A Review on Performance Investigation on Solar Still With PCM and Nano-Composite Materials

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ABSTRACT

Fresh water supply is the basic requirement for the human consumption, agricultural, industrial and domestic purposes. Many countries suffer from the water scarcity due to the excess of population and rapid growth of industries. Solar still is the most widely used application to desalinate the brackish water into potable water using solar energy. Furthermore, the world wide rapid growth of industry and population has resulted in a large boom in demand for fresh water. Survey reveals that about 79% of available water is salty, only 1% is fresh water and the rest 20% is brackish. Numerous experimental investigations revealed that the basin-type solar stills are used in various desalinating process due to its simple construction and limited performance. In this paper, different types of solar still experiments was carried out and their performance has been observed for different modifications and conditions. The productivity rate of the potable water is enhanced by using different types of solar stills. Furthermore, transient mathematical models and the energy equations are analyzed to improve the performance of the still. The implementation results of the solar stills are extensively reviewed in this study.

INTRODUCTION

Adequate supply of fresh water is the basic requirement for domestic, industrial, agricultural and domestic usages. Solar desalination is the technique in which the potable water is obtained by desalinating the water resources containing the dissolved chemicals and brackish water using solar energy. Solar stills are used to desalinate the water with low congestion and limited demand. Fresh water is being contaminated as the drainage pipelines are passing nearby water pipelines. To enhance the yield of the single basin solar still, Badran et al integrated a conventional plate collector with a solar still to augment the production rate [1]. El-Sebaii investigated theoretically and experimentally a shallow solar-pond integrated with a baffle plate [2]. velmurugan et al Investigated the integration of fins at the basin of the still and compared with other types and found that daily productivity was increased from 1.88 to 2.8 kg/m^2[3].Thermal performances of stills were compared in typical sunny (23/05/2009) and partially cloudy (13/05/2009) days. Furthermore, the effect of flow rate on total productivity of the stills was investigated in five sunny consecutive days through 23 to 27 of May 2009. Another method that may be used to improve the productivity of solar stills is by using storage systems either sensible or latent heat systems. This method utilizes the heat dissipated from the bottom of the still. Aybar has carried out mathematical modelling for an inclined solar water distillation System [4].Tanaka and Nakatake presented the theoretical analysis of a titled-wick solar still with an inclined flat plate external reflector and proved that the daily amount of distillate would be 15% to 27% greater than the conventional still[5]. Due to the loss of heat of condensation, solar still suffers from low productivity which can be enhanced by using the liberated heat to heat brine multi-effect stills or can be improved by storage systems either sensible or latent heat systems.

CATEGORIES

To overcome the contamination of freshwater in different aspects, the energy conversion takes place in three types namely,

- Solar still with energy storage
- Solar still with Phase change material(PCM)
- Nano fluids

Solar stills are used to desalinate the water with low congestion and limited demand. The solar stills are of different types namely,

- Solar still using stepped type basin
- Solar still with internal reflector
- Solar still with integrated mini solar pond
- Solar still using single slope basin

Other method

- Solar desalination

These types are experimentally and theoretically studied and are explained below

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ENERGY STORAGE

Two cascaded solar stills were constructed with & without latent heat thermal energy storage system (LHTESS). Channelization can be reduced by covering the evaporation surface with the thin layer of water. Paraffin wax is selected as phase change material (PCM) which acts as LHTESS. The thermal performances of the two cascaded solar stills can be compared in partially cloudy days and typical sunny days. The two solar stills were designed based on the inclination through the year for Zahedan days. All the experiments were started at 8AM & ended at 9 PM. It has been observed that the productivity increased from 1.88 to 2.8 kg/m^2. A schematic top view of water flow path on the absorber plate is shown in Fig 1. The flow rate values that used in five sunny days are 0.055, 0.07, 0.085, 0.1 and 0.115 kg/min. H.M.Qiblawey has said direct solar stills use the solar energy to produce distillate directly in the solar collector and the systems that combine conventional desalination system with solar collector are called indirect systems [6]. Souza et al have investigated the effect of inclination of tilt evaporator and observed that higher efficiencies were attained when the inclination of the collector was adjusted monthly [7]. A.sharma et al Paraffin wax with 57 °C melting point was selected as a PCM due to its medium storage, safety, reliability, congruent melting and moderate cost. Paraffin wax is chemically inert and stable below 500 °C [8].

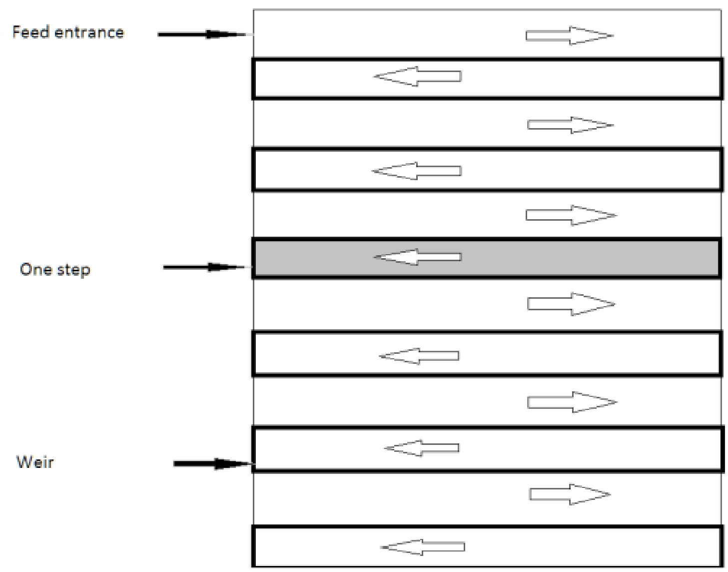


Fig 1: A schematic top view of water flow path on the absorber plate

Weirs are used to keep the water film as shallow as possible while avoiding dry spots. Residence time can also be increased when the weir is used at each step which leads to the force flow. Cross sectional view of a schematic diagram of cascade solar still is shown in Fig 2. Nocturnal distillation of still with LHTESS is not considerable in the continuous mode a cause to accelerate the discharge process. Due to decrease in the operating temperature with ambient temperature, high amount of distillate water cannot be produced when there is heat transfer from PCM on to the operation surface. Distilled water can be used for drinking purposes when it is mixed with little amount of free water and also for domestic usages as per the results of preliminary tests. The total productivity of still without LHTESS is slightly higher than the still with LHTESS in sunny days. There is a significant difference in productivity of still: 3.4 kg/m^2 day for still with LHTESS and 2.1 kg/m^2 day for still without LHTESS in partially cloudy day. Thus, still without LHTESS is preferred for sunny areas because of its simplicity and low construction costs and still with LHTESS is proposed for partially cloudy areas due to the higher productivity and its stable condition regard to change in the weather conditions. Increasing the flow rate results in decreasing the total productivity. Highest total productivity achieved in the lowest possible flow rate (0.055 kg/min) are about 4.85 and 5.14 kg/m^2 day for still with and without LHTESS in the sunny day (23/05/2009), respectively.

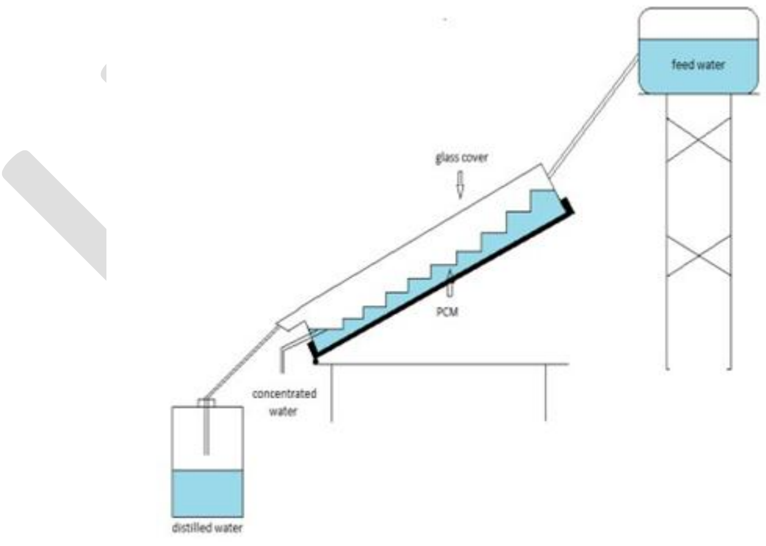


Fig 2: Cross sectional view of a schematic diagram of cascade solar still

This paper presents a new approach to improve the efficiency of a solar still by introducing a medium to provide large evaporation surface and utilize the latent heat of condensation and deals with the experiments conducted on a conventional single slope solar still and on a regenerative solar still with jute cloth. The conventional still has been modified with the energy storage medium viz. Jute cloth is kept vertically in the middle of basin saline water and also attached to the rear wall of the still. Mona M. Naim et al designed a simple solar still with a phase change materials viz., paraffin wax and paraffin oil as the energy storage media to make use of its latent heat of fusion for storing the excess solar energy at noon [9]. This stored energy could be used to evaporate the water during off sunshine hours in the evening and night. They achieved the average daily still yield of 2.5 kg/m^2 with 15% improvement in the yield. Also Mona M. Naim et al used charcoal particles as heat absorption medium and charcoal acted as wick to provide more surface area to increase the rate of evaporation [10]. Sakthivel et al have conducted experiments with black granite gravel size of 6 mm as an energy storage medium kept in the basin of a single slope solar still with basin area of 1 m×0.5 m[11]. In this work, experiments have been conducted for different depths of saline water in the conventional still to optimize the quantity of saline water and for different depths of gravel layer with optimized quantity of saline water in the modified regenerative still. Mathematical model has been developed to validate the experimental observations. It has been found that the daily still yield is about 3.9 kg/m^2 which is 20% more than the conventional still and efficiency of the still has increased from 44% to 52%.As per their findings, the daily still yield was approximately 2.5 kg/m^2 for 40 mm depth, 3.5 kg/m^2 for 50 mm depth & 2.8 kg/m^2 for 80 mm depth under the maximum solar intensity of 1016 w/m^2 in the month of July 2007. A schematic diagram of a single slope solar still with jute cloth are shown in Fig 3. In which the jute cloth is placed vertically on the middle basin of saline water and also attached to the rear wall of the still. They show the view of the still optimum quantity of saline water can be obtained by conducting the experiments for the different quantities of saline water in the conventional still. From the various experiments conducted, it has been found that the maximum yield was obtained for the conventional still with 30 kg saline water. Experimental observations for the regenerative still with jute cloth and with 30 kg of saline water are gain in table 1 with 30 kg of saline water the cumulative yield in the regenerative still with jute cloth is 4 kg/m^2 about 20% more than the conventional still, whereas for 20 kg & 40 Kg the yield is more or less the same. The cumulative yield will vary within ±10% for different quantities of saline water in the regenerative still with jute cloth. Whereas in the conventional still the variation will be more. The effects of both sensible & latent heat type materials and also different kinds of attachments like flat plate collector coupled with evaporator, separate condenser, air blowing equipment etc. These modifications still are analyzed in different manner.

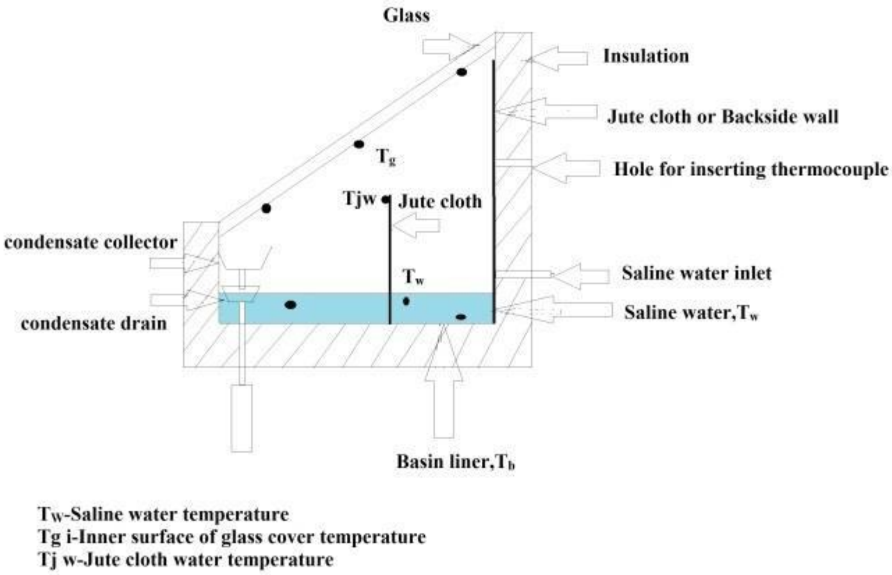


Fig 3: Schematic diagram of a single slope solar still with vertical jute cloth

Brackish water can be desalinated using passive solar still with the help of transient mathematical model. In this process, Energy is stored by PCM's when the aggregate solid state is changed into liquid. As for Dashtban and Tabrizi theoretically studied a weir-type cascade solar still, integrated with latent heat thermal energy storage system. It was designed with the view of enhancing productivity [12]. In this research investigation, the paraffin wax was used as a heat storage system which keeps the operating temperature of the still high enough to produce distillate water during the lack of sunshine, particularly at night. As for the article, it undertook a hybrid (PV-T) solar still which is a combination of solar still and flat plate collector (FPC) integrated with glass–glass photovoltaic module [13]. The comparative performance of these two methods has also been estimated in terms of root mean square percentage (RMS) error. Indeed, to improve the productivity of solar stills, two thermal storage systems could be used: either sensible or latent heat system. M.Faith Demirbas Due to its capability of storing thermal energy and almost constant temperature for charging and discharging, the latent heat thermal energy storage (LHTES) technique has received significant attention [14]. A schematic diagram of a passive solar still with built in PCM is shown in Fig 4. Desalination of the brackish water using a passive solar still with a heat energy storage system put under the basin liner of the still is analysed.

The economical study proved that the cost of one Litre of fresh water will be weakly affected by the implantation of storage system in the solar still device.

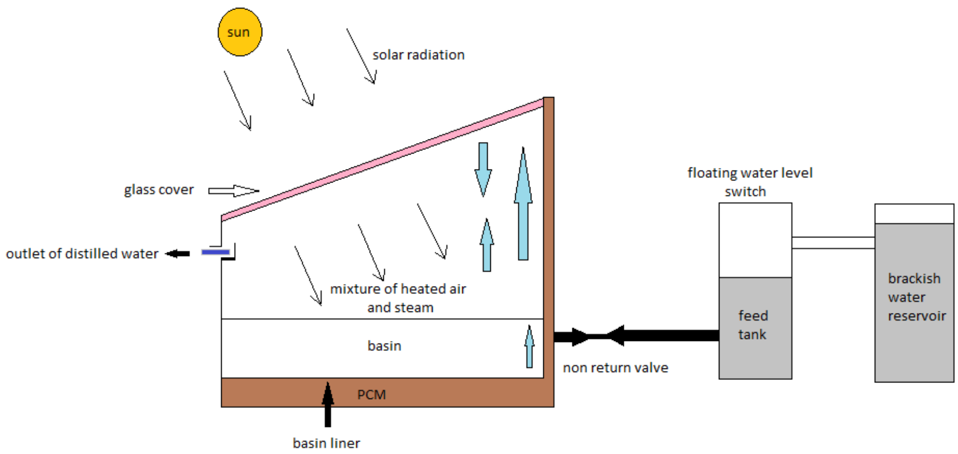


Fig 4: Schematic diagram

SOLAR STILL WITH PCM

The productivity of the still was enhanced by using the weir type cascade solar still integrating with LHTESS. Various technologies are being used for desalination of saline water such as multistage flash, multiple effect vapor compression, reverse osmosis, ion exchange, electro dialysis, phase change and solvent extraction. These technologies are costly, however, for the production of small amount of fresh water. Also, the use of conventional energy sources (hydrocarbon fuels) to drive these systems has harmful environmental impacts. Unlike other desalination methods, solar stills use solar energy to distillated water in an environmentally friendly manner. Velmurugan et al investigated the integration of fins at the basin of the still and compared with other types [15]. They found that the daily productivity was increased from 1.88 to 2.8 kg/m^2. A heat reservoir with 2 cm thickness is incorporated with the still beneath the absorber plate and filled by PCM that acts as latent heat thermal energy storage system (LHTESS). A.Sharma et al Paraffin wax is chosen as PCM because of its medium storage, safety, reliability, uniform melting and moderate cost [16]. A still was fabricated to increase the amount of distillated water as shown in Fig 5.

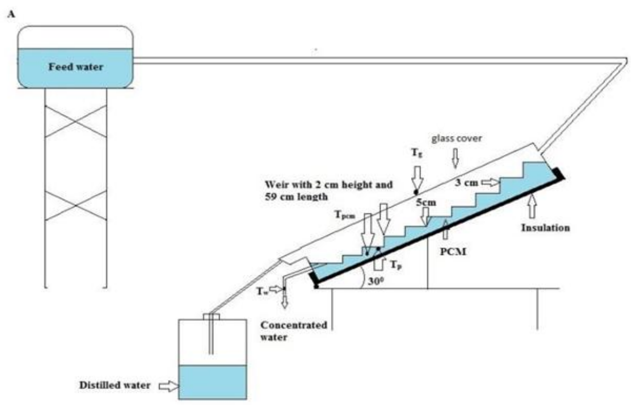
The following assumptions are applied in development of the mathematical models:

- There is no leakage of saturated air from the still.
- Heat losses from the sides of the still are negligible.
- Water layer is assumed to be stagnant and has a constant thickness of water.
- The temperature of the stagnant water layer is assumed to be homogeneous on the absorber surface.
- No convection in PCM layer.
- For simplicity, there is no temperature gradient across the PCM because of its small thickness.

The energy balance for PCM is calculated with time. Due to small thickness, there is no temperature gradient across PCM.The daily productivity of the still decreases from 6.75 to 4.12 kg/m^2 day by increasing the water from 2 to 10 cm. A weir-type cascade solar still with built-in latent heat thermal energy storage System was fabricated to improve the still productivity. Another still with the same characteristics without PCM was also constructed for investigation of the internal convective heat transfer coefficient.

Moreover, the experimental and theoretical investigations of the still with and without PCM were also carried out, and the important conclusions were drawn:

- Using a weir on the edge of each step of the stills leads to even distribution of water onto the evaporation surface and increases the residence time.
- Increasing the level of water on the evaporation surface and decreasing the air gap in the still lead to decrease and slightly increase in the total productivity of the still, respectively.
- The still with PCM is superior in productivity (31% improvement) compared with still without PCM by considering a limited set of data in a typical day.



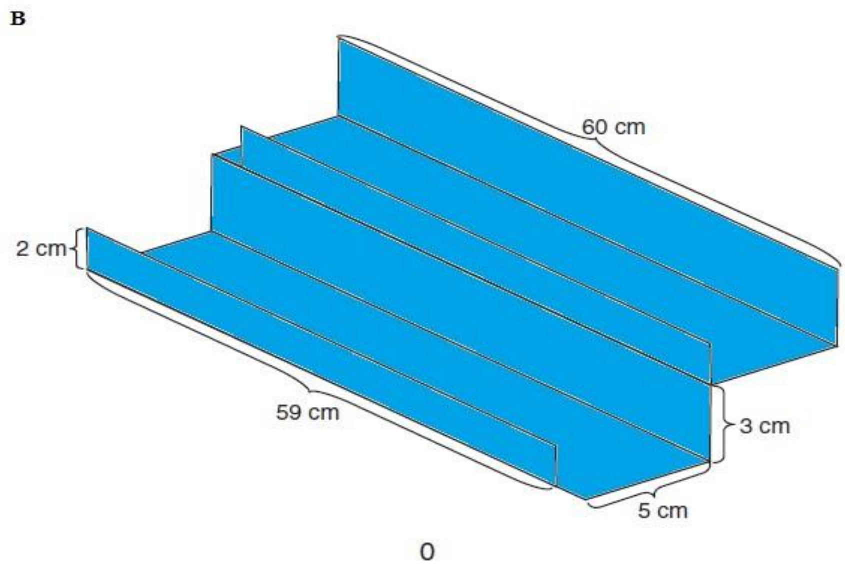


Fig 5: Cross sectional view of schematic diagram of cascade solar still

The daily productivity was theoretically obtained about 6.7 and 5.1 kg/m^{2}day for still with and without PCM, respectively. The overall thermal efficiency of the still with PCM was 64% and for still without PCM was 47%.

Transient mathematical model are presented for single slope basin solar still with and without phase change material (PCM) under basin liner of the still. Solar stills are broadly classified into passive and active solar stills. Schematic diagram of the investigated solar still with built in phase change material (PCM) as a storage medium is shown in Fig 6. Recently, many papers have appeared concerning the use of PCM as storage media integrated with some solar-thermal energy systems; such as solar cookers [17, 18], domestic hot water systems [19] and greenhouses in order to compensate for a temporal mismatch of supply and demand of solar energy [20]. With a thin layer of PCM under the basin liner of a solar still, a considerable amount of heat will be stored within the PCM during sunshine hours instead of wasting it to surroundings. During solidification of the PCM, the stored heat discharges to keep the basin water at a temperature enough to produce fresh water during the night even with thin layers of basin water. This causes an enhancement of the still productivity especially during the night period.

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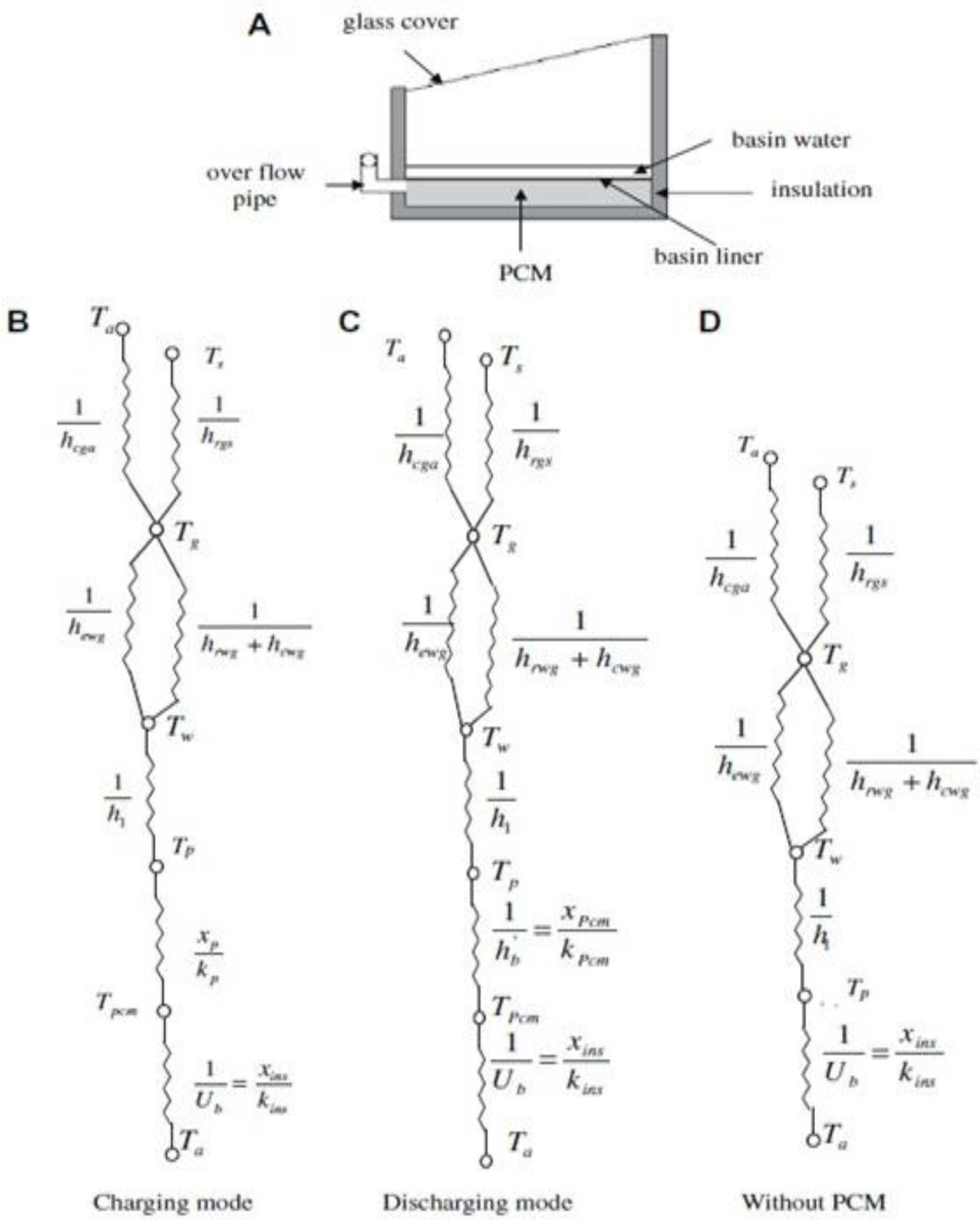


Fig 6: A schematic diagram of the single slope-single basin solar still with the PCM (A) and the thermal resistance networks of the still elements for the charging (B) and discharging (C) modes and without the PCM (D)

In the last few years, due to the wide variety of engineering applications in LHTESS it is used in the numerous thermal desalination processes. In this study, the considered passive solar still coupled with latent heat storage system is given by the Fig 7. Parametric study is performed to investigate the temporal variations of the storage medium, energy destruction of the solar still and that of the PCM, the pure water productivity and energy efficiency. To improve the productivity of a solar still, Dashtban and Tabrizi have been investigated theoretically the thermal analysis of a weir type cascade solar still integrated with PCM storage system [21]. In this research work, the paraffin wax was used as a heat storage system which keeps the operating temperature of the still high enough to produce distillated water during the lack of sunshine, particularly at night. Theoretical models were developed for the still with and without PCM, and the calculated results were compared with the experimental data. Moreover, important parameters affecting the performance of the still, such as water level on the absorber plate and distance between water and glass surfaces, were theoretically investigated. As for Kumar and Tiwari, they developed an expression for instantaneous exergy efficiency of a passive solar still [22]. The effect of some influencing parameters related to the system design and climatic conditions have been considered. They essentially found that decreasing an absorptivity of basin-liner (0.9 to 0.6) entails decreasing of the energetic and exegetic efficiencies by 21.8% and 36.7% respectively. In addition, it is shown that the effect of glass cover tilt is insignificant whereas these efficiencies increase rapidly up to a wind velocity of 2 $m \cdot s^{-1}$. K.R.Ranjan et al and his collaborators performed the exergy analysis of a single-effect, single-slope horizontal passive solar still under climatic condition of India [23]. It has been shown that energy and exergy efficiencies are 30.42 and 4.93% respectively. Also, exergy destruction has been evaluated in the process of each component and the global exergy efficiency of the solar still is estimated as 23.14%. The result shows that when the latent heat storage mode takes place, the irreversibility is crucial in the absorber and PCM medium.

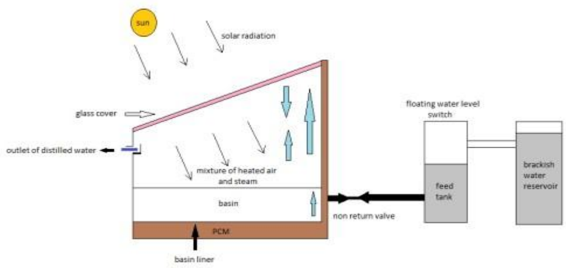


Fig 7: system schematic diagram

NANOFLUIDS

Nano fluids are the proficient heat transfer carriers for harvesting thermal energy in solar thermal applications. A systematic diagram of passive double slope solar still (DSSS) has been shown in Fig 8.

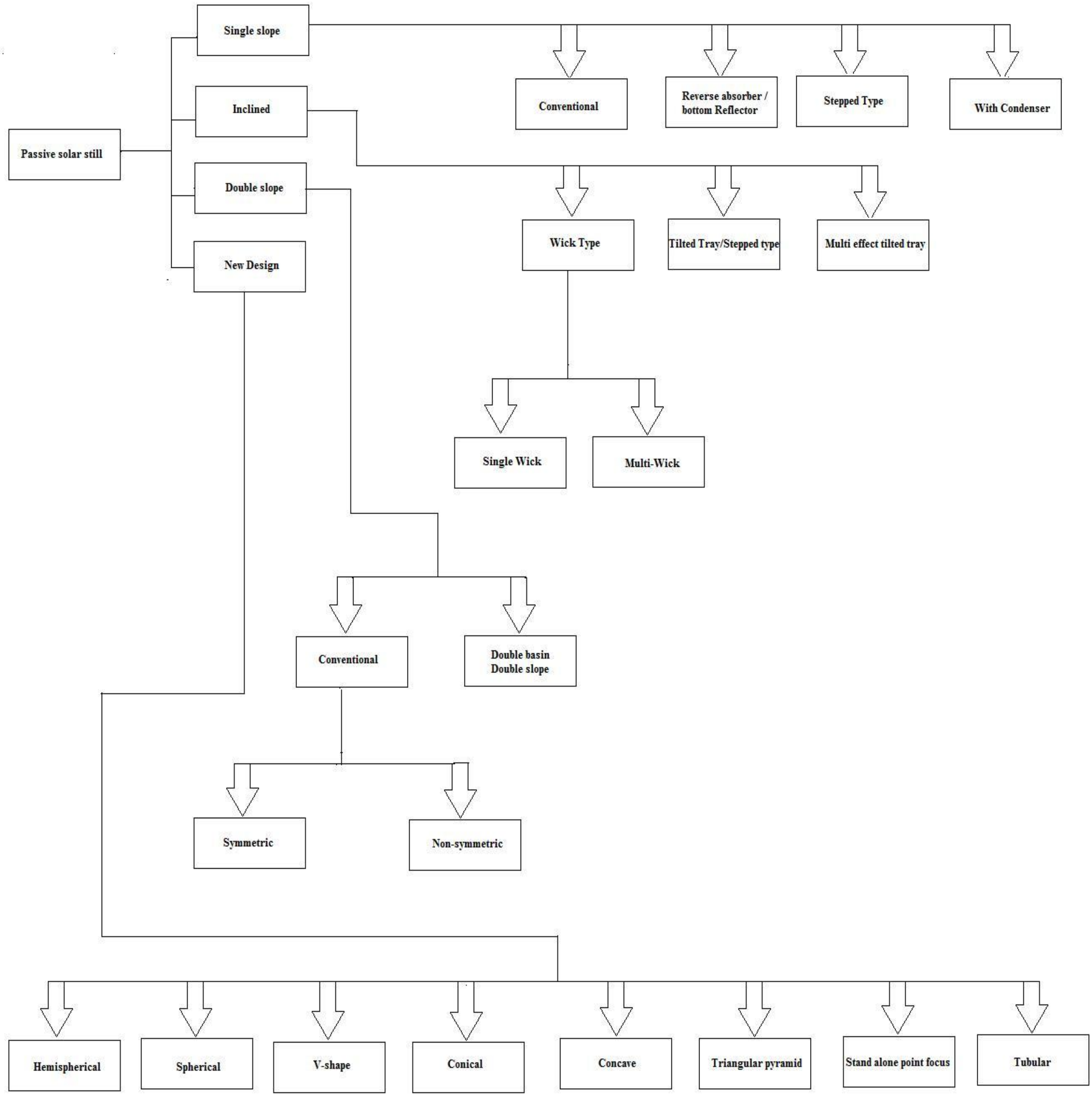


Fig 8: Classification of passive solar stills.

Heat transfer in Nano fluids takes place through the basic mechanisms such as Brownian motion, nanoparticle clustering, nature of heat transport across nanoparticles, and liquid layering at an interface of liquid and particle. Stability of Nano fluids is also a main concern which depends on the characteristics of assisting metallic nanoparticles and base fluid. Metallic nanoparticles often have a tendency of agglomeration due to Vander Waals forces of attraction which further leads to sedimentation [24]. In solar devices, the use of Nano fluid as an absorber fluid is a nominal approach to enhance the heat transfer mechanisms. The optical properties of Nano fluids can be tailored by altering the shape and size of the nanoparticles; and properties of the base fluid, hence it provides an opportunity to amalgamate a specific Nano fluid for the specific requirement [25]. Most of the researchers have done theoretical and experimental works using Nano fluids in flat plate collectors but very few literatures has been found for Nano fluids utilization in solar stills. Kabeel et al have studied the productivity of single slope solar still integrated with vacuum fan and using Al_2O_3–water based Nano fluid [26].

Modern Nanotechnology produces metallic or non-metallic particles of Nano metric dimensions that have unique properties. Exploitation of Nano fluids in the solar systems offers advantage over other conventional stills. Tiwari et al studied a Nano fluid based flat-plate collector theoretically [27]. They demonstrated enhancement of collector efficiency and the potential of reducing 31% in CO_2 emission in comparison with the conventional models. Tyagi et al Theoretically investigated the performance of a direct absorption solar collector (DAC) exploiting aluminium-water Nano fluid as the absorbing medium [28]. In the schematic of a Nano fluid based DAC of their study with glass surface on the top and completely isolated at the bottom side. They supposed a steady state two-dimensional model for heat transfer. Ijam and Saidur investigated the influence of Sic-water and TiO_2-water Nano fluids as the coolant in a mini channel heats ink, the results exhibited an improvement in thermal conductivity compared to base fluid [29]. It shows the schematic of a Nano fluid-based DAC of their study with glass surface on the top and completely isolated at the bottom side.

- Efficiency of the solar system is enhanced by the thermal conductivity of the Nano fluid but a higher solid fraction does not always enhance the efficiency.
- Thermal resistance at interfaces is reduced by the volumetric absorption of Nano fluid in solar collectors; hence the higher efficiency is expected.

- Since the pH value of Nano fluid diverges positively or negatively from the Iso electric point, less agglomeration appears and consequently leads to better thermal conductivity. Utilizing Nano fluid in solar systems comprises many environmental and economical beneficial aspects. This research is needed for better understanding the effects of utilizing Nano fluids in solar systems as it depends on many parameters such as particle size, poly- dispersity of particles, agglomeration, etc. The challenge is the limitation of nanoparticles; also their specifications are not accurate. Hence development of the particle production and decreasing in costs is essential for the Nano fluid research.

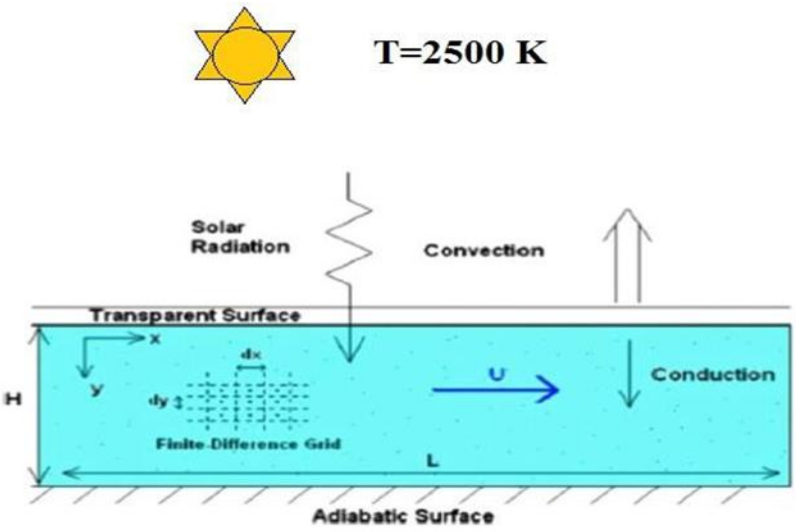
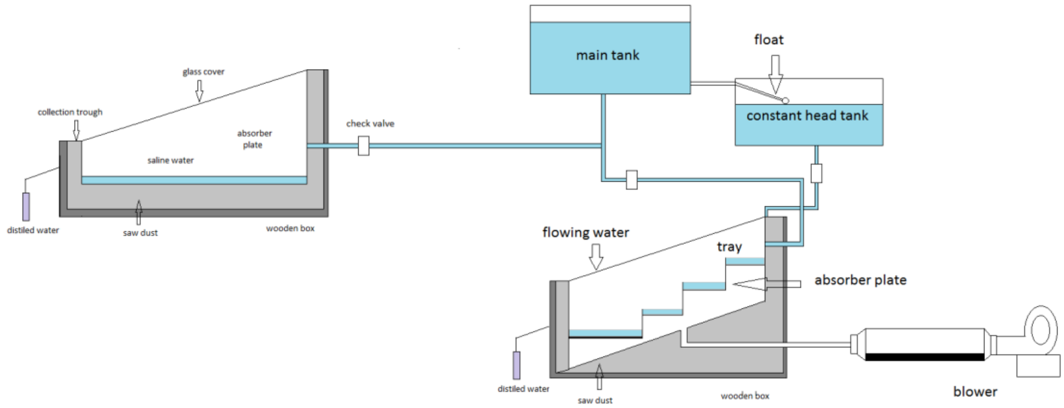


Fig 9: Schematic of the Nano fluid-based direct absorption solar collector in Tyagi's study

SOLAR STILL USING STEPPED TYPE BASIN

A single slope passive solar still (conventional still) and stepped active solar still integrated with a solar air-heater collector were fabricated with an area of 0.5 m^2. The saline water is heated by the passage of hot air under the base of stepped solar still through the solar air heater. Additional thermal energy supplied from the hot air increases the higher saline water temperature. The factors affecting the productivity of the solar still are basin area, free surface of the water, depth of the water and water temperature in the still. The performance of desalination system can be compare by designing & constructing the two solar stills. The schematic view of experimental set up is shown in Fig 10. Velmurugan et al used a stepped still and a settling tank to desalinate the textile effluent

[30]. A maximum increase in productivity of 98% is reported in stepped solar still when fin, sponge and pebbles are used in this basin. Tabrizi et al tested a wire type cascade solar still with various flow rates [31, 32]. The results showed that increasing flow rates caused to decrease in daily productivity and overall thermal efficiency. A weir-type cascade solar still, integrated with latent heat thermal energy storage system, was designed with the view of enhancing. A heat storage system with 18 kg mass of paraffin wax beneath the absorber plate was used, to keep the operating temperature of the still high enough to produce distillated water during the lack of sunshine, particularly at night. The wind speed is varied from 0.1 to 3.5 m/s, the ambient temperature is varied from 27 to 35^0 c and the solar intensity to 30-110 w/m^2 depending on the weather condition at different days. Increasing the water temperature by the hot air supplied from solar water heater increases the fresh water productivity of the still. The glass cover cooling technique increases the productivity to 65% higher than the conventional still. The productivity can also be integrating aluminum filling as simple solar energy system beneath the absorber plate 53% higher than the productivity of conventional still.



schematic diagram of the experimental setup

Fig 10: Schematic diagram of the experimental setup single slope passive solar still (conventional still) and stepped active solar still

The conventional still and the stepped solar still are used simultaneously and the experiments are conducted at the same conditions. The schematic view of the experimental setup is shown in Fig 11. Kabeel has said that concave wick surface was used for evaporation, whereas four sides of a pyramid shaped still were used for condensation, [33]. A basin type double slope solar still with mild steel plate was fabricated and tested with minimum mass of water and different wick materials like light cotton cloth, sponge sheet, coir mate and waste cotton pieces in the basin both the stills use saline water [34]. The vacuum tube solar collector is use to vary the feed water temperature. The influence of depth and width of trays on water the performance of the stepped solar still is investigated. A wick is added on the vertical sides of the still for the further yield. The experimental and theoretical results are observed.

The results of the stepped and conventional still the following condition can be drawn:

- The productivity can be obtained by pre-heating the feed water of the stepped solar still while the efficiency reduces approximately to half.
- Increase in water depth decreases the productivity of the still.
- The augmentation of the daily productivity of the stepped still by using a wick on the vertical sides from 3 to 5 %.
- The higher performance can be achieved at the depth of 5 mm and width of 100 mm.
- The daily efficiency and the estimated cost per litre of distillate is approximately 53% -0.039$ for both the stills.

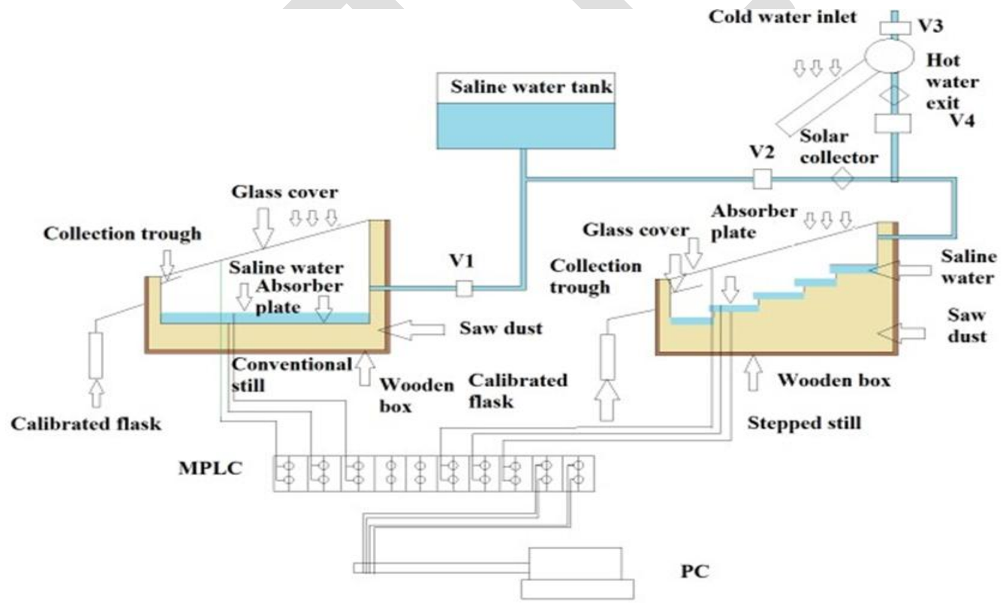
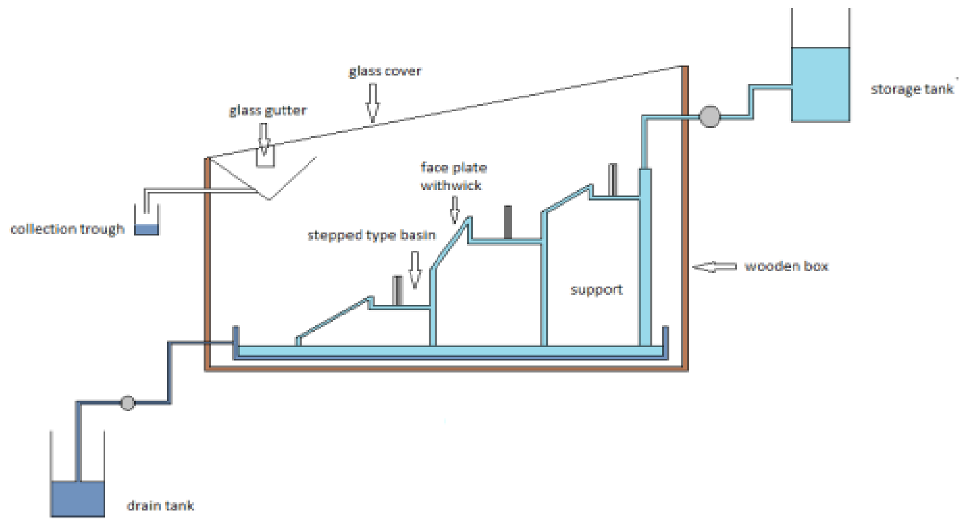


Fig 11: Schematic diagram of the experimental setup conventional still and the stepped solar still

The concept of integrating stepped solar still along with inclined flat plate collector is introduce in this research work. Abdel-Rehim and Lasheen used the oil heat exchanger to preheat the saline water inside the solar still and got 18% increase in productivity [35]. Aybar et al tested the absorber plate with black cloth, wick materials and the experimental results showed an increase in the fresh water generation rate by two to three times more than the conventional system [36]. Suleiman studied the effect of water depth on productivity and their experimental results showed that a higher productivity of 6.7 L/day was obtained for a low water depth [37]. The experimental setup is shown in Fig 12.The experiments were conducted with some modifications which are listed below.

- The stepped tray is maintained at the constant depth of 2 cm and the conventional basin at the different depth of 2 cm, 3 cm and 4 cm.Wick is packed with different packing materials namely wooden chips, coal and is placed on the infinite flat plate collector.
- Sponges are used to increase the free water surface area and the capillary effect in the conventional basin and steppe trays. In this work 12 sponges of 12.5, 6.5,8 cm^3 and 24 sponges of 4.4.4 cm^3 are placed on the stepped still and conventional basin. The volumetric ratio of 20% is maintained between the sponges & water.
- Rocks and pebbles are placed on both the stepped tray and conventional basin. For improving the evaporation rate, the two basins are constructed along with an inclined flat plate collector. Maximum productivity of 1468 kg/cm^2 was obtained for 2 cm water depth and lowest production of 1150 kg/m^2 at 4 cm water depth with sponge's combination



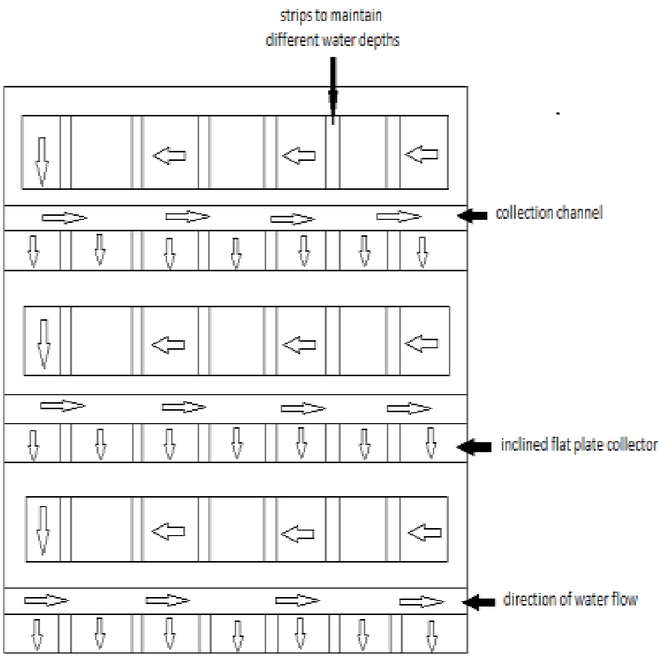


Fig 12: (a) Sectional views of the stepped type solar still. (b) Top view the stepped type basin

SOLAR STILL WITH INTERNAL REFLECTOR

This paper discuss the modification and comparison study of stepped solar still through internal reflectors with the conventional still to evaluate the performance of the desalination systems under the same climatic conditions. The various factors affecting the productivity of solar still are solar intensity, wind velocity, ambient temperature, water–glass temperature difference, and free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water. Reflectors are used to maximize the yield of the solar still. Monowe et al designed a portable thermal–electrical solar still with an external reflecting booster and an outside condenser results show that the efficiency of such still could be up to 77% if the preheated saline water is used for domestic purposes, and it could be up to 85% if preheated saline water is used to operate the still during night times and to recharge the still by the next batch of preheated water [38]. Tanaka analyzed theoretically a basin type solar still and a tilted wick solar still with flat plate external bottom reflector [39, 40]. The solar intensity, wind velocity, ambient temperature cannot be controlled as they are metrological parameters, whereas the remaining parameters can be varied to enhance the productivity of the solar stills. When sponges, fins and pebbles are used in the basin, the maximum productivity is reported to be 98%. A wick is added to the vertical sides of the still in which the daily productivity is augmented approximately 3% to 5%. The analytical results are obtained by solving of the energy balance equations for the absorber plate, saline water and glass cover of the solar still. The saline water temperature, basin plate temperature and glass cover temperature can be evaluated at every instant. The following assumptions were taken into consideration:

- Steady state conditions throughout the solar still.
- The solar still is vapor leakage proof.
- Make up water is at atmospheric temperature and takes heat from basin.
- Heat loss from the side of the still is negligible.

The thermal performance of the stepped solar still is investigated by adding the mirrors on the vertical sides of the steps and the productivity obtained is approximately 75% and 57% with and without internal mirrors which is higher than that of the conventional still.

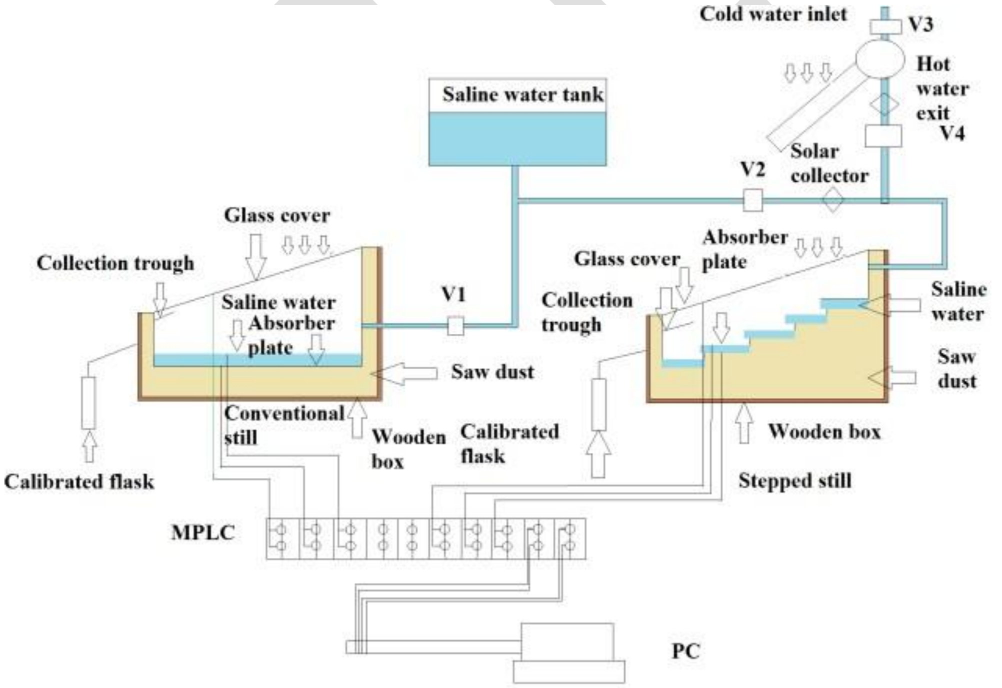


Fig 13: Schematic diagram of the experimental setup stepped solar still through internal reflectors with the conventional still

Issue 7, Vol. 3 (May 2017)
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This study investigated the effect of an internal reflector (IR) on the productivity of a single-slope solar still (during the summer and winter) experimentally and theoretically. Fig 14. Illustrates a schematic view of a single slope solar still. El-Swify et al added IR's on the back and sidewalls and concluded by using mathematical models and conducted experiments that the distillate increase of 82.6% and 22% was obtained during winter and summer respectively when using IR's [41]. Khalifa et al experimentally examined the performance of a basin-type solar still with IRs and ERs from June to December and concluded that using IRs increased the yield by the average of 19.7% during this period [42]. Tanaka H et al By reflecting the extra solar radiation, ERs increase both brine and glass temperatures which can even decrease the distillate production of a still with both IRs and ERs in comparison with one with only IRs [43].This model was suggested to calculate the yield of stills using IR's installed on the various walls. The result revealed that the installation of IR's on the front and side walls increased the efficiency of the still by 18% and at the back walls installation was around 22% on average basis during the same year.
Nevertheless, the effect of utilizing IR on the back wall varies during various months and the maximum and minimum percentage increases in the distillate production after using IR are in December and June (12th and 6th months) and their values are about 46.7% and 3.3%, respectively. In addition, installing IR on all walls can enhance distillate production during the winter, summer and entire year by 65%, 22% and 34%, respectively. Furthermore, the effect of cloud factor on the installation of IR was investigated and it was revealed that as the cloud factor increases, the effect of utilizing IR decreases significantly, when the sky is completely cloudy (CF = 1), using IR improves the production by about a constant value of 18% for a year. In brief, since the capital cost of IRs is low and their use incurs no operating cost, their installation is proposed to increase still productivity, especially in regions with high latitude and low cloud factors.

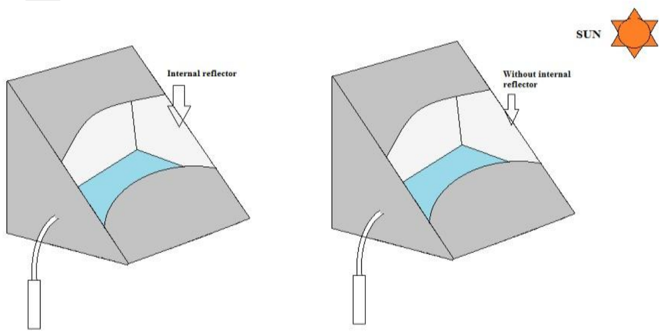

Fig 14: Current experimental set-up

SOLAR STILL WITH MINI SOLAR POND

Freshwater is one of the Earth's most valuable renewable resources. To preheat the saline water, a mini solar pond was integrated with these stills. Both the stills were operated with mini solar pond and tested individually. A.A.El-Sebaii et al the daily efficiency of the solar still is increased by 85.3%, when phase change material was used as storage medium [44]. A.A.El-Sebaii et al the daily productivity of the single basin solar still was increased by 52.4%, when a shallow solar pond was integrated [45]. K.Vinoth Kumar et al an improved condensation technique in solar still was presented and a performance study was carried out with different samples such as tap water, seawater and dairy industry effluent [46]. The schematic diagram of the experimental set up is shown in the Fig 15.

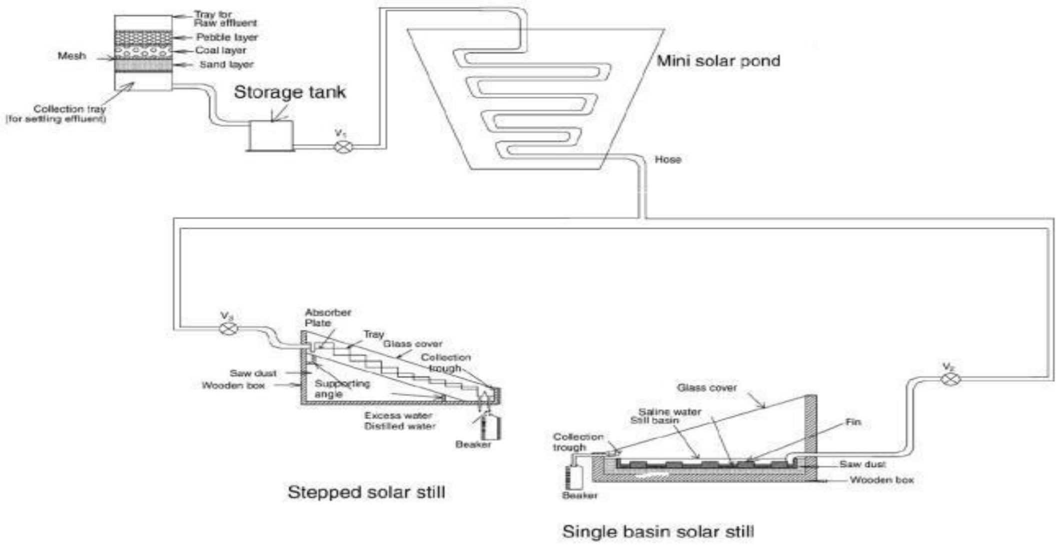

Fig 15: Schematic diagram of the experimental set-up of mini solar pond

Solar pond coupled with fin type stepped solar still and pebble and sponge in the basin

Combination of fin, pebble and sponge were tried in the stepped solar still. For preheating the saline water, solar pond was coupled.

Solar pond coupled with fin type single basin solar still

Introduction of fins enrich the contact surface area and thereby reduces the preheating time required for the saline water. In this work, 5 fins with height, length and breadth 35 mm, 900 mm and 1 mm respectively were used. Also mini solar pond was integrated with this still.

Solar pond coupled with fin type single basin solar still with sponges in the basin.

To increase water exposure area, sponges were used in fin type solar still and were integrated with a mini solar pond. In this experiment, 450 sponges of size 20×35×35 mm^3 were used. Due to capillary force, sponges absorb more water and water exposure area increased. Hence productivity increased.

Solar pond coupled with fin type stepped solar still and pebble in the basin

In addition to the fins similar to the previous section, pebbles were used to enhance the productivity of the stepped solar still. As pebble's sensible heat storage was very high, the duration of evaporation rate can be increased.

Solar pond coupled with fin type single basin solar still and black rubber in the basin

Black rubber was used in the fin type solar still and was acting as a heat storage medium. It absorbed more solar radiation and the preheating time for the saline water got decreased. Thus the productivity of the solar still enhanced.

Solar pond coupled with fin type stepped solar still and sponges in the basin

Sponges with fins were used in the stepped solar still and integrated with solar pond.

Solar pond coupled with fin type single basin solar still and sand in the basin

As sand being as a sensible heat storage material, it was used in the gap between the fins. The productivity increases due to increase in sensible heat. Also the solar still was integrated with a mini solar pond. Other experimental procedures are similar to the previous Section.

Solar pond coupled with fin type stepped solar still.

The productivity of the solar still increases with increasing basin area. To increase the basin area, fins are attached in each tray. Nails of diameter 1 mm and length 5 mm are used as fins. About five numbers of nails are welded in each tray of the stepped solar still. There are such 50 trays with 250 numbers of fins were used to increase the absorber surface area. The diameter and length of the fins were 1 mm and 35 mm respectively.

Solar pond coupled with fin type single basin solar still and sand and sponge in the basin

Apart from integrating a mini solar pond, similar to the Sections 3.3 and 3.4, sand and sponges were used in the saline water of the fin type Single basin solar still. Around 450 sponges with a size 20×35×35mm were made to float over the water surface and sand was placed in Between the fins.

The thermal energy stored by the mini solar pond is used to preheat the saline water and the experiments are carried out with different salinity in the fin type single basin and stepped solar stills was found that the optimum value of mini solar pond was 80 g/kg . Solar stills uses industrial effluent as raw water and the effluent settling tank was designed and fabricated to settle the effluents. Individually the mini solar pond was integrated with the single basin and stepped solar still and the performance was calculated. The productivity was enhanced by some modifications in the single basin and stepped solar stills. The results shows that the maximum productivity was obtained while modifying stepped solar still with pebbles and sponges. It was found that the productivity increases with increase in solar intensity and water-glass temperature difference and decreases with increase in wind velocity. Economic analysis was made. The payback period of the set up was 417 days.

A single basin solar still, stepped solar still and a mini solar pond was connected in series to enhance the productivity. The construction is simple by using locally available materials and it does not require skilled person. This experimental set up, a mini solar pond, a stepped solar still and a single basin solar still are connected in series as shown in the Fig 16. For augmenting the evaporation rate of industrial effluents, Srithar and Mani developed a pilot plant with an open fiber reinforced plastic (FRP) flat plate collector (FPC) and spray network systems and their performances were analyzed [47]. A wick basin type solar still was designed by Minasian and Al-Karaghouli. The wick basin type produce 85% more than the basin type and 43% more than the wick type solar still [48]. Tanaka and Nakatake presented a theoretical analysis of a titled-wick solar still with an inclined flat plate external reflector and proved that the daily amount of distillate of a still with an inclined reflector would be about 15% to 27% greater than the conventional still [49]. In the second type of experiments, the single basin solar still is slightly modified with a reservoir and a wick. The wick type solar still is connected with the stepped solar still as shown in Fig 16. The wick sucks the water from the reservoir due to capillary action and maintains uniform minimum depth over the inclined basin. The effluent is evaporated and condensed easily as minimum depth is maintained at the inner side of the glass cover. Pebbles, baffle plates, fins and sponges are used in the stepped solar still for further productivity augmentation. The productivity during day and night are calculated. It is found that maximum productivity of 78% occurred, when fins and sponges are used in the stepped solar still. Pebbles store more thermal energy and releases after the sun set. So, more night productivity is obtained, when pebbles are used in the solar stills. Industrial effluent is used as feed.

Theoretical analysis gives very good agreement with the experimental results.

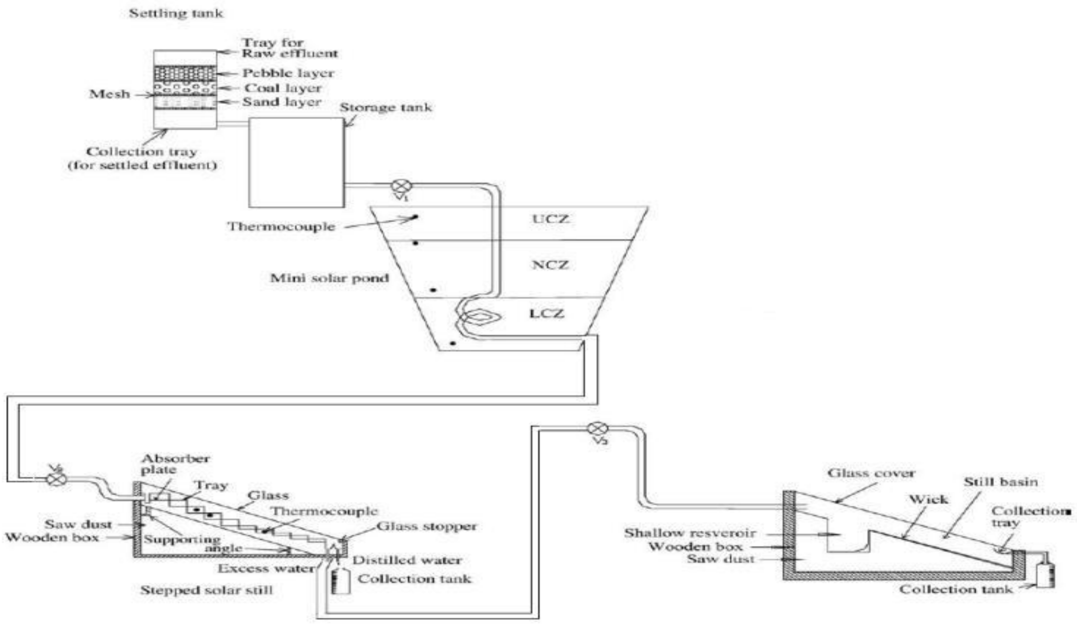

Fig 16: Combination of stepped solar still and wick type solar still with solar pond

SOLAR STILL WITH SINGLE BASIN

The orientation and inclination are optimized to receive maximum radiation .To enhance the evaporation rate different materials are used in basin along with water. Rubber is the best basin material to improve heat capacity, absorption the evaporation rate. The performance of a solar still with different size sponge cubes placed in the basin was studied experimentally as shown in Fig 17.

From the above review on single basin passive type solar still, the different methods used to improve the productivity are listed below.

- The orientation of the glass cover depends on the latitude of the place. For northern latitude south facing and southern latitude north facing stills are used.
- For lower latitude places double slope stills are preferred with south–north orientation.
- The inclination of the cover is optimized for rate of condensation of water on the bottom surface of the cover and to collect it without the mass accumulated drops fall back into the basin. Hence it depends on the intensity of solar radiation, rate evaporation and condensation, material used for cover and its wetting property.
- Glass is most suitable material for cover. It has the properties such as higher transmittance, wetting property with water to have less transmittance loss for solar

radiation during condensation, higher thermal conductivity and stable transmittance during continuous exposure to sun radiation for long period. Other plastic material lacks in above properties.

- The day-time and night-time productivity greatly depends on depth of water and heat capacity of the basin.
- For lower sun radiation intensity places shallow basin still is preferable.
- For higher sun radiation intensity places deep basin still is preferable to improve nocturnal Production.
- To improve the absorption and surface heating effect black dye is most suitable with deep basin still.
- Other basin materials like rubber, gravel, glass sand, saw dust and sponge are having the properties of absorbing and storing of solar radiation in different proportions along with increasing the exposed area for evaporation of water.
- Rubber is the best basin material to improve absorption, storage and evaporation effects.
- Surface heating of water mass along with higher heat storing improves day-time and night-time production.
- Mica sheet as suspended absorber is better material for surface heating.
- To reflect the solar rays falling on the side walls of the still onto the basin reflecting mirrors are fixed one the side walls. This increases the insulation effect also.
- To increase the area for condensation, to avoid production loss by falling back of water drops back into basin from glass lower surface and to receive the solar rays close to normal always solar still with built in condenser is preferred.
- The last method eliminates most of the draw backs in the conventional still and gives better result.

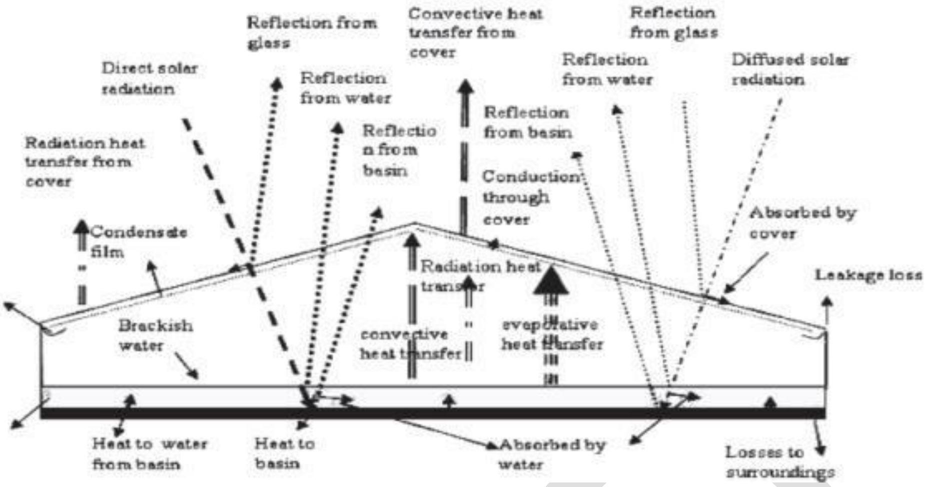

Fig 17: Energy flow diagram of a basin type still.

Out of all water on the earth, only 3% is the fresh water in which 1% is consumed by humanity and the rest is covered in the polar ice in the form of glaciers, ice and snow. Jordan Authority utmost planned for the development of water supply in the future by desalinating the saline water into potable water by exploiting the arid areas. The design modifications involved were: (a) fixing interior reflecting mirrors, (b) manufacturing a step-wise water basin instead of a flat basin, and (c) coupling the step-wise solar still with a sun tracking system. First of All, the performance of the traditional still design was evaluated as reference to measure the improvements due to new modifications. The traditional single slope solar still has an inclined top cover of 32E (Fig.18.1) made of glass (4 mm thickness), with an interior surface made of a water proof membrane. In order to minimize the loss of energy, the reflecting mirrors are added inside the walls of the still. Hiroshi Nakatake and Yasuhito Nakatake found that the addition of internal and external reflectors increases the distillate productivity for the entire year around 48% [50]. Fig 18.2 represents the new modified design for the basin. It has a step-wise shape to replace the common flat type basin. The new basin shape provide an extra 40% of the contact surface which will definitely provide more heat and mass transfer area. Finally, Fig.18.3.illustrates the complete designed system in three dimensions where it shows the solar still with step-wise basin coupled with a sun tracking system. The modification design of the still shows the considerable improvement on the performance. Modifying the still design from a flat basin into step-wise basin gave a higher production rate with an average increase of 180%. Also,

Issue 7, Vol. 3 (May 2017)
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coupling the modified still design with a sun tracking system gave further improvement, reaching up to a 380% increase in the production rate of distilled water. The still design modified from a flat basin into step-wise basin improved the production rate to 180% and the coupling of still design with sun tracking system increases the distillate water productivity to 380%. It can be utilized for industrial applications for economical bulk production of distilled water for battery charging, chemical laboratories, educational institutions, and for gas station services.

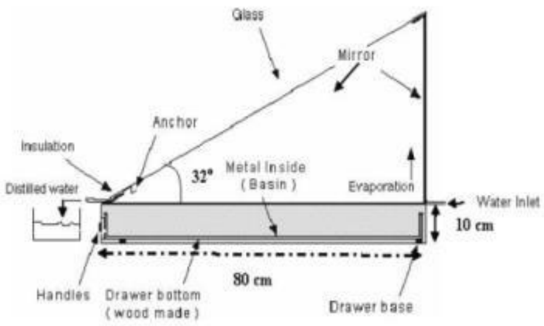


Fig.18.1 Schematic diagram of a single slope solar still

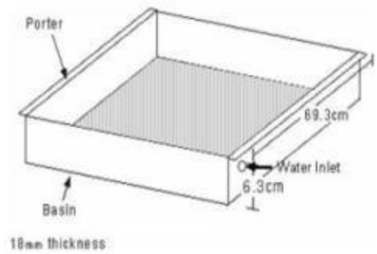


Fig.18.2 Perspective view of the solar still basin

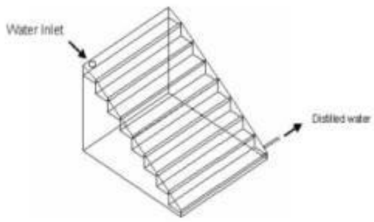


Fig.18.3 Isometric view of the step-wise water basin

SOLAR DESALINATION

Solar desalination is the one of the cheapest process in converting the brackish water into pure fresh water. Solar stills are widely used in desalinating process. Many research works are carried out to enhance the productivity. An ordinary basin type solar still integrated with fins at the basin plate is used for experimentation. The experimental setup consists of an effluent settling tank, a storage tank and a single basin solar still as shown in Fig 19. Modifications are made to augment the evaporation rate of the fin type solar still. The productivity rate increases with the increase in temperature as fin type acts as the extended surface.

Fin type solar still with sponges

The free surface area of the water in fin type solar still is $0.9955m^2$. To enhance the productivity, sponges are also used. About 450 sponges with a size 20 mm height, 35 mm length and 35 mm breadth are used. The sponges are floated with 20% volumetric ratio. Due to the capillary action sponges suck water on the top exposure area. Hence, the exposure area of the water increases to 1.3105 m^2. Thus, more water is exposed to solar radiation, which increases the productivity.

Fin type solar still with pebbles

Sensible heat storage materials like pebbles are used in this modification to increase the temperature of the water. Though they used black gravel in single basin solar still, In this work; pebbles are used in fin type single basin solar still. Pebbles absorb more energy due to its highest volumetric heat capacity. Thus, the temperature of raw water increases when they are used in stills.

Fin type solar still with black rubber

It used black rubber in the single basin solar still to enhance its productivity. In this work, five numbers of black rubbers are properly cut and placed in between the fins. The thermal energy of the basin water increases when black rubber is used in the solar still.

Fin type solar still with sand

To enhance the productivity of the solar still, sand is used. When sand is used in between the fins, the temperature of water increases due to increase in sensible heat of sand. Thus, productivity increases.

Fin type solar still with sand and sponges

In this modification, sand and sponges are used together to enhance the productivity.

Modifications in still

Simulation work is also extended for the following modifications in the solar still.

Fin type solar still with sponges

In the area of the basin plate and area of the free surface water are taken as 1.18 and 1.3105m^2 on account of the inclusion of fin and sponge exposure area. Now, the mass of the basin plate (mb) with fin is taken as 8.5 kg. The volumetric ratio between sponge and water is maintained as 20%.

Fin type solar still with pebbles

Surface area of the base is taken as 1.18m^2. The saline water surface area is reduced to 0.9955 m^2. The mass of the pebble taken for experimentation is 10 kg. The density and specific heat of the pebble are taken as 2700 kg/m^3 and 800 J/kg K, respectively.

Fin type solar still with black rubber

The mass of the black rubber is taken as 0.4 kg. In this analysis, in Eq. (1), in addition to the heat capacity of the basin plate (mbCpb), the heat capacity of the black rubber (myCpy) is also added. Density and specific heat of the black rubber are taken as 1200 kg/m^3 and 1382 J/kg K, respectively.

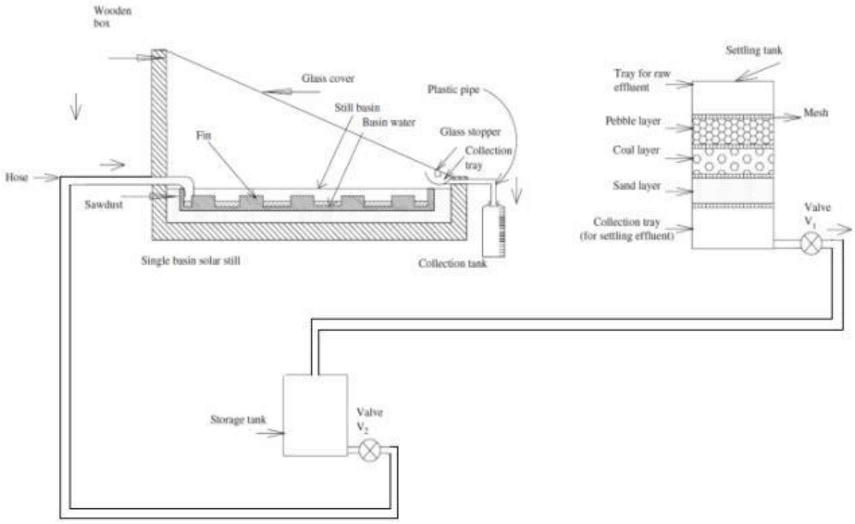


Fig 19: Schematic diagram of the experimental setup

Fin type solar still with sand

Theoretical simulation for this modification is very similar to the previous sections. But the area of the basin is taken as 1.0685m^2. Four kilograms of sand is taken in the still. The heat capacity of the sand is included with heat capacity of the basin plate. Density and specific heat of the sand are taken as 1500 kg/m^3 and 796 J/kg K, respectively.

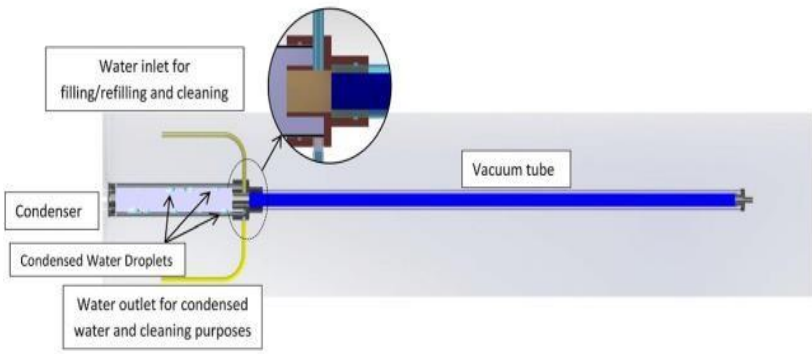
Fin type solar still with sand and sponges

In this modification, the area of the free surface water and basin are taken as 1.3105 and 1.0685 m^2. The heat capacity of sand is added with the heat capacity of the basin plate. The heat capacity of the sponge is considered as negligible. Other equations are similar to the previous sections.

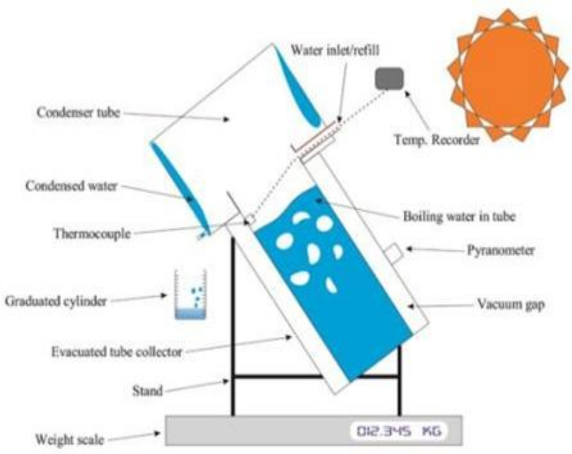
A new passive solar desalination system which has twin- glass evacuated tube collectors is introduced in this work. The twin glass evacuated tube collector is used as a solar thermal collector and also as a basin to heat the water. Hence, the thermal resistance between the collector and basin is virtually eliminated. A picture of the experimental setup, a schematic of the tube collector, and a schematic of the system and attached measurement devices are shown in Fig.20.(a), (b), and (c) respectively. The following assumptions are made for the thermal analysis:

- The heat transfer process is quasi-steady state.
- The temperature gradients in the longitudinal and rotational directions are neglected.
- The change of the physical properties with the temperature is negligible.
- The changes of boiling heat transfer coefficient by changes of tube angles are neglected, and the effect of the inclination angle on the condensation rate is captured by modifying the effects of gravity forces in the corresponding equation [51].
- The saturation temperature for the model is assumed to be constant as 97 °C based on boiling phenomenon observed around midday Hours.

(a)



(b)



(c)

Fig 20: (a) Picture of the experimental setup, (b) schematic of the tube (c) schematic of the system and attached measurement instruments (not to scale).

The innovation of using evacuated tube collector (ETC) to directly transfer the heat to the salty water improves the performance of the desalination system. Innovating ETC'S to transfer the heat directly to the salty water and eliminating the need for separate basin, enhances the highest rate of production to 80% when filled with water in the tube, increases the efficiency of absorbed solar radiation and reduces the heat losses in the surroundings while the lower filling ratios affect the heat transfer in the tube. When the tube is filled with stainless steel wool (SSW), increase in the thermal conductivity and decrease in the convective heat transfer of the system takes place which enhances the rate of heat transfer. The effect of the inclination angle of the ETC on the performance was also investigated. It was shown that decreasing the inclination angle decreases the performance of the system and the optimum inclination angle is 35°c, which is the latitude of the location of experiments. The yield is decreased when there is deviation in the optimum inclination angle. It was shown that for a system with SSW and inclination angle of 35°C for 25 years of operation, the CPL value is as low as 0.0134 $/l/m^2. Finally, proposed theoretical results were compared to the experimental data obtained around solar noon. This comparison presented a good agreement, indicating that the model is suitable for the proposed analysis.

CONCLUSION

The various research work done on solar stills to improve its productivity are reviewed. The concluded results are shown below. Stepped solar still enhances the productivity rate when there is increase in the water temperature and while using wicks on the vertical sides of the still. Solar still with LHTESS is preferred for sunny days due to its low cost and simple construction. Solar still without LHTESS is preferred for cloudy days due to its higher productivity and stable condition during climate changes. Maximum productivity and efficiency of the still is obtained when cheap material like jute cloth is used. The appropriate influencing parameters should be selected to improve the performance of the still. Baffle plates, sponges and pebbles are used in the basin with internal reflector to enhance the productivity. A step wise basin type solar still integrated with a sun tracking system provides a potential on high performance solar still. Wicked type solar stills, a water purifier and stepped solar still were developed to maintain the minimum depth.

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