depths. It was revealed that at 0.5 cm water depth, black cotton was getting the highest productivity. Productivity of the modified solar still increases due to

low water depth, good capillary action and high radiation absorption properties of the black cotton cloth.

Sharshir et al. [17] used graphite and copper oxide nanoparticles in the basin water, a mixture of water and nanoparticles increases the productivity of SS by 53.95% and 44.93% respectively than the conventional SS. External solar collectors were used by Tiris et al. [18] in simple basin type solar still, they achieve 5.18 l/m² distilled water in a day through modified still and 2.575 l/m² days by the conventional still and Sebaili et al. [19] used the solar pond for increasing the performance of SS, respectively by preheating water before the inlet to the still. The saline/brackish water is preheated in solar collectors and then it is supplied to the solar still. So, less amount of heat is needed to evaporate the saline water. Tanaka and Nakatake [20] attached an inclined and vertical reflectors to the solar still. The greater amount of solar radiations are incident on the inclined reflector as compare to the vertical reflector, hence the inclined reflector improved the output of the SS by around 16% as compared to the vertical reflector. For increasing absorption of radiation on the SS, Deniz [21] studied various parameters that affect the productivity like the angle of the glass cover, the cooling system of the glass surface, and distance among the condensing cover and base fluid surface.

Tiwari et al. [22] carried out the energy analysis of passive and active solar stills in a review paper. They suggested that the double slope passive solar still provides superior yield than single slope, and PVT-FPC based single slope active solar still provides better yield than PVT-FPC integrated double slope active solar still. A review paper was made by Arun Kumar et al. [23], in which they considered the stills having productivity of more than 5 litres/m²/day. Omara et al. [24] studied the effect of nanoparticles on heat and mass transfer of modified solar still in a review paper. It was found that the performance of nanoparticles based still was better than the without nanoparticles based still. They reported that the thermal conductivity of the nanofluids depends on the grain size, shape, and amount of the nanoparticles. Singh et al. [25] showed the performance of newly designed single basin passive solar still in terms of their efficiency, fabrication cost and daily productivity.

The effect of PCM on the productivity of different solar still had been studied by Shukla et al. [26]. Due to heat storage property, PCM based still provides continuous production even after sunset. Hence the distilled water productivity of PCM based setup was higher than the conventional setup. Grewal et al. [27] reported in their review paper that the PCM based solar still gives 50–160% higher production than conventional still and PCM is more effective at lower water depth. Kabeel et al. [28] make a review paper on the effect of various heat exchange mechanisms on the productivity of solar still like PCM, other energy storage materials, glass cooling process, and water depth. It was found that all heat exchange mechanisms increases the heat transfer rate and productivity of the still. Recent

developments and new techniques adopted in the 21st century for productivity enhancement of solar still had been reported by Das et al. [29]. It was suggested that productivity can be improved either by increasing the basin water temperature or by decreasing the glass cover temperature. In the review paper of Pansal et al. [30], it was concluded PV based solar stills provide 25% more overall thermal efficiency than the conventional one.

As no review paper reported till now showing the effect of nanoparticles and PCM on the productivity and efficiency of still along with consideration of heat and mass transfer analysis of active and passive single and double slope solar stills. The objective of this paper is shown below:

- The paper encapsulates the different modifications applied by various researchers to increase the efficiency and productivity of SSs.
- Application of PCMs, nanoparticles, separate condensers, modification in stepped solar still, and some other recent modifications are reported in the paper.
- The paper covers the energy balance established for the various parts of the still such as condensing cover, basin water, basin liner, and basin surface and also covers the procedure to carry out the heat and mass transfer study of single and double slope active and passive solar still done by different researchers.

MODIFICATIONS ON PASSIVE SOLAR STILL

The solar stills operating naturally without the aid of any external devices are called passive solar still. Single slope passive solar still (SSPSS) was constructed by Agarwal and Rana [31] in which V-shaped thermocol wrapped with black jute cloth is let to float above the basin water of SS as shown in Figure 2. As Jute Cloth has good capillary properties so it continuously absorbs the basin water and the thermocol was used due to its lightweight and good thermal resistance. The V-shaped floating wick absorbs more radiation due to increased absorption area and results in an increased evaporation rate. The productivity of modified solar still (SS) increases by 3.20 litres/day as compared to conventional solar still with the same basin area.

Rattanpol et al. [32] had developed a mathematical model for predicting the quantity of water mass with the help of the Spalding theory of convection and Fick's law of diffusion. Steel fin was provided in the inner basin surface to increase radiation absorption capacity and ethanol solution was mixed in the basin water to increase convection and diffusion capacities of the mixture even at low temperatures. The productivity of still was found 15.5% higher than the without ethanol-based stills and setup efficiency was increased up to 46% with an increase in the number of fins.

Nanoparticles act as a thermal storage material that increases the heat-absorbing capacity of still due to increased

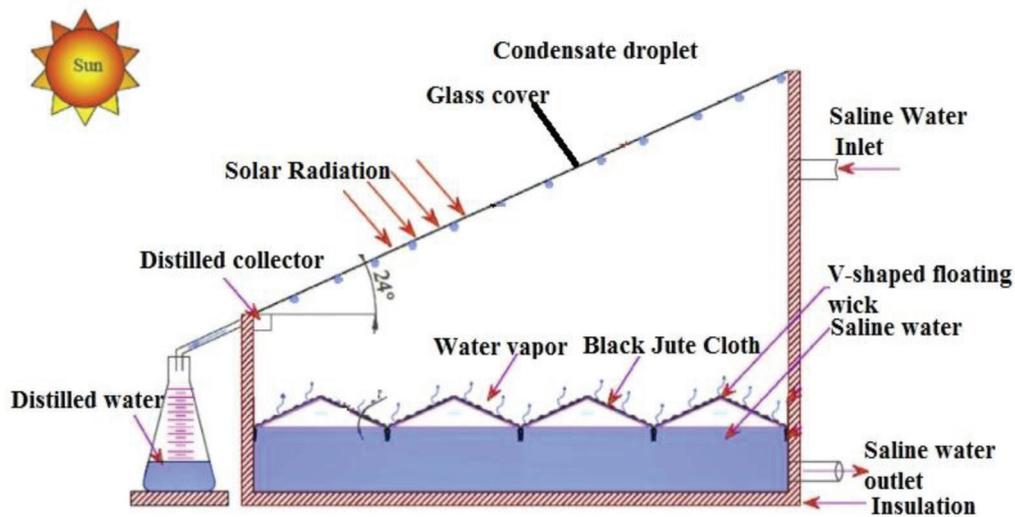


Figure 2. V-shaped wick placed inside the SS basin [31].

heat-absorbing surface area. As more heat is absorbed, so more heat is transferred to the water and due to this the evaporation rate gets increased and results in more distillate output than conventional still [33]. The effect on productivity and efficiency of still when the nanoparticle is mixed with basin water is shown in Table 1.

Sahota and Tiwari [34] constructed a double slope passive solar still (DSPSS) in which aluminium oxide (Al_2O_3) nanoparticles was used with different concentration. Nanoparticles based still gives 12.2% more productivity than the plain water-based still. The daily productivity of the setup was 2.77 l/m^2 . Gupta et al. [35] tested the solar still (SS) having white painted sidewalls and CuO nanoparticles have been mixed in the basin water. The white sidewall reduces the heat loss to ambient from the basin also the incident radiation on the sidewall is reflected the basin liner, which increases its temperature. The daily maximum productivity of the modified setup was 3.445 l/m^2 .

Kabeel et al. [36] constructed a solar still (SS) in which the inner basin surface and side walls were coated with nanoparticles mixed the black paint. The nanoparticles based black paint increase the heat transfer rate between the wall and basin water that will increase the temperature and evaporation rate of the saline water. The distilled output of the modified still was 16% greater than the conventional still with the same basin area.

Nijmesh et al. [37] had used $KMnO_4$ and $K_2Cr_2O_7$ nanoparticles in the single slope solar stills (SSSS). It was found that $KMnO_4$ based solar still gives the productivity of 4.7 l/m^2 while $K_2Cr_2O_7$ based solar still gives 4.1 l/m^2 . The thermal conductivity of $KMnO_4$ is higher than that of $K_2Cr_2O_7$, hence that $KMnO_4$ stores a superior quantity of thermal energy and keeps the basin water warmer for longer as compared to $K_2Cr_2O_7$. Gupta et al. [38] constructed solar still (SS) attached with a water sprinkler as shown in

Figure 3. Cuprous oxide (Cu_2O) nanoparticles were mixed in the basin water. Daily yield and efficiency of sprinkler added SS increase by 1.2 l/m^2 and 12%, respectively than the simple SS.

El-sebaili [39] constructed a SS with a suspended absorber, which was made of mica, glass, and plastic and installed in the middle of basin water. Due to the low thermal conductivity of mica, radiation heat does not occur from the lower part. Therefore, the entire radiation remains in the upper part and increases the water temperature. It was found that mica suspended absorbers give 23% higher productivity than the copper suspended absorber still. Previously, aluminium, steel, and copper materials had been used as suspended absorbers but these materials have the problem of corrosion, and mica is cheaper than the rest of the material and is rust free.

Arun Kumar et al. [44] constructed a hemispherical type of solar still (SS) with side walls filled with sawdust to reduce side heat loss. Water was flowed over the glass cover of SS to rise the condensation rate of evaporated water and hence the productivity of still increases. The efficiency of the modified setup was greater by 8% than simple still.

The effect of water depth on the performance of inverted SS has been studied by Rahul Dev et al. [45] It was found that at minimum water depth the productivity or distilled output was high, because, in the minimum water depth, the basin water takes less time to heat due to which the water starts to evaporate in a very short time. Inverted absorber type systems have the advantage that setup does not have bottom heat loss, but rather gives extra heat from the bottom surface of the basin, which helps to raise the evaporation rate of water.

Nafey et al. [46] constructed a solar still in which a black painted perforated aluminium floats above the basin water. A skinny layer of saline water is formed above the

Table 1. Effect of Nanoparticle on productivity and efficiency of still

Authors	Type of Still	Productivity(L/m ² .day)	Thermal efficiency(%)
Gupta et al. [35]	Solar still painted with white paint mixed with CuO	3.445 (with nanoparticles)	37.40 (with nanoparticles)
		2.814 (without nanoparticles)	30.55 (without nanoparticles)
Gupta et al. [38]	Solar still with Water sprinkler and Cu ₂ O as nanoparticles	4 (with nanoparticles)	34 (with nanoparticles)
		2.8 (without nanoparticles)	22 (without nanoparticles)
Sharshir et al. [40]	Solar still with Graphite and CuO nanoparticles	3.722 (with graphite nanoparticles)	41.18 (with graphite nanoparticles)
		3.479 (with CuO nanoparticles)	38.16 (with CuO nanoparticles)
		2.634 (without nanoparticles)	29.17 (without nanoparticles)
Kabeel et al. [36]	Solar still side wall painted with CuO mixed black paint	4.25 (with nanoparticles)	39.8 (with nanoparticles)
		3.65 (without nanoparticles)	21 (without nanoparticles)
Shanmugan et al. [41]	Solar still with Al ₂ O ₃ and C ₁₈ H ₃₆ O ₂ nanoparticles	7.46(summer)	59.14 (summer)
		4.12 (winter)	27.1 (winter)
Sharshir et al. [17]	Solar still with Graphite and CuO nanoparticles with glass cooling	Productivity increases by 57.6% (with graphite nanoparticles)	49 (with graphite nanoparticles)
		Productivity increases by 47.8% (with CuO nanoparticles)	46 (with CuO nanoparticles)
Elango et al. [42]	Solar still with Al ₂ O ₃ , SnO ₂ and ZnO Nano-particles	0.935 L/day (with Al ₂ O ₃ nanoparticles)	Efficiency increased by 62%
		0.805 (with SnO ₂ nanoparticles)	
		0.750 (with ZnO nanoparticles)	
		0.655 (without nanoparticles)	
Sahota and Tiwari [34]	Al ₂ O ₃ nanoparticles have been used in DSSS.	2.744 (with nanoparticles)	—
		2.445 (without nanoparticles)	
Nijmeh et al. [37]	KMnO ₄ and K ₂ Cr ₂ O ₇ are used in SSSS.	5.83 L/day (with KMnO ₄ nanoparticles)	26 (with KMnO ₄ nanoparticles)
		5.5 L/day (with K ₂ Cr ₂ O ₇ nanoparticles)	17 (with K ₂ Cr ₂ O ₇ nanoparticles)
		4.2 L/day (without nanoparticles)	14.6 (without nanoparticles)
Gnanadason et al. [43]	Carbon nanotubes (CNT) are used in vacuum SSSS.	5 L/day (With CNT)	50 (with CNT)
		3.1 L/day (Without CNT)	

perforated aluminium plate, which heated up in very little time, and due to the black surface of the plate the radiation absorption ability increases which enhance the evaporation rate of the basin water. Maximum radiation is absorbed by a black-painted aluminium plate so that the radiation does not reach to the bottom and thus no bottom heat loss. The productivity of perforated aluminium plate based SS increases up to 40% as compared to simple SS.

Sarhaddi et al. [48] constructed a cascade type SS and studied the effect of PCM on the productivity of solar still (SS). The daily efficiency was improved by 57% and the daily yield increases by 1.6 l/m². Phadatare and Verma [47] studied the effect of different water depths (2cm–12cm) on the internal heat transfer and productivity of the SS, made of plastic SS as shown in Figure 4. The transparent plastic body was insulated from all sides to reduce side and bottom loss. It was

found that as the saline or basin water deepness increases, the productivity of distilled water decreases because due to the large water mass quantity, the water will take a longer time to heat up. But efficiency rises with an increase in water depth, as maximum efficiency was 37% at a maximum water depth of 12 cm.

MODIFICATIONS ON ACTIVE SOLAR STILL [ASS]

When external devices are attached to passive solar still, it is called active solar still. Various modifications have been done in the active single and double slope SSs to improve their productivity and efficiency. Stepped solar stills are one such modification that increases the productivity of water by increasing the basin surface area in the form of steps.

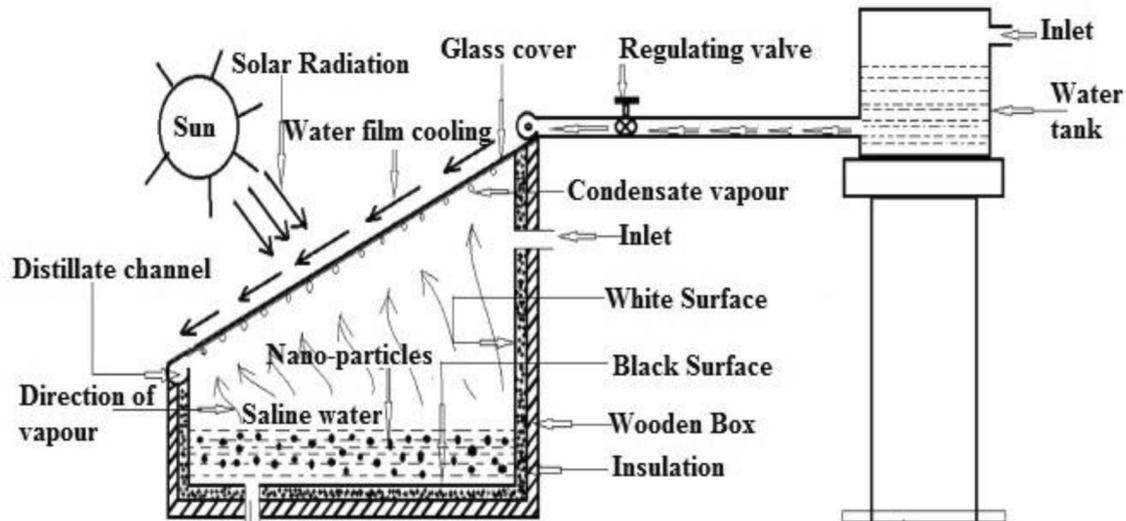


Figure 3. Sprinkler added to solar still [38].

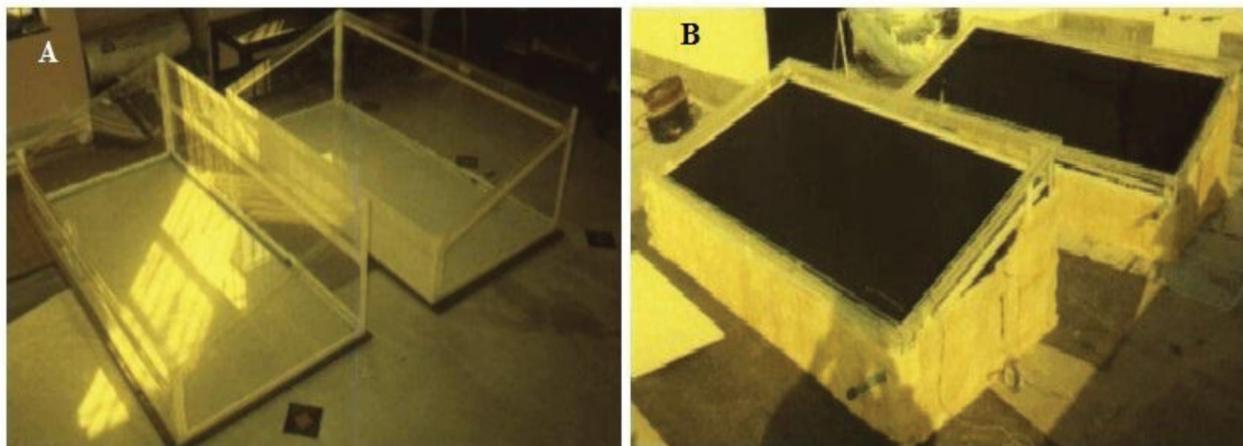


Figure 4. Plastic materials have been used to make SS (A) Transparent setup (B) Insulated side body of SS [47].

Omara et al. [49] constructed the stepped SS with a vertical reflector mirror as shown in Figure 5.

The solar radiations were reflected the black stepped surface through the mirrors which increases the water surface temperature. It was found that the mirror integrated stepped still gives 75% higher productivity than conventional solar still while the efficiency of modified still was greater than conventional still by 21% [43]. The stepped solar still with storage tank and black painted cotton was constructed by El-Agouz [44]. Cotton absorbs a sufficient amount of radiation and also water due to the capillary property, which increases the heat and mass transfer rate within the basin. The daily thermal efficiency of the modified setup was 70% while the thermal efficiency of the traditional still was 48%.

Modified stepped solar still has been constructed by Velmurugan et al. [56] using fins and sponges. The heat transfer area of the basin surface increases due to fins,

causing a substantial amount of heat transfer to the water mass and due to capillary action, sponges sucked the brackish water and thereby increased the water exposure area. Modified stepped still gives 98% productivity as compare to simple stepped still. The maximum hourly productivity of the modified setup was 1.65 l/m². El-Samadony and Kabeel [57] studied the effect of film thickness and flow rate of water flowing over the condensing cover on the productivity of stepped still. They found that, at constant film thickness, with an increase in water flow rate, the film cooling rate was increased.

The use of a flat-plate collector is another modification done on active solar stills. The saline/brackish water is pre-heated in solar collectors and then it is supplied to the solar still. So, less amount of heat is needed to be supplied to evaporate the saline water. Thus the evaporation rate increases, as more water is evaporated at the same time as compared to traditional still. Kabeel et al. [58] designed a stepped SS

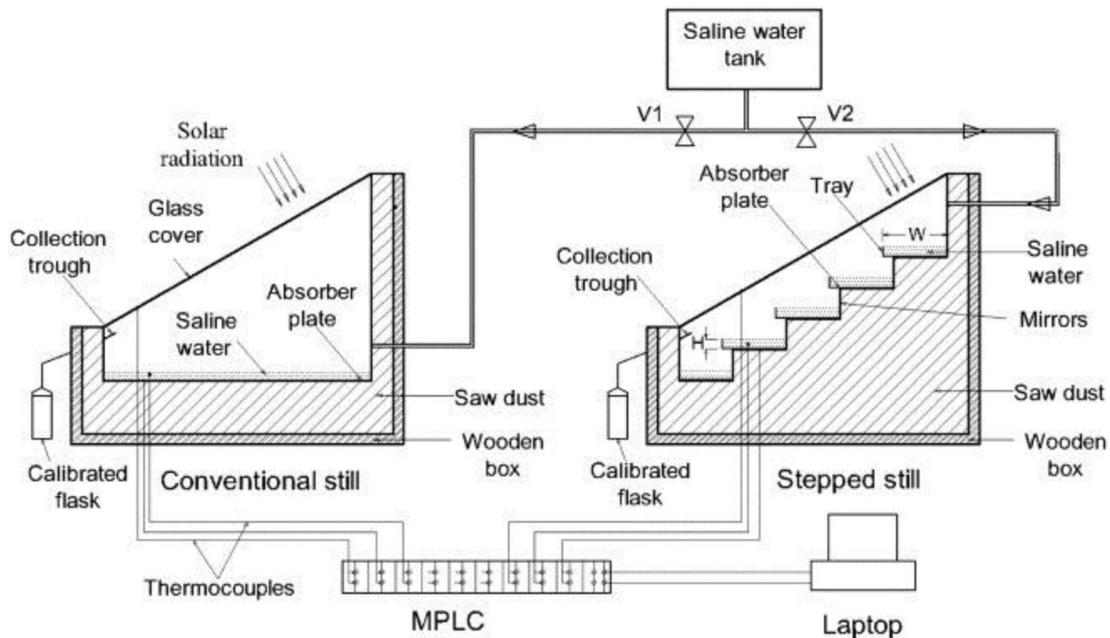


Figure 5. Schematic diagram of an internal reflector placed inside the stepped SS [49].

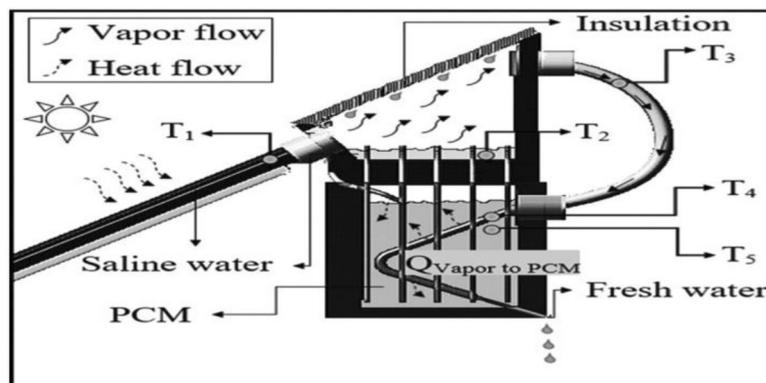


Figure 6. Schematic diagram of external condenser added with SS and condenser filled with PCM [50].

in which wick was used in the vertical side and basin water had been preheated in the collector. For the same condition and area, the daily thermal efficiency of the modified setup gives 53%, and while the traditional still gives 33.5%.

Rajaseenivasan et al. [59] constructed a flat-plate collector (FPC) based solar still (SS) and six separate compartments are made on the basin surface. The yield of the modified setup was 60% higher than the traditional SS with the same basin area while the efficiency of the modified SS and conventional SS is 60% and 37% respectively. FPC has preheated the saline water after supplied to the basin and with the help of the separate compartment, the mass of the basin water is divided, which reduces the water mass in the compartment, but the water mass in the basin remains the same as before, so at the same water, depth gets higher evaporation rate.

A flat-plate collector was attached to double slope solar still (DSSS) by Badran et al. [60] and its performance was evaluated with plain water and saline water. It was found that the yield of the setup was 231% with plain water while it was only 52% with saline water. Due to low density, the heat transfer rate in the plain water is very high, whereas the density of saline water is high, so it does not transfer the heat properly.

Faegh and Shafii [50] constructed a SS with an external condenser with PCM and a heat pipe placed inside it, as presented in Figure 6. Generally, the latent heat released by water vapour is lost in SS, but in this setup, the latent heat is immersed in the PCM and transmitted back to the basin water through the heat pipe. The use of PCM increases the operating time of still per day, due to which the productivity increases. The yield of the modified setup was 86% higher

than the without PCM based SS. The effect on productivity and efficiency of stills by using PCMs is shown in Table 2.

Singh et al. [61] carried out the thermal analysis of SS with an evacuated tube attached to it as shown in Figure 7. After analysing the experimental data, it was found that the

energy efficiency of the system increases with a decrease in water depth. 33% energy efficiency and 2.5% exergy efficiency was achieved by the evacuated tube collector (ETC) based still. Evacuated tube collector helps to preheat the basin water, so less amount of energy is needed to heat the

Table 2. Effect of PCMs on productivity and efficiency of still

Authors	Modification using PCM	Productivity (L/m ² .day)	Thermal efficiency (%)
Shalaby et al. [11]	Solar still with v-corrugated basin liner and Paraffin wax PCM	3.76 (With PCM)	37.1 (With PCM)
		3.35 (Without PCM)	32.9 (Without PCM)
Faegh and Shafii [50]	Solar still with External condenser filled with PCM	6.55 (With PCM)	Daily efficiency increased by 50% using PCM
		5.43 (Without PCM)	27 (Without PCM)
Erfan et al. [5]	Double slope solar still with PV/T collector and PCM	6.5 (With PCM)	Daily efficiency increased by 45%.
Arabi et al. [51]	FPC attached solar still with Glass cooling and 3 different PCMs	6.3 (With PCM) 5.1 (Without PCM)	52–54.6 (With 3 different PCMs)
Mazraeh et al. [52]	Solar still with PV module and Paraffin wax PCM	4.55 (With PCM)	17.93–35.78 (With PCM)
		3.64 (Without PCM)	12.58–16.65 (Without PCM)
Al-harshshah et al. [53]	Solar still with solar collector and Sodium thiosulfate penta hydrate PCM	4.30 (With PCM)	Daily efficiency was increased by 40%.
Cheng et al. [54]	Double slope solar still with shape stabilised PCM	3.67 (With PCM)	42.3 (With PCM)
		2.42 (Without PCM)	28.6 (Without PCM)
Sarhaddi et al. [48]	Cascade type solar still with Paraffin wax PCM	6.63 (With PCM)	56.45 (With PCM)
		7.05 (Without PCM)	75.68 (Without PCM)
Shanmugan et al. [41]	Solar still with C ₁₈ H ₃₆ O ₂ as PCM	7.46 (With PCM)	59.14 (With PCM)
Vigneswaran [55]	Multi PCMs used in the single slope solar still.	4.4 (With Multi-PCMs)	38.72 (With Multi-PCMs)
		4.02 (With single PCM)	42.29 (With single PCM)
		3.68 (Without PCM)	46.29 (Without PCM)

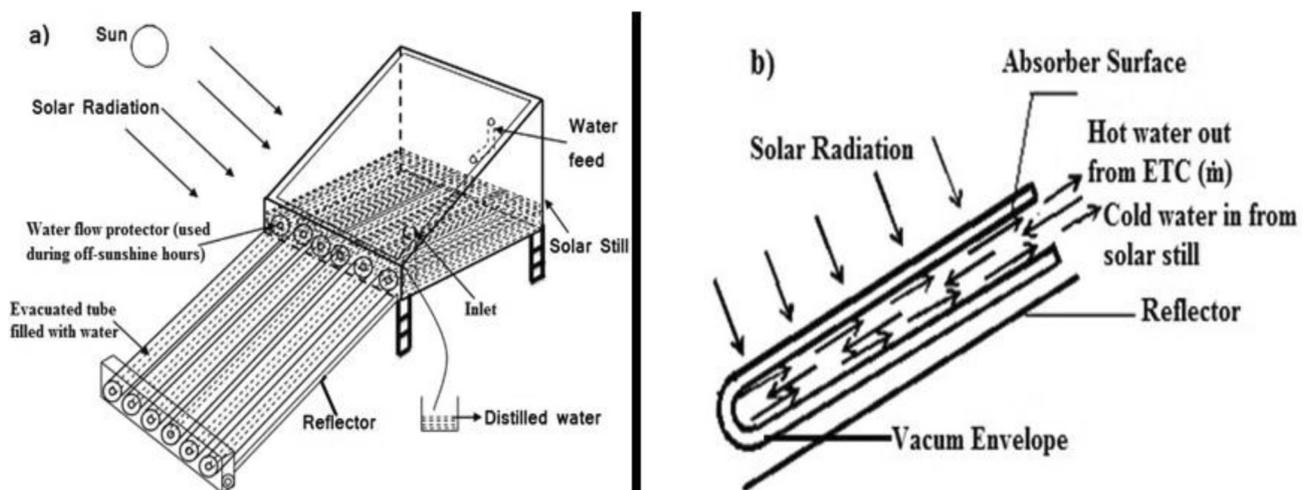


Figure 7. (a) Evacuated tube collector (ETC) coupled system working on natural circulation mode (b) Thermo-syphon performance in each evacuated tube [61].

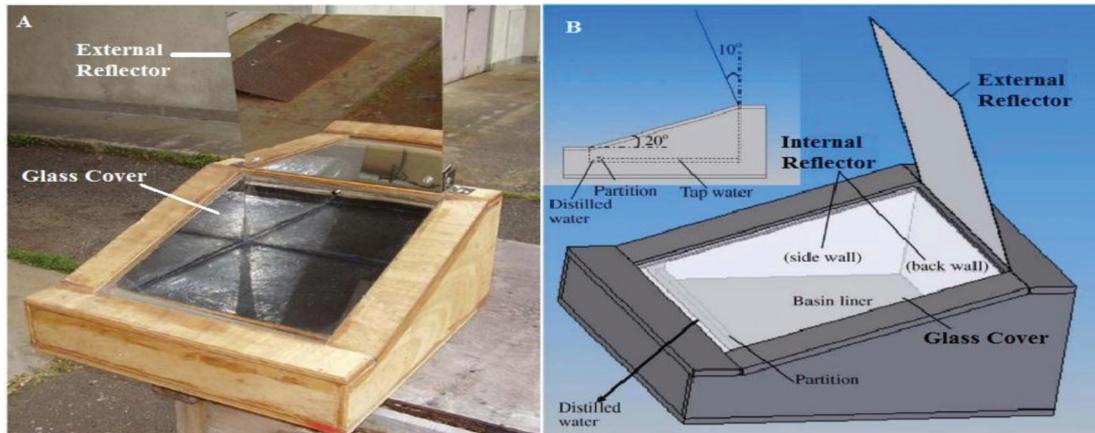


Figure 8. Internal and external reflector added to solar still (A) Experimental setup (B) Schematic Diagram [64].

water inside the basin, due to ETC basin water started to evaporate at very less time.

The energy and exergy analysis was carried out by Kumar et al. [62] inactive solar still (ASS) with ETC. The mass flow rate of evacuated tube collectors to solar basins and basin water depths was optimised. At 0.01 m and 0.03 m, water depth the daily productivity was 3.47 l/m² and 3.9 l/m² and efficiency was 33.8% and 2.6%, respectively at 0.006 l/s water flow rate. It was observed that at the same configuration, the annual performance of the forced mode system was better than the natural mode system.

Mohamed et al. [63] evaluated the effect of different sizes (1, 1.5, and 2 cm) of fine black stone on the heat and mass transfer rate occurring inside the solar still (SS). The efficiency of SS was increases maximum by 123% for 2 cm stone size as compared to conventional solar still. External and internal reflectors had been installed in simple SS by Tanaka [64] as shown in Figure 8. The heat and mass transfer rate inside the basin was increased with the help of internal and external reflectors. The daily productivity of the setup was increased by 70% to 100%.

Radiations that are falling outside of the solar still can be transferred inside the basin with the help of reflectors. Reflectors also increase the intensity of solar radiation and at the same time collect the radiation at one place and more radiation transfer to the basin liner [65].

Monowe et al. [66] constructed a solar still in which an external reflecting booster and an external condenser were attached to utilise the latent heat, as shown in Figure 9. The reflectors attached to the still transmit more solar radiation inside the still and hence the more heat is available inside the still to evaporate water. The latent heat released during the condensation of evaporated water in the outer condenser is utilised to preheat the saline water. Efficiency can be up to 85% when preheated salty water was used at night and water productivity was 10 l/day.

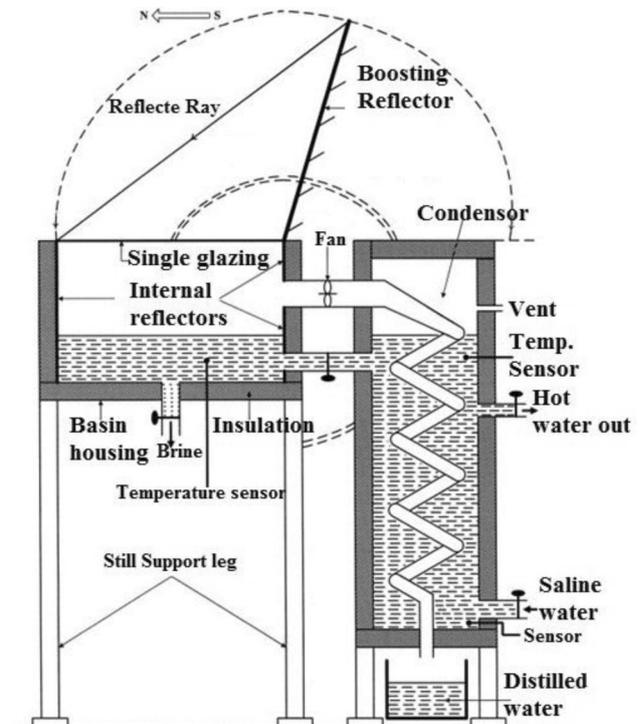


Figure 9. Thermal electrical solar still with external condenser [66].

HEAT TRANSFER ANALYSIS ON SINGLE AND DOUBLE SLOPE PASSIVE SOLAR STILLS

Assumptions

The thermal modelling of solar stills (SSs) can be understood through the energy balance of various parts of SSs such as water mass, basin liners, basin absorbers, and glass cover [67].

Some important assumptions considered for the energy balance in solar still (SS) are:

- The water quantity inside still was considered constant throughout its operating time.
- Heat loss due to evaporation of water inside the SS is neglected.
- The temperature of the water is considered uniform throughout its depth.
- The heat absorption ability of glass cover and insulated material is neglected.
- The area of the glass cover, basin water, and basin are considered the same.
- Solar still should be completely airtight and there should not be any water vapour leakage.

Generally, for all solar still, the basin water is found by solving first-order differential equations, in the form as shown below [68]:

$$\frac{dT_w}{dt} + aT_w = f(t)$$

The differential equation is solved by assuming some boundary conditions and assumption as shown below-

- Δt is the time interval between 0 and t .
- T_{bw0} is the initial basin water temperature at $t = 0$.
- During time interval Δt , the value of 'a' is constant.
- $\bar{f}(t)$ is the average value of $f(t)$ between time interval 0 and t .
- The value of T_{amb} and $I(t)$ can be considered as an average value among '0' and 't'

Heat transfer from the exterior of the SSs takes place through convection, conduction, and radiation modes,

whereas heat and mass transfer inside the SS takes place through convection, radiation and evaporation modes [68]. Figure 10 shows the heat transfers occurring through different modes in single slope solar still (SSSS).

The thermal modelling of solar stills (SSs) can be understood through energy balance on various parts of SSs such as water mass, basin liner, basin absorber, and glass cover [69]. The energy balance equations were developed considering the unit area of the SS component.

ENERGY BALANCE ON OUTER GLASS COVER

Heat energy conducted to the internal glass cover is equal to the heat lost by the radiation and convection from the outer glass cover to the ambient, following energy balance is given by Dev et al. [70] for the glass cover.

$$q_{cd,ci-co} = q_{cn,co-amb} + q_{rd,co-amb} \tag{1}$$

$$q_{cd,ci-co} = q_{tl,co-amb} \tag{2}$$

All unknown factors are given in the appendix.

Using the energy balance equation given by Eq. (1) and Eq. (2), the following relation for outer glass surface temperature (T_{co}) can be obtained as [70]:

$$T_{co} = \frac{(K_c/L_c)T_{ci} + h_{tl,co-amb}T_{amb}}{(K_c/L_c) + h_{tl,co-amb}} \tag{3}$$

ENERGY BALANCE ON INNER GLASS COVER

The total rate of energy lost by the outer glass surface is equal to the addition of total energy absorbed by the glass from solar radiation and the total energy received on the

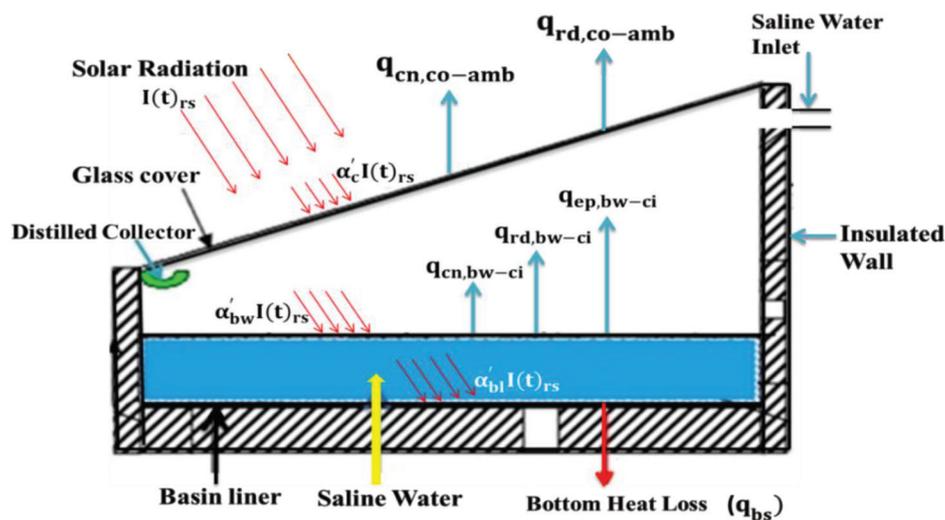


Figure 10. Schematic diagram of single slope solar still.

internal surface of the glass by convection, radiation, and evaporation. Energy balance on the inner glass surface is developed by Ferna et al. [72], given as:

$$\alpha'_c I(t)_{rs} + q_{cn,bw-ci} + q_{ep,bw-ci} + q_{r,bw-ci} = q_{cd,ci-co} \quad (4)$$

Or

$$\alpha'_c I(t)_{rs} + q_{tl,bw-ci} = q_{cd,ci-co} \quad (5)$$

After arranging the Eq. 4 and 5 temperature of inner glass cover surface (T_{ci}) is given by Dev et al. [70]:

$$T_{ci} = \frac{\alpha'_c I(t)_{rs} + h_{tl,bw-ci} \times T_{bw} + U_{tl,ci-atm} \times T_{amb}}{h_{tl,bw-ci} + U_{tl,ci-amb}} \quad (6)$$

Dev and Tiwari [75] assumed the heat absorptivity of the glass as negligible ($\alpha_c=0$) and then the inner glass temperature is given as:

$$T_{ci} = \frac{h_{tl,bw-ci} T_{bw} + U_{HT,ci-amb} T_{amb}}{h_{tl,bw-ci} + U_{HT,ci-amb}} \quad (7)$$

ENERGY BALANCE ON BASIN LINER OR ABSORBER

Total radiation absorbed by the basin liner is equal to the total rate of energy lost by the basin liner through convection and conduction to basin water and ambient, respectively [70].

$$\alpha'_{bl} I(t)_{rs} = h_{bl-w}^{cn} (T_{bl} - T_w) + h_{bl-am}^{cd} (T_{bl} - T_{am}) \quad (8)$$

$$\alpha'_{bl} I(t)_{rs} = q_{bl} + q_{bs} \quad (9)$$

After rearranging the equation (8), the basin liner temperature (T_{bl}) is expressed as:

$$T_{bl} = \frac{\alpha'_{bs} I(t)_{rs} + h_{bl-bw} T_{bw} + h_{bs-sn} T_{air}}{h_{bl-bw} + h_{bs-sn}} \quad (10)$$

For phase change material (PCM) charging and discharging mode, El-Sebaei et al. [76] give the following equation for basin liner (absorber).

For PCM charging mode:

$$T_{bl} = \frac{I(t) \tau_c \tau_{bw} \alpha_{bl} + h_{cn,bl-bw} T_{bw} + h_{cn,bl} T_{pcm}}{(h_{bl-bw} + h_{bl})} \quad (11)$$

For PCM discharging mode [76]:

$$T_{bl} = \frac{h_{cn,bl-bw} T_{bw} + h_{cd,pcm-bl} T_{pcm}}{(h_{cd,pcm-bl} + h_{bl-bw})} \quad (12)$$

All unknown value is given in appendix A of El-Sebaei et al. [76].

ENERGY BALANCE ON BASIN WATER

Energy received by basin water is equal to the energy loss from the basin water. Solar radiation absorbed by basin water + Heat energy received from basin liner = Energy stored in the basin water + Total heat transfer from the water surface to the inner glass surface. The energy balance for basin water is shown below, given by Velmurugan et al. [56] and Zurigat et al. [70]:

$$\alpha'_{bw} I(t)_{rs} + q_{bl} = m_{bw} C_{bw} \frac{dT_{bw}}{dt} + q_{ev,bw-ci} + q_{r,bw-ci} + q_{cn,bw-ci} \quad (13)$$

Or

$$\alpha'_{bw} I(t)_{rs} + q_{bl} = m_{bw} C_{bw} \frac{dT_{bw}}{dt} + q_{tl,bw-ci} \quad (14)$$

The temperature of basin water (T_{bw}) can be calculated through the following equation [70]:

$$T_{bw} = \left(\frac{\alpha_{eff}}{U_L} I_{sw} + T_{am} \right) (1 - e^{-at}) + T_{bw0} e^{-at} \quad (15)$$

Where T_{bw0} is the initial temperature of the water, when the initial temperature of the water is zero, i: $e t = 0$, ($T_{bw/t=0} = T_{bw0}$).

All unknown values are given in the appendix.

The following equation is given by El-Sebaei et al. [76] to calculate the mixture of PCM and basin water temperature.

The temperature of water in terms of PCM charging mode:

$$T_{bw} = (\overline{f(t)}/a) [1 - \exp(-at/x)] + T_{bw0} \exp(-at/x) \quad (16)$$

Where $\overline{f(t)}$ is the average value of $f(t)$ between time intervals 0 and t . [77].

$$f(t) = I(t)_{rs} \tau_c \alpha_{bw} + \left[I(t)_{rs} h_{cn,bl-bw} \tau_c \tau_{bw} \alpha_{bl} / (h_{cn,bl-bw} + h_{bl}) \right] + \left\{ \left[I(t)_{rs} h_{tl,bw-ci} \alpha_c + h_{tl,bw-ci} h_{r,c-sky} T_{sky} \right] + \left[h_{tl,bw-ci} h_{ega} T_a + h_{cn,bl-bw} h_{bl} T_{pcm} \right] / (h_{tl,bw-ci} + h_{ext}) \right\} \quad (17)$$

and

$$a = \left[h_{cn,bl-bw} h_{bl} / (h_{cn,bl-bw} + h_{bl}) \right] + \left[h_{tl,bw-ci} h_{bl} / (h_{tl,bw-ci} + h_{ext}) \right] \quad (18)$$

HOURLY YIELD

Hourly distilled water productivity can be obtained by the following equation which is given by Sahota et al. [78]:

$$\dot{m}_{ep} = \frac{q_{ev,bw-ci}}{L} = \frac{h_{ev,bw-ci}(T_{bw} - T_c)A_b}{L} \times 3600 \quad (19)$$

Where L is the latent heat of the vapour

THERMAL EFFICIENCY OF THE SINGLE SLOPE PASSIVE SOLAR STILL

The ratio of thermal energy used to evaporate water to the total energy incident over the solar still (SS) is termed as thermal efficiency.

The thermal efficiency of passive single slope SS (PSSSS) can be obtained by the following relation, given by Sahota and Tiwari [79]:

$$\eta_{ss} = \frac{\dot{m}_w \times L}{[A_c I(t)rs] \times 3600} \times 100 \quad (20)$$

Dev et al. [80] give the relation for Instantaneous gain efficiency:

$$\eta_{gain} = \frac{\{h_{ew} \times (T_{bw} - T_{ci})\}}{I(t)rs} \quad (21)$$

And also instantaneous loss efficiency relation is obtained by Dev et al. [80]:

$$\eta_{loss} = \frac{\{m_w C_w \times (T_{bw} - T_{wo})\}}{I(t)rs} \quad (22)$$

DOUBLE SLOPE PASSIVE SOLAR STILL (DSPSS)

Double slope SS (DSSS) has two slopes, which permits more solar insolation inside the basin than a single slope but it has extra thermal losses. The schematic diagram with the representation of heat transfer occurring from DSSS is shown in Figure 11.

ENERGY BALANCE ON DIFFERENT PARTS OF DSPSS

More radiations are travel inside the double slope SS compare to the single slope because in the double slope, solar radiations are incident on two facings. Double slope SS is placed in the East-West orientation, due to which solar radiations are fall on the surface of setup in the early morning and for a long time till the sunset [81].

Energy balance on East side glass surface is developed by Sahota and Tiwari [78]:

$$\alpha_c I_{c,ES} + h_{tl,E}(T_{bw} - T_{ciE}) - h_{r,EW}(T_{ciE} - T_{ciW}) = h_{co-amb,E}(T_{co,E} - T_{amb}) \quad (23)$$

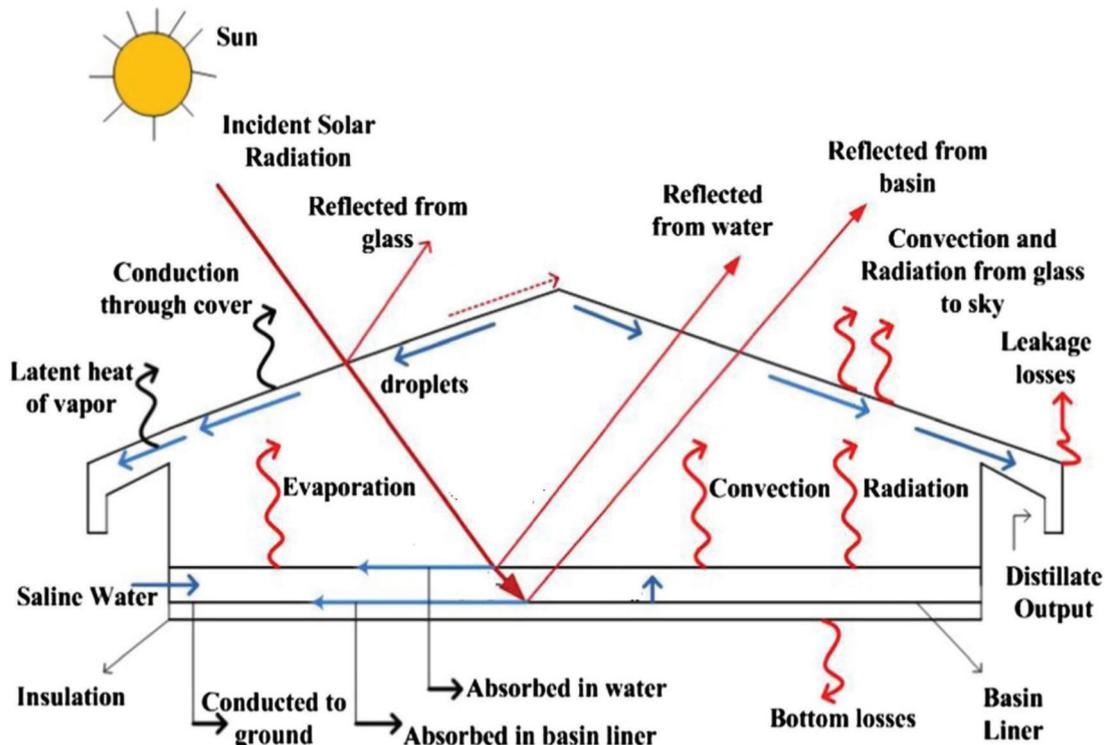


Figure 11. Schematic diagram of DSPSS [79].

Taylor et al. [82] gives the Energy balance on West side glass surface:

$$\alpha_c I_{c,WS} + h_{tl,W}(T_{bw} - T_{ciW}) - h_{r,EW}(T_{ciE} - T_{ciW}) = h_{co-amb,W}(T_{co,W} - T_{amb}) \quad (24)$$

Energy balance on basin water mass [82]:

$$m_{bw} C_{bw} \frac{dT_{bw}}{dt} = \alpha_{bl}(I_{c,ES} + I_{c,WS}) + 2h_{bl-bw}(T_{bl} - T_{bw}) - h_{tl,E}(T_{bw} - T_{ci,E}) - h_{tl,W}(T_{bw} - T_{ci,W}) + \dot{Q}_{u,cr} \quad (25)$$

Where

$$\dot{Q}_{ue} = A_{cr} F'[(\alpha\tau)I_{ETC}(t)] - U_{HT,b}(T_{bw} - T_{amb}) \quad (26)$$

Energy balance on basin liner [82]:

$$\alpha_{bl}(I_{c,ES} + I_{c,WS}) = 2h_{bl-bw}(T_{bl} - T_{bw}) + 2h_{bl-amb}(T_{bl} - T_{amb}) \quad (27)$$

TEMPERATURES EQUATIONS FOR VARIOUS PARTS OF THE DSPSS ARE GIVEN BELOW

Outer glass surface temperature for east and west direction can be calculated using Eq. 28 and Eq. 29, an equation for calculation of east and west side inner glass temperature is developed by Sahota and Tiwari [79]:

$$T_{co,E} = \left[\frac{(K_c / L_c)T_{ci,E} + h_{tl,c-E}T_{amb}}{(K_c / L_c) + h_{tl,c-E}} \right] \quad (28)$$

$$T_{co,W} = \left[\frac{(K_c / L_c)T_{ci,W} + h_{tl,c-W}T_{amb}}{(K_c / L_c) + h_{tl,c-W}} \right] \quad (29)$$

Inner glass surface temperature which located in the east direction ($T_{ci,E}$) and in west direction ($T_{ci,W}$) can be calculated through the following equation, given by Sahota and Tiwari [79] and Taylor et al. [82], respectively:

$$T_{ci,E} = \frac{\left[\alpha_c I_{c,ES} A_{cE} + h_{tl,E} T_{bw} \left(\frac{A_b}{2} \right) + h_{r,EW} T_{ci,W} A_{cE} + U_{HT,E} T_{amb} A_{cE} \right]}{\left[h_{tl,E} \left(\frac{A_b}{2} \right) + h_{r,EW} A_{cE} + U_{HT,E} A_{cE} \right]} \quad (30)$$

$$T_{ci,W} = \frac{\left[\alpha_c I_{c,WS} A_{cW} + h_{tl,W} T_{bw} \left(\frac{A_b}{2} \right) + h_{r,EW} T_{ci,W} A_{cW} + U_{HT,W} T_{amb} A_{cW} \right]}{\left[h_{tl,W} \left(\frac{A_b}{2} \right) + h_{r,EW} A_{cW} + U_{HT,W} A_{cW} \right]} \quad (31)$$

The temperature of basin liner (T_{bl}) and basin water (T_{bw}) can be calculated using the following equation [79]:

$$T_{bl} = \frac{\left[\alpha_{bs}(I_{c,ES} + I_{c,WS}) + 2(T_{bw} h_{bl-bw} + T_{amb} h_{bl-amb}) \right]}{2(h_{bl-bw} + h_{bl-amb})} \quad (32)$$

$$T_{bw} = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{bw0} e^{-a\Delta t} \quad (33)$$

T_{bw0} = Initial basin water temperature when time $t = 0$
Where

$$\overline{f(t)} = \frac{[C_{22} + T_{amb} C_{33} + C_{44}]}{M_{bw} C_{bw}} \quad \text{and} \quad a = \left[\frac{C_{11} + C_{33}}{M_{bw} C_{bw}} \right]$$

The value of C_{11} , C_{22} , C_{33} , and C_{44} , are given in appendix A of Sahota and Tiwari [79].

Bahi and Inan [83] developed the expression of water temperature for two parallel glass SS with separate condenser:

$$T_{bw} = \frac{\tau_g^2 \alpha_w I(t)_{rs} + h_{tl,bw-co} T_{g1} + h_{tl,bw-cs} T_{co} + h_{bs-sf} T_b}{H_{bw} b_1} \times (1 - e^{-b_1 t}) + T_{w0} e^{-b_1 t} \quad (34)$$

T_{w0} = Water temperature at $t = 0$
Where

$$b_1 = \frac{h_{tl,bw-co} + h_{tl,bw-cs} + h_{bl-amb}}{H_{bw}} \quad (35)$$

The hourly yield of double slope SS can be calculated through the following equation [83]:

$$\dot{M}_{bw} = \frac{h_{fc}(T_{bw} - T_c)}{L} \times 3600 \quad (36)$$

Where L is the latent heat of vapourisation can be obtained through the following relation [78]:

$$L = 3.1625 \times 10^6 + [1 - (7.616 \times 10^{-4} \times (T_v))]; \text{ For } T_v > 70^\circ\text{C}$$

And

$$L = 2.4935 \times 10^6 \left[1 - \left(9.4779 \times 10^{-4} \times (T_v) + 1.3132 \times 10^{-7} \right) \times (T_v^2) - 4.7974 \times 10^{-3} \times (T_v^3) \right];$$

For $T_v < 70^\circ\text{C}$

T_v is the temperature of the vapour.

THERMAL EFFICIENCY OF THE DOUBLE SLOPE PASSIVE SOLAR STILL (DSPSS)

The ratio of thermal energy used to evaporate water to the total energy incident over the solar still (SS) is termed as thermal efficiency.

The Thermal efficiency of DSPSS obtained through the following equation, which was given by Singh et al. [84]:

$$\eta_{ds} = \frac{(\dot{m}_{bw,E} + \dot{m}_{bw,W}) \times L}{[A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS}] \times 3600} \times 100 \quad (37)$$

INSTANTANEOUS EFFICIENCY

The amount of energy absorbed and lost by solar still during the operating period is called gain and loss of Instantaneous efficiency respectively. Sahota and Tiwari [85] developed the Instantaneous gain efficiency equation:

$$\eta_{gain} = \frac{[h_{ebf,E} \times (T_{bw} - T_{ci,E}) + h_{ebf,W} \times (T_{bw} - T_{ci,W})] \times A_b}{(A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS})} \quad (38)$$

And also the Instantaneous loss efficiency equation is given by Sahota and Tiwari [85]:

$$\eta_{loss} = \frac{m_{bw} C_{bw} \times (T_{bw} - T_{wo})}{(A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS})} \quad (39)$$

HEAT TRANSFER ANALYSIS ON SINGLE AND DOUBLE SLOPE ACTIVE SOLAR STILLS

SINGLE SLOPE ACTIVE SOLAR STILL (SSASS)

The productivity of the active SS depends on the performance of the external device. Many factors affect the performance of solar stills (SSs) that we cannot control such as solar insolation, pressure, and temperature of the atmosphere and airflow direction. But some parameters can be controlled to boost up the yield of SSs like water depth, base fluid temperature, angle of the glass, fabrication materials, location of setup and thickness of insulation etc. [22].

ENERGY BALANCE ON DIFFERENT PARTS OF THE SSASS:

The energy balance of SSASS for glass cover is done in the same way as in the case of single slope passive SS given by Eq. 1 and 4. In the case of active SS, the energy balances of additional components are needed to be carried out [51, 55].

Kumar et al. [86] develop energy balance on basin water:

$$\alpha'_{bw} I(t)_{rs} + q_{bl} + Q_u = m_{bw} C_{bw} \frac{dT_{bw}}{dt} + q_{ev,bw-ci} + q_{r,bw-ci} + q_{cn,bw-ci} \quad (40)$$

All unknown value of heat transfer rate can be calculated through the equations which are given in the appendix.

In the case of passive SS there is no need of external device:

$$\therefore Q_u = 0$$

Energy balance on basin liner:

Due to small contact surface area, heat loss from the sidewall is neglected, energy balance on basin liner is given by Singh et al. [61] and Kumar et al. [61]:

$$\alpha_{bl} I(t)_{rs} A_b = h_{cn,bl-bw} (T_{bl} - T_{bw}) A_b + U_{HL,b} (T_{bl} - T_{amb}) A_b \quad (41)$$

Energy balance of evacuated tube water mass can be expressed as [62]:

$$h_{tube-w} A_{cm,t} (T_{tube} - T_{w,ETC}) N_t = (\dot{m}_{cr} C_{bw}) (T_{w,ETC} - T_{bw}) + (M_{ETC} C_w) \frac{dT_{w,ETC}}{dt} \quad (42)$$

Where dT_w is varied from small time interval dt ($0 < t < dt$)

Energy balance of water mass inside the still with evacuated tube collector (ETC) [62]:

$$(\dot{m}_{cr} C_{bw}) (T_{w,ETC} - T_{bw}) + \alpha_w A_b I(t)_{rs} + h_{bl-bw} (T_{bl} - T_{bw}) A_b = h_{il,bw-c} (T_{bw} - T_{ci}) A_b + (M_{bw} C_{bw}) \frac{dT_{bw}}{dt} \quad (43)$$

TEMPERATURE OF VARIOUS PARTS OF THE SSASS

After rearranging the above equations 41–43, the equation of basin liner temperature, the temperature of basin water and the evacuated tube water temperature has been calculated which is given below, following equations is given by Singh et al. [61] and Kumar et al. [61]:

The Temperature of inner and outer glass cover:

For inner glass:

$$T_{ci} = \frac{\alpha'_c I(t)_{rs} + h_{il,bw-ci} \times T_{bw} + \frac{K_c}{L_c} \times T_{amb}}{h_{il,bw-ci} + \frac{K_c}{L_c}} \quad (44)$$

Sampathkumar et al. [87] give the outer glass temperature:

$$T_{co} = \frac{\alpha'_c I(t)_{rs} h_c + U_{wo} T_{bw} + h_{il,c-amb} T_{amb}}{h_{il,c-amb} + U_{wo}} \quad (45)$$

Basin liner temperature[87]:

$$T_{bl} = \frac{\alpha_{bl} I(t)_{rs} + h_{cn,bl-bw} T_{bw} + U_{HL,b} T_{amb}}{h_{cn,bl-bw} + U_{HL,b}} \quad (46)$$

Basin water temperature:

Kumar et al. [62] developed the expression of water temperature for evacuated tube collector (ETC) integrated active solar still:

$$T_{bw} = \frac{1}{(\beta^+ - \beta^-)} \left[\begin{aligned} &g_1(t) \left\{ \frac{(1 - e^{-c^+t})}{c^+} - \frac{(1 - e^{-c^-t})}{c^-} \right\} \\ &+ g_2(t) \left\{ \frac{\beta^+(1 - e^{-c^+t})}{c^+} - \frac{\beta^-(1 - e^{-c^-t})}{c^-} \right\} \\ &+ T_{w0,ETC} (e^{-c^+t} - e^{-c^-t}) + T_{bw0} (\beta^+ e^{-c^+t} - \beta^- e^{-c^-t}) \end{aligned} \right] \quad (47)$$

Where, $T_{w0,ETC}$ = Initial water temperature of evacuated tube collector at $t = 0$ and T_{bw0} = Initial basin water temperature at $t = 0$.

Kumar et al. [62] gave the equation for calculating the water temperature of the evacuated tube collector (ETC), which is written below:

$$T_{w,ETC} = \frac{1}{(\beta^+ - \beta^-)} \left[\begin{aligned} &g_1(t) \left\{ \frac{\beta^+(1 - e^{-c^-t})}{c^-} - \frac{\beta^-(1 - e^{-c^+t})}{c^+} \right\} \\ &+ \beta^+ \beta^- g_2(t) \left\{ \frac{(1 - e^{-c^-t})}{c^-} - \frac{(1 - e^{-c^+t})}{c^+} \right\} \\ &+ T_{w0,ETC} (\beta^+ e^{-c^-t} - \beta^- e^{-c^+t}) \\ &+ \beta^+ \beta^- T_{bw0} (e^{-c^-t} - \beta^- e^{-c^+t}) \end{aligned} \right] \quad (48)$$

All unknown factors of the above equations are given in Appendix 'A' of Singh et al. [61] and Kumar et al. [61]

Singh et al. [88] developed the expression of water temperature for PVT integrated flat-plate collector (FPC) based active solar still:

$$T_{bw} = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{bw0} e^{-a\Delta t} \quad (49)$$

Where

$$f(t) = \frac{N_t A_{cm} (\alpha\tau)_{eff,N_t} I_{ETC}(t) + \alpha_{eff} I(t) r_s A_b + (N_t A_{cm} U_{HT,b} + U_{OL} A_b) T_{amb}}{M_{ay} C_w} \quad (50)$$

$$a = \frac{(N_t A_{cm} U_{HT,b} + U_{OL} A_b)}{M_{ay} C_w} \quad (51)$$

THERMAL EFFICIENCY OF ACTIVE SINGLE SLOPE SOLAR STILL:

The ratio of thermal energy used to evaporate water to the total energy incident over the solar still (SS) is termed as thermal efficiency.

The hourly thermal efficiency of single slope active SS can be calculated as [88]:

$$\eta_{ds} = \frac{(\dot{m}_{bw}) \times L}{[A_{Ex} \times I_{Ex} + A_b \times I(t)_{rs}] \times 3600} \times 100 \quad (52)$$

Where A_{Ex} is the area of the additional device, I_{Ex} is the solar intensity on external device and \dot{m}_{bw} is the hourly distilled out-put (kg/h)

Tiwari and Sahota [89] have been developed the equation for calculation of overall thermal efficiency for PVT base single slope active solar still.

$$\eta_{ds} = \frac{(\dot{m}_{bw}) \times L}{[A_{Ex} \times I_{Ex} + A_b \times I(t)_{rs}] \times 3600} \times 100 + \frac{FF \times V_{oc} \times S_{sc}}{0.38 \times A_m \times I(t)_c} \times 100 \quad (53)$$

Where FF is the Fill factor of the module, V_{oc} is the open circuit voltage, S_{sc} is the short circuit current, $I(t)$ is the solar intensity on the collector and A_m is the area of the module.

ENERGY BALANCE ON DOUBLE SLOPE ACTIVE SOLAR STILL (DSASS)

Based on the first law of thermodynamic, the energy balance of DSSS is shown below. The equation of glass temperature, basin water temperature, and basin liner temperature is given based on heat and mass transfer analysis [37,40].

For inner and outer glass surface:

Energy balance on the inner and outer glass surface of the DSASS is the same as the double slope passive SS as shown by Eq. (23) to (27).

Energy balance on basin liner:

Total radiation absorbed by the basin water is equal to the total rate of energy lost from the basin water through convection and conduction [74]. Due to the black surface, the maximum solar radiation is absorbed by the basin liner; the absorbed radiation is converted into the heat and transfers into the basin water through the convection and loss to the atmosphere through conduction. The total rate of energy loss to the ambient from the basin water and basin liner is given by Kumar et al. [62], which is given below:

$$\alpha_{bl} I(t)_{rs} = h_{cn,bl-bw} (T_{bl} - T_{bw}) + U_{HL,b} (T_{bl} - T_{amb}) \quad (54)$$

Now rearrange the Eq. (54) and it can be expressed as the following equation, Kumar et al. [62] and Dev et al. [75] Gives the equation of basin liner temperature:

$$T_{bl} = \frac{\alpha_{bl} I(t)_{rs} + h_{cn,bl-bw} \times T_{bw} + U_{HL,b} \times T_{amb}}{h_{cn,bl-bw} + U_{HL,b}} \quad (55)$$

Energy balance on water mass:

The energy balance equation for the mass of water is given by Nijmesh et al. [37] and Sharshir et al. [40]:

$$\alpha_{bl} I(t)_{rs} + q_{cn,bl-bw} + Q_{ex} = m_{bw} \times C_{bw} \times \frac{dT_{bw}}{dt} + q_{ev,bw-ci} + q_{r,bw-ci} + q_{cn,bw-ci} \quad (56)$$

After rearranging the equation (56), temperature of the water can be expressed through the following equation which is obtained by Tiwari and Sahota [22] and Sampathkumar et al. [87]:

$$T_{bw} = \frac{f(t)}{a} \times [1 - e^{-at}] + T_{bw0} \times e^{-at} \quad (57)$$

T_{bw0} = Initial basin water temperature at t equal to 0

All unknown factors of the above equations are given in the Appendix of Sampathkumar et al. [87].

TEMPERATURES EQUATIONS FOR VARIOUS PARTS OF THE DSASS

When an external device is added to the double slope passive SS, then it is called double slope active SS. External devices such as flat-plate collector, heater, fan, PVT, external condenser and glass cooling system, etc. [90]. Temperature equations of the different parts of the SS are written below:

Dwivedi et al. [91] developed the temperature equation for DSASS which is given below:

$$T_{bw} = \frac{f'(t)}{a} [1 - e^{-a\Delta t}] + T_{bw0} e^{-aHt} \quad (58)$$

Where

$$f(t) = \frac{1}{m_{bw} C_w} \left[\left(\alpha_{bw} + \frac{\alpha_{bl} h_{bl-bw}}{h_{bl-bw} + h_{bl-amb}} \right) (I_{c,ES} + I_{c,WS}) + A_{cr} F'(\alpha\tau) I(t)_c + \frac{h_{tl,E} A_1 + h_{tl,W} B_1}{P} + \left(A_{cr} F U_{HT,cr} T_{amb} + \frac{2h_{bl-bw} h_{bl-amb}}{h_{bl-bw} + h_{bl-amb}} T_{amb} \right) \right] \quad (59)$$

The temperature of the inner and outer glass surface of the east and west direction is calculated by following equation [91]:

$$T_{ci,E} = \frac{A_1 + A_2 T_{bw}}{P} \quad (60)$$

$$T_{ci,W} = \frac{B_1 + B_2 T_{bw}}{P} \quad (61)$$

$$T_{co,E} = \frac{(K_c / L_c) T_{ci,E} + h_{tl,co-ambE} T_{amb}}{(K_c / L_c) + h_{tl,co-ambE}} \quad (62)$$

$$T_{co,W} = \frac{(K_c / L_c) T_{ci,W} + h_{tl,co-ambW} T_{amb}}{(K_c / L_c) + h_{tl,co-ambW}} \quad (63)$$

Basic basin liner temperature of double slope SS is obtained through the following equation [91]:

$$T_{bl} = \frac{[\alpha_{bs} (I_{c,ES} + I_{c,WS}) + 2(T_{bw} h_{bl-bw} + T_{amb} h_{bl-amb})]}{2(h_{bl-bw} + h_{bl-amb})} \quad (64)$$

THERMAL EFFICIENCY OF DOUBLE SLOPE ACTIVE SOLAR STILL [DSASS]

The basic thermal efficiency equation of double slope SS is given by Singh et al. [84]:

$$\eta_{ds} = \frac{(\dot{m}_{bw,E} + \dot{m}_{bw,W}) \times L}{[A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS}] \times 3600} \times 100 \quad (65)$$

Some changes had been done in the thermal efficiency of the DSASS by Singh et al. [92], external device parameters are added in the thermal equation, the thermal efficiency of double slope active solar still is given below:

$$\eta_{ds} = \frac{(\dot{m}_{bw,E} + \dot{m}_{bw,W}) \times L}{[A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS} + A_{Ex} \times I_{Ex}] \times 3600} \times 100 \quad (66)$$

Where, E is the East direction and W is the West direction Singh et al. [92] developed an equation for calculating the thermal efficiency of PVT integrated flat-plate collector (FPC) based DSASS:

$$\eta_{ds} = \frac{(\dot{m}_{bw,E} + \dot{m}_{bw,W}) \times L}{[A_{c,E} \times I_{c,ES} + A_{c,W} \times I_{c,WS} + (A_c + A_{pv}) \times I(t)_c] \times 3600} \times 100 \quad (67)$$

Where, A_{pv} is the area of the PV module.

CONCLUSIONS

The productivity of solar stills are found still low nearly about 10 litres/day and various researches are putting their effort to further improve the output of solar stills by implementing various modification on solar stills. The

productivity of any solar still depends on the internal and external heat transfer rates. The study on the heat transfer analysis and modifications in still are concluded as follows:

- To increase the internal heat transfer rate of passive solar stills, heat-absorbing materials such as PCM, nanoparticles, and fine stones were used in the setup.
- Based on literature review it is found that the thermal efficiency of nanoparticles and PCM based solar still lies between 17–62% and 17.93–59.14%, respectively.
- Due to heat storage properties, PCM based still provides 3–4 hours more production after sunset.
- Reflectors, flat-plate collectors, and external condensers are used to increase the evaporation rate of water inside the active solar stills.
- The productivity of passive solar still can be increased by 50–85% if an external device is used.
- The productivity of modified passive and active solar still was found maximum up to 6 litres and 10 litres, respectively.
- Stepped solar stills can also raise the evaporation rate inside the setup as there is a thin layer of basin water in each step which does not take much time to evaporate and rapidly converts into vapour.
- The productivity of the solar still has also been enhanced by the flow of cold water over the glass cover. Through this method the temperature difference between the glass and water surface ($T_w - T_g$) is increases, this increases the evaporation and condensing rate of water.
- The present work is limited to the modifications made in passive and active solar still while an extensive review can be made by considering all the modifications in still like single slope, double slope, multi basin and multi-stage etc. along with heat and mass transfer analysis done on hybrid active solar stills. The exergy analysis can also be included to make a more exhaustive review of solar stills.

NOMENCLATURE

A_{ar}	Solar collector aperture area, m^2
A_{cr}	FPC (flat-plate collector) surface area, m^2
a''	Efficiency co-efficient of solar collector, W/m^2
A_b	Basin area, m^2
$A_{c,E}$	Surface area of glass cover located in east direction, m^2
$A_{c,W}$	Glass surface are which located in west direction, m^2
$A_{cm,t}$	Each tubular absorber circumferential area, m^2
A_c	Collector area, m^2
C_{bw}	Basin water specific heat capacity, $J/kg-K$

C_c	Condensing cover specific heat, $J/kg-K$
d_{tube}	Evacuated tube diameter, m
\dot{E}_{evp}	Evaporative energy flow rate, W
F'	Flat-plate collector efficiency factor
H_{bw}	Basin water heat capacity, J/kg
h_{tube-w}	Heat Transfer Coefficient (HTC) among tube and water, W/m^2C
h_{ext}	Total external HTC, W/m^2C
$h_{tl,bw-cs}$	Total HTC from basin water surface to condensing cover, W/m^2C
h_c	HTC of glass cover, W/m^2C
h_{ev}	Evaporative HTC from basin water to glass surface, W/m^2C
$h_{cn/bl-bw}$	Convective HTC from basin liner to water mass, W/m^2C
h_{bs-sn}	HTC among basin and surrounding, W/m^2C
$h_{cd'pcm-bl}$	Conductive HTC from PCM to basin liner, W/m^2C
$h_{r,EW}$	Internal radiative HTC among east and west condensing cover, W/m^2C
h_{bl-amb}	HTC from basin liner to ambient, W/m^2C
$h_{tl-bw-co}$	Total HTC basin water-internal surface of glass, W/m^2C
$h_{tl,co-amb}$	Total HTC outer condensing-atmosphere, W/m^2C
h_{bl}	HTC of basin liner, W/m^2C
$h_{r,c-sky}$	Radiative HTC glass to sky, W/m^2C
$h_{cr,co-amb}$	Convective-radiative HTC from outer glass cover to ambient, W/m^2C
$I_{ETC}(t)$	Solar radiation over the ETC, W/m^2
$I(t)_{rs}$	Solar intensity on the still, W/m^2
$I(t)_c$	Solar intensity on the collector, W/m^2
K_c	Thermal conductivity of glass, W/m^2C
L_c	Glass cover thickness, m
M_{dw}	Daily distilled output, Kg/m^2 day
m_{bw}	Basin water mass, kg/m^2
\dot{m}_{cr}	Natural circulation rate of each tube, Kg/s
M_{ETC}	Water mass in the ETC
M_{ay}	Annual yield, kg
N_t	Number of tube in collector
P	Partial saturated vapour pressure, N/m^2
$q_{cd,ci-co}$	Heat transfer rate (HTR) by conduction inner glass surface-outer glass surface, W/m^2
$q_{cn,co-amb}$	HTR by convection outer glass surface-ambient, W/m^2
$q_{r,co-amb}$	HTR by radiation outer glass surface-ambient, W/m^2
q_{cn}	HTR by convection basin water- inner condensing surface, W/m^2
\dot{q}_{ev}	Evaporative HTR, W/m^2
q_{bw}	HTR among basin liner-water mass, W/m^2
q_{bs}	HTR between basins- ambient, W/m^2
Q_{ex}	Useful thermal energy gain from external devices, W/m^2

Q_u	Rate of thermal feed from external devices to solar still, W/m ²
\dot{Q}_{ue}	Useful thermal energy gain from collector, W/m ²
R_c	Glass cover reflectivity
R_{bw}	Basin water reflectivity
T_{co}	Temperature of outer glass surface, °C
T_{amb}	Ambient temperature, °C
T_{ci}	Inner condensing surface temperature, °C
$T_{w,ETC}$	Water temperature in evacuated tube collector (ETC), °C
$U_{HT,b}$	Overall heat transfer coefficient (HTC) through the still, W/m ² °C
$U_{HT,cr}$	Overall HTC of flat-plate collector, W/m ² °C
U_{HTE}	Overall HTC between east side outer glass surface-ambient air, W/m ² °C
$U_{HT,W}$	Overall HTC in west direction among outer glass surface-ambient air, W/m ² °C
$U_{HL,T}$	Overall top heat loss or HTC among water mass-atmosphere, W/m ² °C
U_{eff}	Effective Overall HTC, W/m ² °C
U_{OL}	Overall HTC by the still, W/m ² °C
$U_{HL,b}$	Overall bottom heat loss coefficient (HLC) from water mass to atmosphere, W/m ² °C
U_{bs}	Total HLC of bottom and side among water mass-ambient, W/m ² °C
$U_{i,HL}$	Maximum internal HLC water surface to the condensing cover, W/m ² °C
Pr	Prandtl number
Re	Reynolds number
Gr	Grashof number
HTC	Heat Transfer Co-efficient
HLC	Heat loss co-efficient
HTR	Heat transfer rate

Subscripts

amb	ambient
atm	Atmosphere
bl	Basin liner
bs	Basin surface
bw, w	Basin water, water
c	Glass cover
ci	Inner glass cover
E	East direction
co	Outer glass cover
W	West direction
ETC	Evacuated tube collector
tl	Total

Greek words

τ_c	Transitivity of glass
τ	Reflection co-efficient
α	Absorption co-efficient
η_{it}	Instantaneous thermal efficiencies
η_{iL}	Instantaneous thermal loss efficiencies

APPENDIX

Absorptivity of different component of solar still can be obtained through following equations, given in the paper of Sampathkumar et al. [87] and Tiwari et al. [93]:

$$\alpha'_{bl} = \alpha_{bl}(1 - \alpha_c)(1 - R_c)(1 - R_{bw})(1 - \alpha_{bw})$$

$$\alpha'_{bw} = (1 - \alpha_c)(1 - R_c)(1 - R_{bw})\alpha_{bw}$$

$$\alpha'_{eff} = \alpha'_{bs} \frac{h_{cn,bl-bw}}{h_{cn,bl-bw} + h_{bl-amb}} + \alpha'_{bw} + \alpha'_c \frac{h_{tl,bw-ci}}{h_{tl,bw-ci} + U_{HL,co-amb}}$$

$$\alpha'_c = (1 - R_c)\alpha_c$$

Heat transfer rate can be calculated through the following equations given by the Kumar and Tiwari [86] and Zurigat et al. [72]:

$$q_{bl} = h_{bl-bw}(T_{bl} - T_{bw})$$

$$q_{bs} = h_{bs-sn}(T_{bl} - T_{amb})$$

$$q_{tl,bw-ci} = h_{tl,bw-ci}(T_{bw} - T_{ci})$$

$$q_{cd,ci-co} = \frac{K_c}{L_c}(T_{ci} - T_{co})$$

Shiv kumar et al. [62] gives the following equations to calculate the overall heat transfer coefficient,

$$U_{HL} = U_{HL,T} + U_{HL,b}$$

$$U_{HL,T} = \frac{h_{tl,bw-ci} \times U_{HL,ci-atm}}{h_{tl,bw-ci} + U_{HL,ci-atm}}$$

$$U_{HL,b} = \frac{h_{cn,bl-bw} \times h_{bl-amb}}{h_{cn,bl-bw} + h_{bl-amb}}$$

AUTHORSHIP CONTRIBUTIONS

Vikas Kumar Thakur: Materials; Data: Analysis; Literature Search. M.K. Gaur: Concept, Design, Supervision. M.K. Sagar: Supervision. G.N.Tiwari: Critical revision.

DATA AVAILABILITY STATEMENT

No new data were created in this study. The published publication includes all graphics collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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