SOLAR STILL TECHNOLOGY AND POTABLE WATER SUPPLY IN REMOTE AREAS: A REVIEW

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A review of solar still technology and potable water supply in remote and developing areas is presented. Considering the number of condensation surfaces, solar still's operation is grouped as single-effect condensation and multi-effect condensation. Each of these groups could either be passive or active depending on whether the solar still's operation is self-reliant (for passive), or is assisted by external energy sources, in other words, subjected to a forcing function (for active). The performances, applications and influential factors for the selection of solar still designs are reported. Solar stills with multi-effect condensation generally have improved freshwater yield compared to solar stills with single-effect condensation. This is due to the application of the latent heat of condensation in the subsequent effects. Similarly, active solar stills have improved freshwater yield and efficiency compared to passive solar stills. They are also more complex in design compared to passive solar stills due to the configuration of the system. Accordingly, active solar stills with multi-effect condensation are better suited for commercial applications and areas with high load demands. On the other hand, passive solar stills with single-effect condensation are simple in construction and easier to install thus, they are better suited for domestic applications and areas of low and medium load demands. To further improve the performance of existing solar stills, more research work is necessary to enable them compete favourably with conventional distillation systems as a viable alternative.

KEYWORDS: Solar still, Single-effect condensation, Multi-effect condensation, Phase change materials, passive, active

1.0 Introduction

World health organization (WHO) estimates, show that about one billion people (13% of world population) mainly in the developing countries have little or no access to potable water [1]. This statement implies that potable water scarcity is a major global challenge. Factors severally implicated for this problem include population explosion, global warming, pollution of surface water, emptying of none regenerative ground water reservoirs, industrialization, virtual water, etc. Global warming, in particular has been in the front burner in the past two decades. Since the dawn of the industrial age, the levels of carbon (IV) oxide (greenhouse gas) emission into the atmosphere have increased steadily due to human activities, especially burning of fossil fuels and expansion of agriculture in the form of land clearing. The earth's surface is about seventy percent water [2]. Ninety seven percent of the world's global water resources are saline water while two percent are freshwater. Seventy percent of the global freshwater resources are stored in glaciers and polar ice [3]. The continuous rise in temperatures due to the emission of greenhouse gases, have resulted in the melting of this stored form of freshwater. This has led to the increase in the amount of ocean water and thus, contributing to freshwater scarcity.

Potable water supply is a major challenge in remote areas of the world especially, the rural areas in Africa. This is hampered by inadequate funding, poor maintenance culture, insufficient data for planning, lack of professional participation and overbearing bureaucracy on the part of government. The daily potable water requirement of an average adult is between 50 to 100 liters [4]. The access to potable water is defined as the provision of at least 20 liters of potable water per person per day from a source not more than one kilometer from the user's residence [5]. Therefore, people experiencing a daily limit of 20 liters of potable water per person will be exposed to serious hygienic and health concerns. Rural dwellers usually experience worse economic conditions compared to urban dwellers and as such have limited access to potable water supply. The importance of water to man cannot be overemphasized. This is because of its numerous applications like cooking, bathing and drinking, manufacturing and agricultural activities. Apart from its uses by humans, plants and animals also depend on it for survival. Different water qualities are required for different purposes or applications. For instance, water quality required for drinking may not need to be same with that used either for bathing, manufacturing or agriculture. Unfortunately, the quality of water sources in their present form is not good enough for drinking hence the concerns and efforts by international bodies like WHO and UNESCO to ensure safe and potable water is made available to all. Different approaches/processes or a combination of processes are employed to achieve potable water, considering the nature of the source water.

Distillation (evaporation) is one of such approaches where water is evaporated and subsequently condensed. The condensate, which is now free from impurities contained in the source, is cooled and collected. Heat for the evaporation could come from any heat source. When the heat source is solar, it is called solar water distillation system or solar still. Solar water distillation is a simple technology that has been in existence since 1551 when it was first introduced by Arab alchemists [6]. Its most common use in water purification is in desalination: a process of producing freshwater from saline water thereby, leaving the salt behind. The ancient Greeks used evaporation to produce drinking water from seawater. Desalination technology was used during the Second World War to convert saline water to usable water because of the acute scarcity of fresh water [7]. Solar still is very safe, cheap and environmentally friendly means of desalting water. Considering the abundance of solar radiation, solar stills have great potential for application in remote locations with salty streams and without grid connected electricity. There are several reported works on different solar still designs with different degrees of efficiency.

Solar still's operation is broadly grouped as: single-effect condensation and multi-effect condensation. The single-effect type is commonly associated with conventional solar stills. It comprises a single basin with a blackened base and a greenhouse air tight glazing that encloses completely the space above the basin. In the same vein, the multi-effect type comprises more than one basin with glazing for each basin. The lower glazing (which also serves as the base of the adjacent basin) allows the passage of radiation to the lower basin. Solar stills with multi-effect condensation utilize the condensation effect from the lower basin as well as the absorbed solar radiation, to heat up the saline water in the adjacent basin thus, improving the freshwater yield better than solar stills with single-effect condensation. Solar distillation systems could also be grouped as either passive or active system depending on the nature of the system's configuration.

Several design and performance parameters that influence the productivity of solar distillation systems have been reported. These parameters are grouped as environmental and operational parameters. The control of environmental parameters is beyond our reach and they include: wind velocity, solar radiation intensity, ambient air temperature, and relative humidity [8]. On the other hand, operational parameters include: basin water depth, glazing-water temperature difference, absorber plate area, humid air height and inclination angle of the glazing etc. Researchers have made effort in the improvement of freshwater production of solar stills through variation of operational parameters. Examined are, the different solar still designs, their performances, and the extent of their commercialization while proffering solutions that could improve overall deployment.

2.0 Solar distillations systems

2.1 Single-effect condensation.

This system of operation is associated with solar still designs of single basin with one-layer of glazing over the saline water surface. They experience more thermal energy losses compared to multi-effect type due to the underutilization of the latent heat of condensation released at the underside of the glazing. This energy is lost through the glazing to the ambient environment. This system can either be passive or active depending on the design configuration.

2.1.1 Passive solar distillation systems

(a) Basin-type

This design comprises a shallow basin with a blackened base contained in an insulated structure covered with a sloping condensing cover. The basin holds the saline water while the condensing cover transmits radiation for the evaporation of the saline water inside the basin. The efficiency of a solar distillation system as a performance parameter is defined as the ratio of the heat flux transferred by evaporation to the total radiation flux received by the absorbing surface of the system [9]. The application of conventional solar distillation system was first recorded in 1872 in Las Salinas, northern deserts of Chile by Charles Wilson: a Swedish engineer [9]. The system was constructed from wooden bays with blackened bottom and was in operation for forty years. It had a total distillation area of 4,700m^2 and a production capacity of 4.9kg/m^2 [10]. This represents more than 23,000 liters of freshwater yield per day. Mehta et.al. [11] designed a basin-type solar still for the purification of brackish water, using absorber material of high absorptivity, less reflectivity, and less transmittivity. The schematic diagram of the setup is shown Fig.1. The system recorded a daily freshwater yield of 1.85 L/m^2 with total dissolved solids (TDS) of 81ppm and an efficiency of 64.37%.

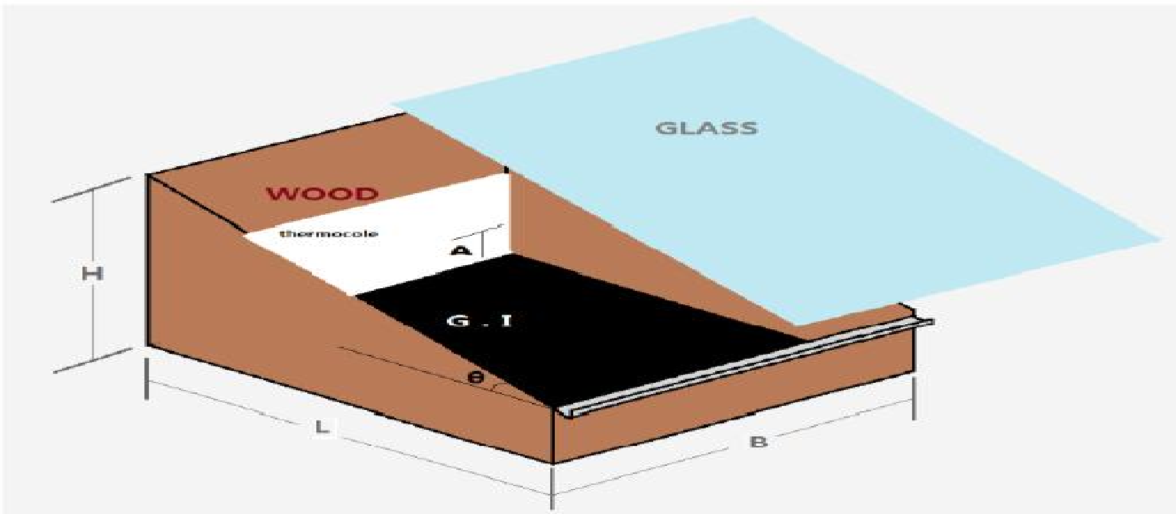

Figure.1: Model of solar still used by Mehta el.al. [11]

Eze and Ojike [12] compared the performances of two passive solar stills with different condensing cover geometries. The first solar still had a rectangular-shaped cover and the other, had a pyramidal-shaped cover. Each of the solar stills had its condensing cover inclined at 22^0 to the horizontal. The inclination was about 15^0 more than the latitude of Nsukka (the test location). The solar still with a rectangular-shaped condensing cover had a higher absorber and saline water temperatures with lower cover temperature compared to the solar still with a pyramidal-shaped condensing cover. Overall, the solar stills recorded mean efficiencies of 36.8% and 28.9% for rectangular-shaped and pyramidal-shaped condensing covers respectively. Ugwuoke et al. [13] designed and tested the performance of a pilot solar water purifier made with glass fiber structure. It had a reservoir for purified water and a raw water evaporation pan. The raw water level was maintained at 1cm and the solar still inclined at 15^o to the horizontal. The solar still was tested at Nsukka, Nigeria from November 2013 to December 2013. The maximum and minimum distillate recorded on the 4th day of the experiment were 1.1 liters at 14 – 16 hours and 0.2 liters at 08 – 10 hours respectively. Badusha and Arjunan [14] carried out a three-dimensional performance simulation of a single slope solar still with the aid of ANSYS CFX. They adopted a two-phase model for the evaporation and condensation processes inside the system. From their investigation, they concluded that ANSYS CFX was a good tool for design and parametric analysis of solar distillation systems.

(b) Wick-type

This class of solar still uses a wick material as part of its absorber. The saline water is passed through the wick at a slow rate by capillary action. The saline water trapped in the wick material absorbs the incident solar radiation and as such, gets evaporated and later condenses at the cooler underneath of the inclined glazing and eventually gets collected in a distillate container. Considering the slow rate of saline water absorption by the wick material, it offers more exposed surface area for evaporation and low saline water thermal capacity. Thus, the saline water heats up faster with subsequent improvement in performance. Mahdi et al. [15] developed a model of an inclined wick-type solar still using a charcoal cloth. The performance was evaluated using different salt concentrations at different indoor and outdoor conditions. They observed that as the salinity increased, the efficiency of the solar still for both indoor and outdoor conditions decreased. The effect of salinity was less in the case of outdoor condition compared to indoor condition. The solar still recorded an output efficiency of 53%. Sengar et al. [16] designed a wick-type solar still with an absorber sandwiched between the wick strips. The absorber had an area of $1m^2$ and was made from a corrugated galvanized iron sheet. The system was tested for different condensing cover inclinations in winter and summer months. The system recorded an average daily yield of $2.3L/m^2$ and $3.4L/m^2$ in winter and summer periods respectively. The maximum yield was recorded at an angle of $40^0 48^1$ in winter period. Efficiencies of 47.14% and 56.29% were recorded in winter and summer periods respectively. Suneesh et al. [17] conducted a performance analysis of a V-shaped solar still with a corrugated wick and a drip system. The solar still recorded an average distillate yield of 2.2 L/m^2. A similar setup with a plane wick recorded an average yield of 2.8 L/m^2. This represents a performance improvement of 27.3% for the system with plane wick. Prakash et al. [18] carried out an experimental analysis of a wick-type solar still with a pyramidal-shaped condensing cover. The saline water container with four tilted portions was placed at the center of the solar still. These portions were covered with a black jute wick material with the remaining material allowed to float on the saline water surface. The experimental setup of the solar still is shown in Fig.2.

Fig.2: Experimental setup of a tilted-wick type solar still with pyramidal glazing by Prakash et.al. [18]

The solar still recorded an average daily freshwater yield of 4.82 L/m^2 and a mean efficiency of 50.25%. It was observed that with the wick arrangement in place, the performance of the solar still improved by 17.68%. Gan et al. [19] developed a solar vapour generator using a fiber rich paper coated with carbon black as its wick material. A block of polystyrene foam was used as an insulation barrier and to enable the system float on water. Thin slits of 25 square sections were cut into this foam. They inserted 25 pieces of this paper through the slits. The foam was covered with a transparent, angled acrylic condensing cover as shown in Fig.3. The system recorded efficiency of 88% and a freshwater production rate of 1.28 kg $(m^2h)^{-1}$. With this result, they concluded that their product had achieved a performance that was 2.4 times that of the leading commercial solar distillation system.

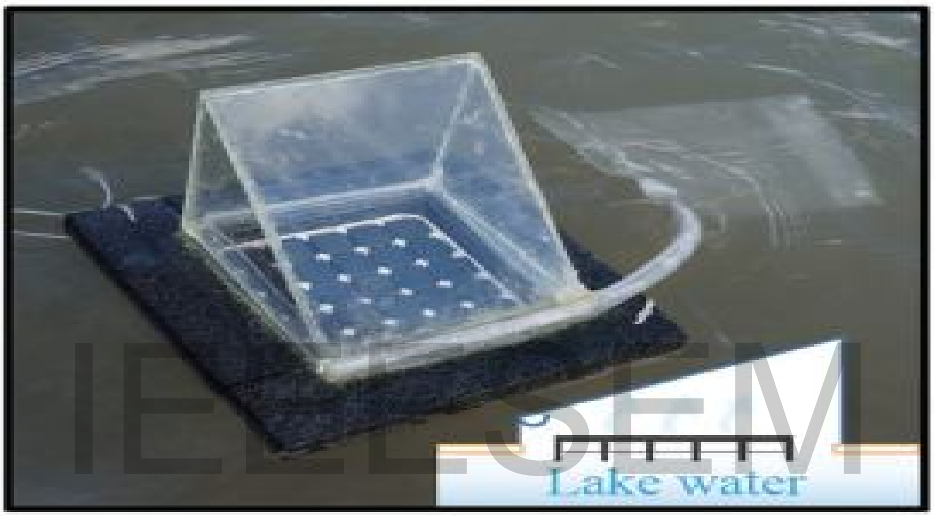

Fig.3: Prototype of the solar vapour generator by Gan et al. [19]

(c) Curved-type

Hammadi et al. [20] evaluated the performance of a passive tubular solar still (TSS) with a transparent Pyrex glass as the condensing cover. A blackened rectangular trough made from polycarbonate material was placed inside the cover to hold the saline water. The system recorded a maximum yield rate of 0.88kg/m^2hr and a maximum daily yield of 6.64kg/m^2. These values were achieved in July when the orientation was in the North-South direction; a performance they attributed to the fact that in the North-South direction, the solar radiation covered maximum area of the trough inside the solar still. Islam and Fukuhara [21] developed a set of heat and mass transfer correlations for the simulation of tubular solar stills (TSS). They took into cognizance, the thermal properties and energy exchanges in the humid air medium. The energy exchanges within and around the system is shown in Fig.4.

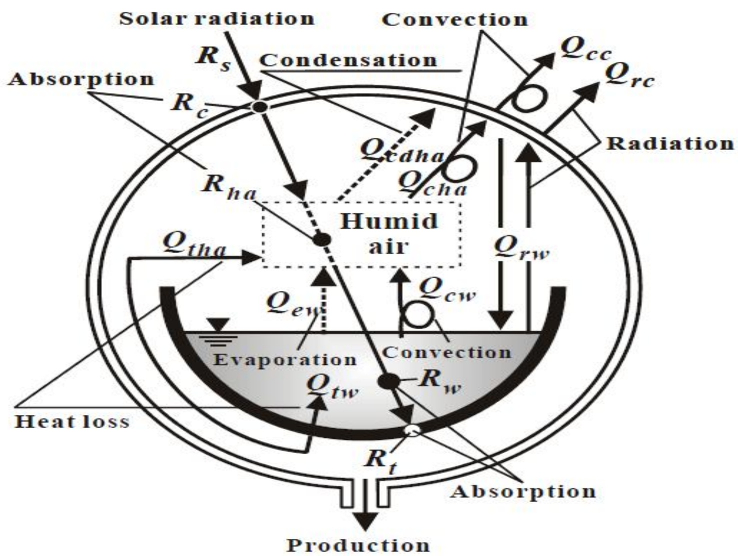

Fig.4: Mass and energy transfer within and outside of the solar still by Islam and Fukuhara [21]

They observed that the predicted results had a good agreement with results obtained from the field. They argued that the correlations for the basin-type solar still overestimated the convective heat transfer coefficient in tubular solar stills. With their results, they concluded that the performance of a tubular solar still can be evaluated with the aid of the proposed correlations. Working with ANSYS CFD, Panchal and Shah [22] evaluated the performance of a hemispherical solar still. The system had a circular basin with a black absorber plate of 0.55m^2 surface area and an acrylic hemispherical cover which intercepted solar radiation from all sides thus, eliminating the need for solar tracking system. The results obtained from the numerical analysis were compared with results generated from experimental investigation and a good agreement between them was established.

2.1.2Active solar distillation systems

A solar still is termed active if ways of augmenting the internal heat transfer processes of the system are sought. Some of the techniques of improving the performance of solar distillation systems are: preheating the incoming saline water feedstock, increasing the condensation rate, provision of vacuum, enhancement of absorber properties and the use of energy storing materials.

(a) Basin-type assisted solar stills

Eze et al. [23] constructed a solar distillation system for the purification of Lagos bar beach water. The system comprised a rectangular-shaped basin and a transparent Perspex condensing cover with a tilt angle of 22^0, facing south. A reflective mirror of area 0.18 m^2, was fitted to the side walls for an increase in incident radiation on the absorber which had a surface area of 0.6m^2. The system recorded a distillation efficiency of 36.8%. Afrand et al. [24] developed a model for estimating the performance of a basin-type solar still with an external reflector. The system had an external reflector area of 0.75m^2. From their observations, the addition of the external reflectors improved the radiation energy input into the system by 20% and the system's efficiency by 44% during peak period. For an absorber area of $0.75m^2$, the system recorded daily distillate yields of 4.6 liters and 4.3 liters for the predicted and measured observations respectively. Comparing this result to a similar work by Eze et al. [23] shows that, increase in absorber and external reflector areas, improves the radiant energy into the system and thus, increase in system's efficiency. Khalifa et.al. [25] carried out an experimental evaluation of a solar still with internal condensers. They concluded that the inclusion of the internal condensers enhanced the evaporation and condensation rates, thus the efficiency and freshwater yield were significantly improved. Bao [26] conducted a numerical evaluation of a basin-type solar still with an external condenser and a pre-heater. The flow of humid air to the external condenser was achieved with the aid of a pump. The thermal properties and energy exchanges with the humid air medium were considered. The schematic diagram of the physical model is shown in Fig.5.

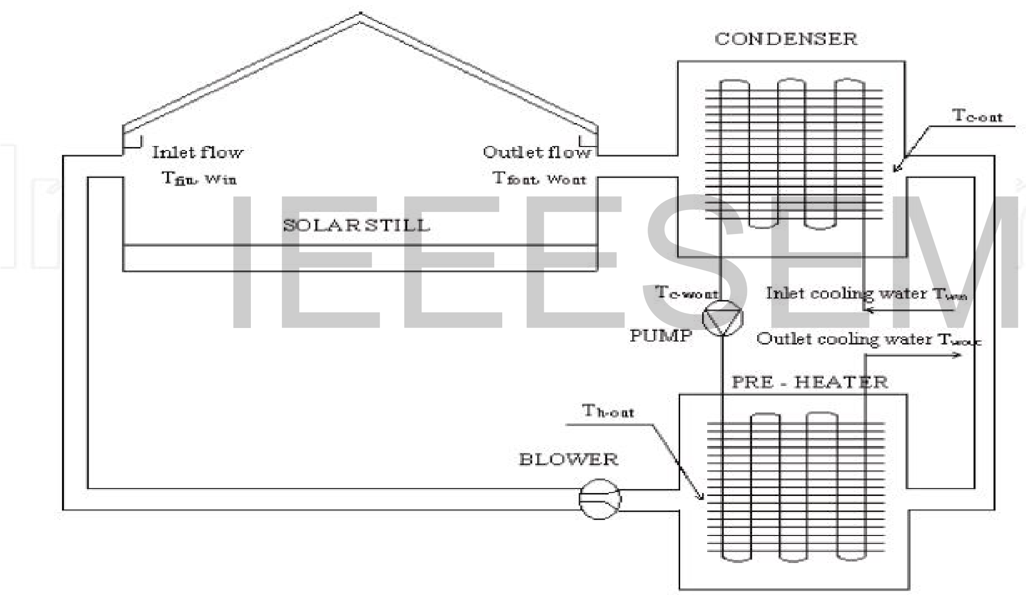

Fig.5: Schematic diagram of the modified solar still used by Bao [26]

Production of distillate occurred both at the underneath of the solar still's condensing cover and also in the external condenser. The maximum predicted and measured freshwater yield rate from the condensing cover were recorded as 0.48 liter/m^2hr and 0.4 liter/m^2hr respectively. The maximum predicted and measured freshwater yield rate from the external condenser were recorded as 4.3 liter/m^2hr and 3.9 liter/m^2hr respectively. They concluded that the numerical model was able to predict the performance of the system. Srithar [27] conducted a comparative evaluation of a vapour adsorption solar still coupled to a mini-solar pond and a single basin solar still. Results obtained showed that the vapour adsorption solar still improved in performance by 32.32% over the single basin solar still. This was attributed to the presence of activated carbon and methanol which improved the thermal properties of the absorbing surface. Shanmugasundaram and

Janarthanan [28] studied the performance of a solar still coupled to a shallow solar pond. The system achieved a daily yield of 6.34litres/m^2 with a solar pond arrangement in place and a yield of 2.7litres/m^2 without a solar pond. Maximum efficiencies of 65 and 48%, were recorded for the system with solar pond and without solar pond respectively.

Panchal et al [29] conducted a comparative evaluation of a basin-type solar still with and without a flat plate collector. After testing for six months, it was observed that the solar still coupled to a flat plate collector achieved a yield of 4.49L/m^2/day while the solar still without a flat plate collector achieved a yield of 3.45L/m^2/day. This represents a performance improvement of 30% when compared to the basin-type solar still. Abdullah et.al. [30] studied the performance of a single slope solar still coupled to a solar preheating system with a cooling water loop arrangement. The water loop cools the condensing surface and preheats the saline water feedstock before admitting it into the system. The effect of basin water depth, pre-heated saline water and the nature of the absorbing surface (finned, flat and corrugated) were considered. They observed that the finned surface gave a 20% increase in freshwater yield while preheating the inlet saline water increased the freshwater yield by 50%. Overall, an average efficiency of 61.9% for the finned absorber surface with pre-heating of inlet saline water was achieved. The freshwater yield of the system increased with decrease in water depth. The system achieved a daily yield of 1.8L/m^2 at 1cm depth. Alaudeen et.al [31] conducted a performance enhancement of a basin-type solar still using a stepped basin. The stepped basin consisted of three trays sandwiched between three inclined flat plate collectors placed above the conventional basin. Wicks were placed on each of the inclined flat plate collectors to increase the evaporation rate by capillary action. The conventional basin had an area of 1m^2 while each of the flat plate collectors had an area of 0.42m^2. The depth of saline water was varied in the conventional basin while the depth was maintained at 2cm in the trays of the stepped basin. The system recorded a maximum yield rate of 0.147kg/m^2h at 2cm depth. The productivity reduced to 0.128kg/m^2h at 4cm saline water depth. The addition of stepped trays and inclined flat plate collectors with wick ensured more evaporation due to the lower depth in the stepped trays and more exposure area due to capillary action in the wicks. Halima et.al. [32] conducted a theoretical study on a simple solar still coupled to a heat pump. The condenser of the heat pump formed part of the basin component while the evaporator was placed below the condensing cover. Heating of the saline water was achieved, partly by the absorption of transmitted solar radiation and partly by the rejected latent energy from the condenser of the heat pump. The evaporator on the other hand, improved the condensation rate beneath the condensing cover. The schematic diagram of the physical model is shown in Fig.6.

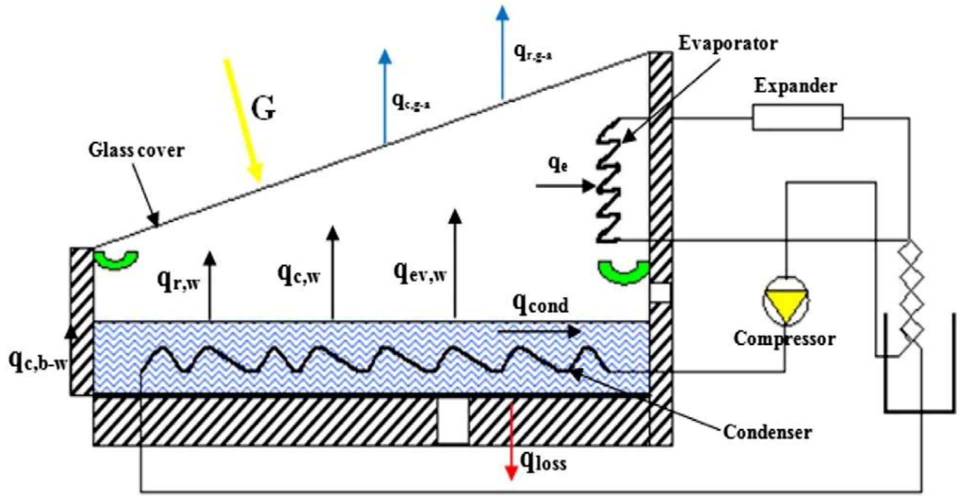

Fig.6: Schematic diagram of a solar still coupled to a heat pump by used Halima et.al. [32]

The system showed an improvement in freshwater yield of 75% when compared to a conventional solar still under the same weather condition. The maximum daily freshwater yield was recorded as 13.5kg/m^2 while the average annual yield was recorded as 9.9kg/m^2. Overall, the freshwater yield was observed to be inversely related to the basin water depth. Boubekri and Chaker [33] developed a model for evaluating the performance of a solar still with internal and external reflectors. They observed that the external reflectors produced a better performance improvement compared to the internal reflectors, with the most improvement recorded during the winter months, followed by the spring and then summer periods. Inclusion of thermal storage facilities also yielded significant performance improvement.

(b) Curved and tubular assisted solar stills

Sharma and Modi [34] observed that the following methods are capable of augmenting the heat and mass transfer processes in a spherical solar still. They include: the use of reflectors, provision of cooling water on the condensing surface, preheating of inlet saline water, provision of vacuum in the solar still cavity, the use of nanofluids, proper condensing cover thickness, use of wick material and tracking system. Arunkumar et.al. [35] examined the performances of seven different solar still configurations. The configurations considered were: spherical solar still, pyramidal solar still, hemispherical solar still, double-basin solar still, concentrator coupled to a single slope solar still, tubular solar still and tubular solar still coupled to a pyramidal solar still. These solar stills were fabricated and tested under the same climatic conditions to analyze the influence of the modifications on their productivity. From their observations, the spherical solar still achieved a distillate yield of 2300ml/m^2/day while the double-basin solar still recorded a yield of 2900ml/m^2/day and the pyramidal solar still recorded a yield of 3300ml/m^2/day. With top cover cooling, the hemispherical solar still recorded a distillate yield of 3659ml/m^2/day. For a concentrator coupled to a single slope solar still, the system achieved a distillate yield of 2600ml/m^2/day. The tubular solar still recorded a yield of 4500ml/m^2/day and when coupled to a pyramidal solar still, a distillate yield of 6928ml/m^2/day was recorded. These results suggested that tubular solar still coupled to a pyramidal solar still produced the highest yield. Arunkumar et.al. [36] reported a significant improvement in distillate yield with a compound parabolic concentrator-concentric tubular solar still (CPC-CTSS) coupled to a pyramidal solar still with top cover cooling. The system achieved a daily yield of 6.928L/m^2 and an efficiency of 21.14%. Without top cover cooling, the system achieved a daily yield of 6.528L/m^2 and an efficiency of 17.01%. Similarly, Arunkumar [37] extended the analysis of Arunkumar et al [36] to a compound parabolic concentrator-concentric tubular solar still (CPC-CTSS) coupled to a single slope solar still (SSSS). The CPC-CTSS recorded a freshwater yield of 4.96L/day and when coupled to the single slope solar still, the freshwater yield increased to 6.46L/day. Solanki et al [38] compared the performances of a hemispherical solar still with and without black ink addition. They observed that the freshwater yield of the solar still with black ink improved by 60% compared to the solar still without black ink. The system recorded a daily mean production of 2.8L/m^2. Mosleh et.al. [39] investigated the performance of a solar distillation system comprising a heat pipe, a twin-glass evacuated tube collector and a parabolic trough collector. The evacuated tube collector housed the heat pipe and the assembly placed along the focal line of the parabolic trough collector as shown in Fig.7. This arrangement aided the solar radiation absorption of the ethanol contained in the heat pipe. The evaporated ethanol inside the heat pipe moved up to the condenser placed inside the basin water and subsequently rejected its latent energy thus, improving the evaporation and distillate yield of the system.

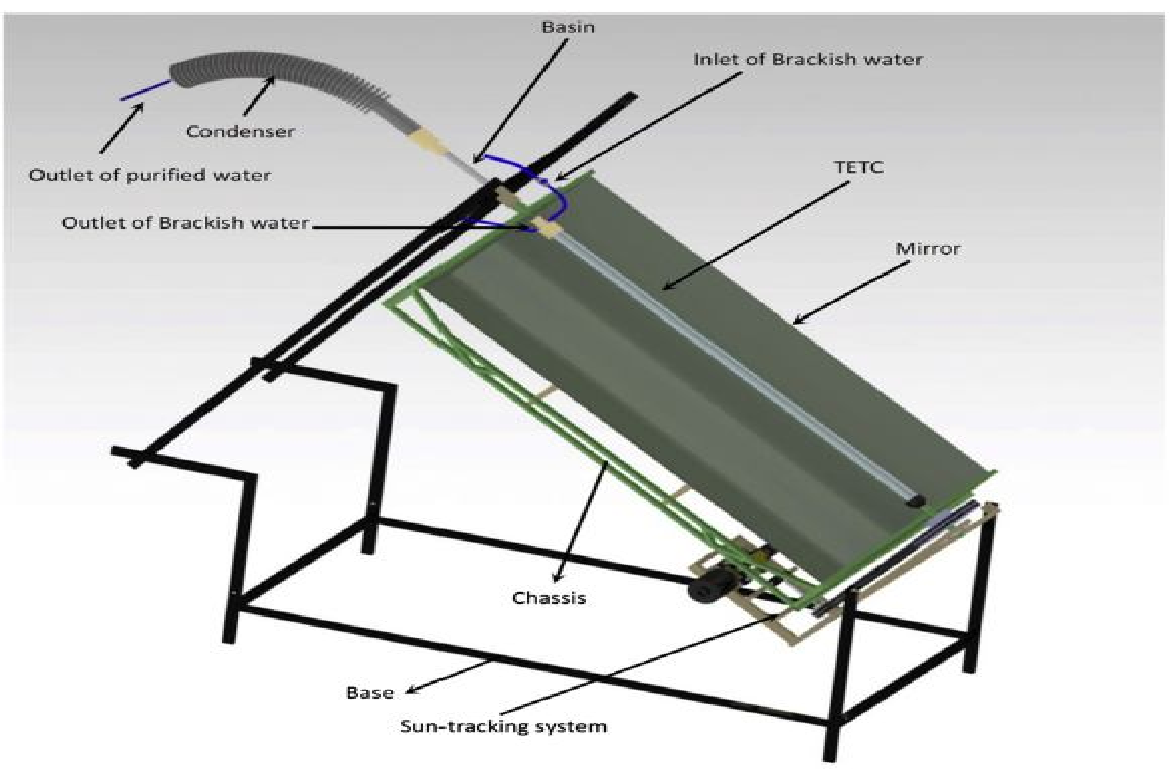

Fig.7: Schematic diagram of the solar distillation system by Mosleh et.al [39]

With aluminum foils as the medium for heat transfer between the twin-glass evacuated tube collector and the heat pipe, the system recorded a yield rate of 0.27kg/m^{2}hr and an efficiency of 22.1%. With oil as the medium for heat transfer, the system recorded a yield rate of 0.933kg/m^{2}hr and efficiency of 65.2%. Chaithanya et.al. [40] applied a novel approach to saline water desalination. They used a single slope solar still with water lens as a concentrator. The system achieved an improved performance with an efficiency of 46% against 21% recorded by the system without water lens. The system recorded a maximum daily production of 0.7 liters for an absorber area of 0.31m^2.

(c) Inverted absorber solar stills

Inverted absorber solar still is characterized by having its solar absorbing surface heated from below by a curved reflector surface. Chaouchi et.al. [41] studied a solar distillation system which worked on the inverted absorber principle and observed that its maximum efficiency occurred at the time when solar radiation was at its peak. However, comparing the experimental and theoretical results revealed an average deviation of 42%. They attributed this development to the imperfections in the paraboloid geometry, the tracking of the sun and the variation in the system's tilt angle. Abdul-Wahab and Al-Hatmi [42] conducted an experimental investigation on the performance of an inverted absorber solar still coupled to a refrigeration cycle. The condenser of the refrigerator formed part of the basin component while the evaporator was placed below the condensing cover. The evaporation of the refrigerant was improved by drawing energy from the humid air underneath of the condensing cover through a flexible air duct as shown in Fig.8.

Fig.8: Experimental setup of an inverted absorber solar still with a refrigerator cycle by Abdul-Wahab and Al-Hatmi [42]

From the obtained results, they observed that the freshwater yield increased with increase in saline water depth. This performance depicts a reverse behaviour as per documented literature. This deviation could be attributed to the amount of energy rejected by the refrigerant in the condenser placed in the basin water. The system achieved 76.8% of the its daily production during nocturnal period. Arunkumar and Ahsan [43] studied an inverted absorber solar still with a hemispherical shaped absorber plate. With the cooling of the condensing cover, the system recorded a daily freshwater yield of 1.67litres and an efficiency of 38.85%. Without top cover cooling, the system achieved a daily freshwater yield of 1.5 liters. Arunkumar et.al. [44] studied an inverted absorber tubular solar still with rectangular black trays inside the concentric tube. The tube and the trays made up the receiver which was mounted at the focal point of a compound parabolic concentrator. The system recorded a daily freshwater yield of $1.9L/m^2$. Comparing the performances of an inverted absorber solar still and a conventional solar still, Kabeel et.al. [45] observed that the inverted absorber type achieved a 52.9% performance improvement over the conventional type.

(d) Solar stills using nanoparticles

Fluids with suspended nano-sized solid particles are known as nanofluids [46]. These suspended particles could either be metallic or non-metallic and have high surface area to volume ratio. Thus, these particles offer the system, an improved surface area with subsequent enhancement in heat and transport properties of fluid in the solar still [46]. Working with a carbon nanotube (CNT)-based nanofluid in a basin-type solar still, Gnanadason et.al. [46] observed that the thermal conductivity of the fluid inside the solar still improved by 40%. This resulted to 60% and 100% improvement in efficiency and freshwater yield respectively. Panitapu et.al. [47] concluded from their study that using Titanium oxide nanomaterial is a promising method of improving distillate yield in solar stills. Singh and Singh [48] found from their study that aluminum Oxide (Al_2O_3) nanoparticle improved the evaporation yield of a solar still by 20%. However, comparing it with results obtained from Gnanadason et.al. [46] shows that carbon nanotube-based nanofluid has superior performance to aluminum oxide based nanofluid. Sain and Kumawat [49] studied the performance of a single slope solar still with the absorber coated with a mixture of black paint and aluminum oxide (Al_2O_3) nanoparticle. They observed a performance improvement of 38.09% over the solar still without nanoparticle. Sharshir et.al. [50] investigated the effect of graphite and copper oxide (CuO) nanomaterials on the productivity of a basin-type solar still. The schematic diagram of the experimental setup is shown in Fig.9.

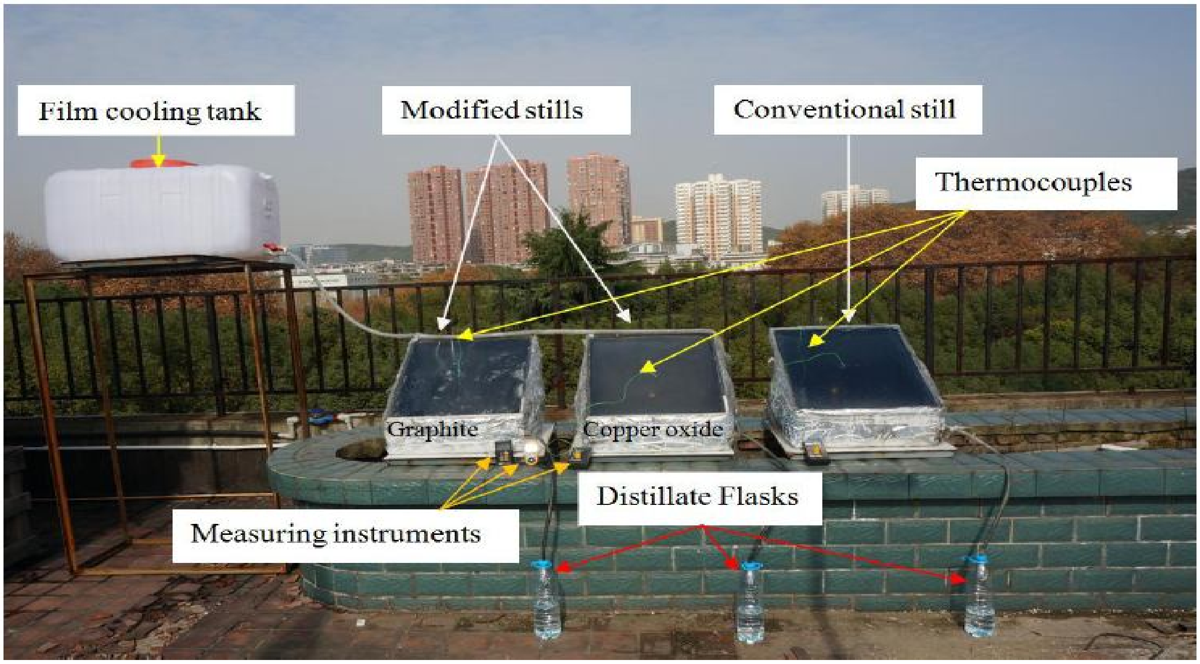

Fig.9: Schematic diagram of the experimental setup used by Sharshir et.al. [50]

It was found that the graphite nanoparticles produced a performance improvement of 43.10% while the copper oxide nanoparticles produced 37.02% performance improvement. The better performance obtained using graphite was attributed to the graphite's superior thermal conductivity to copper oxide as well as the fact that graphite has less density than copper oxide and as such had a better suspension in the saline water than the copper oxide. With the cooling of the condensing cover, the performance improvement of the system increased to 53.95% and 44.91% for graphite and copper oxide respectively. Kabeel et.al. [51] carried out a numerical evaluation of a single basin solar still modified with nanofluids. The system comprised a conventional solar still, a vacuum fan and an external condenser as depicted in Fig.10. Different concentrations of aluminum oxide (Al_2O_3) and cuprous oxide (Cu_2O) nanofluids were tested.

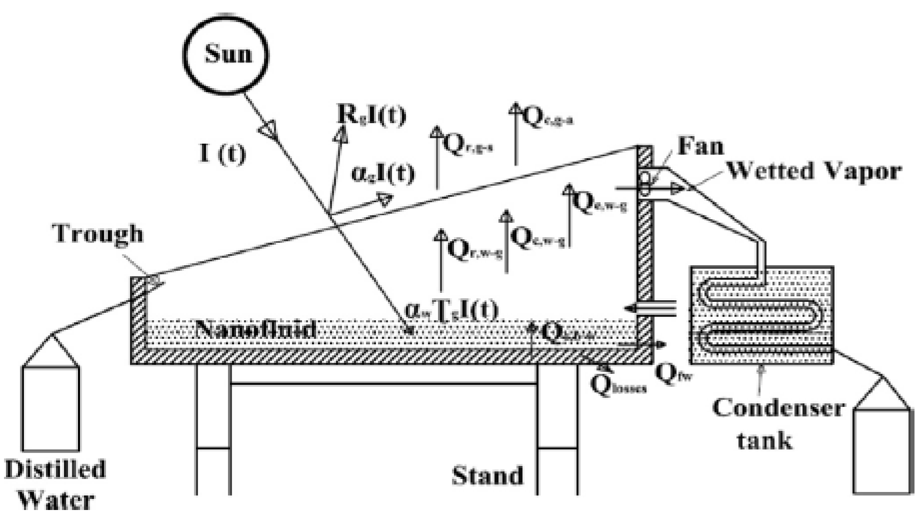

Fig.10: Schematic diagram of a solar still modified with nanofluids by Kabeel et.al. [51]

For nanofluids concentration of 0.02%, the system achieved daily freshwater yields of 4.09L/m^2 and 2.875L/m^2 with cuprous oxide and aluminum oxide nanofluids respectively. With nanofluids concentration of 0.2%, the system recorded maximum daily efficiencies of 84.16% and 73.85% for cuprous oxide and aluminum oxide nanofluids respectively. The conventional solar still achieved a daily efficiency of 34%. Navale et.al. [52] investigated the effects of increase in concentrations of aluminum oxide (Al_2O_3) and copper oxide (CuO) nanoparticles on the performance of a masonic solar still. They observed that the productivity of the solar still increased with increase in concentration of the nanoparticles. For aluminum oxide-based nanofluid, the freshwater production increased by 29.52%, 35.57% and 45.19% at the concentrations of 0.1%, 0.2% and 0.3% respectively. While with copper oxide-based nanofluid, the production increased by 33.65%, 54.32% and 89.42% at the concentrations of at 0.1%, 0.2% and 0.3% respectively.

(e) Solar stills with phase change and energy storage materials

Any material that absorbs or releases significant amount of energy at phase transition when exposed to heat or cold is categorized as a phase change material (PCM). They are used to store thermal energy and to balance temporary temperature alternations [53]. Phase change materials have high heat of fusion and specific temperature ranges for phase transition. They are grouped as organic, inorganic or eutectic phase change materials. Attempts have been made by several researchers to augment the productivity of solar distillation systems using phase change materials and sensible energy storage materials. Working with different masses of lauric acid, Al-hamadani and Shukla [54] studied its effect on the performance of a single slope solar still. They observed that its inclusion improved the solar still's productivity by 30%. Gowtham et.al. [55] studied the effect of different combinations of phase change and energy storage materials on the performance of a parabolic concentrator-solar still. The materials tested were: paraffin wax; paraffin wax and sponges; paraffin wax and pebbles; and paraffin wax and mild steel billets. Results of the tests showed performance improvements of 33.34%, 38.41%, 42.85% and 54.08% by paraffin wax, paraffin wax and sponges, paraffin wax and pebbles, and paraffin wax and mild steel scraps respectively. Using bitumen as an energy storage material, Kantesh [56] recorded a 2% improvement in freshwater yield from a double slope solar still. Panchal et.al. [57] conducted an experimental investigation on the performance of a single basin solar still using cow dung cakes as an energy storage material. The experimental setup comprised a control solar still and a modified solar still with cow dung cakes as part of its absorber. Picture of the cow dung cakes and the experimental setup are shown in Fig.11a and Fig.11b respectively.


Fig.11a: Cow dung cakes used by Panchal et.al. [57] Fig.11b: Experimental set up by Panchal el.al. [57]

From their observations, the modified solar still with cow dung cakes recorded a higher evaporative heat transfer coefficient and produced 25% more of freshwater yield compared to the control solar still. Ramasamy and Sivaraman [58] compared the performances of two solar stills: one with paraffin wax and the other without paraffin wax with an absorber area of $0.76m^2$. The solar still with paraffin wax recorded a distillate yield of $1.68liters/m^2$ and efficiency of 52.62% while the solar still without paraffin wax recorded a distillate yield of $1.85liters/m^2$ and efficiency of 60.11%. The explanation to this deviation stem from the fact that a fraction of the solar radiation input is stored by the paraffin wax during diurnal hours. Sarada et.al. [59] observed from their work that Sodium Sulfate ($Na_2SO_410H_2O$) was a better phase change material than Sodium Acetate ($C_2H_3NaO_2$.). The performance of a single slope solar still was independently studied by Somanchi et.al. [60] and Khan and Nawaz [61] using magnesium sulphate heptahydrate ($MgSO_4.7H_2O$) and sodium sulphate ($Na_2S.7H_2O$) as phase change materials. They observed that magnesium sulphate heptahydrate performed better. Agrawal [62] applied paraffin wax in a stepped-type solar still and achieved 35 – 40% improvement in freshwater yield over a similar solar still without a paraffin wax. Also, using paraffin wax and applying solar tracking, Chaichan and Kazem [53] achieved 307.54% performance improvement in a conical distiller coupled to parabolic dish. With honey beeswax, Sonawane et.al. [63] tried optimizing the angle of an absorber surface integrated with a phase change material and achieved a maximum freshwater yield corresponding to 62% improvement in performance at an angle of 34^o. A similar result was achieved by Kuhe and Edeoja [64] while working with beeswax in a parabolic concentrator-single slope solar still. In the same vein, Arunkumar et.al. [65] used six copper balls loaded with paraffin wax to investigate the possible performance improvement of a parabolic concentrator-single slope solar still, as shown in Fig.12.

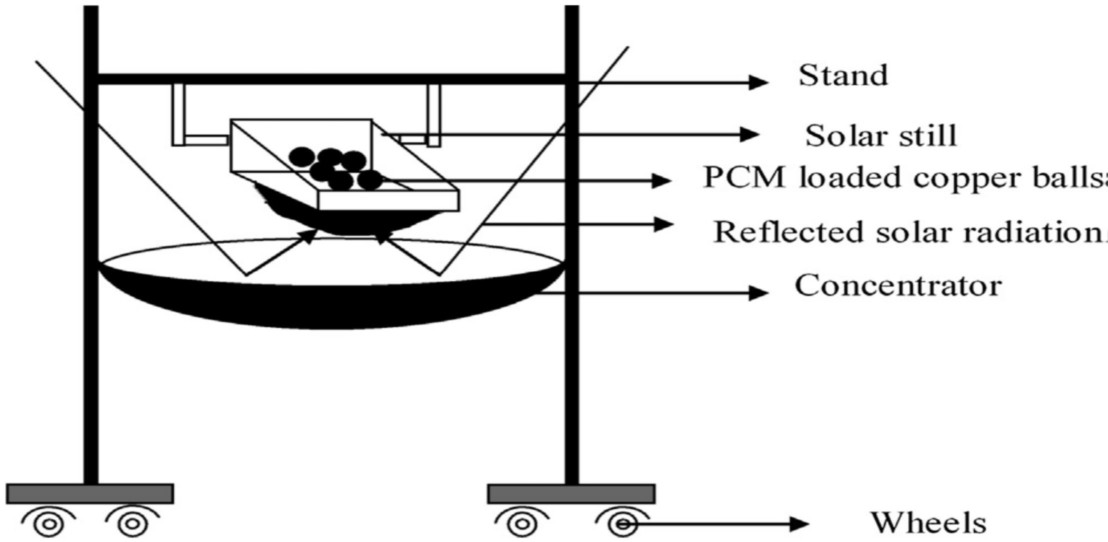

Fig.12: Schematic diagram of the solar still with paraffin loaded copper balls by Arunkumar et.al. [65]

To further improve the performance of the system, top cover cooling was introduced at the rate of 0.1 L/min. The system recorded a daily freshwater yield of 3.8 L/m^2. Using stearic acid as a phase change material, Hari and Kishore [66] investigated the performances of different configurations of a stepped basin solar still. The configurations considered were: stepped basin solar still; stepped basin solar still with stearic acid; evacuated stepped basin solar still with stearic acid; and evacuated stepped basin solar still with stearic acid and an intermittent water collector. They observed that the evacuated stepped basin solar still with stearic acid and an intermittent water collector produced the highest yield rate of 1.1 liters between 14.00-15.00 hrs. Therefore, the presence of vacuum and intermittent water collection helped in improving the freshwater production. Working with a stepped basin solar still, Kumar et.al. [67] compared the effects of three different phase change materials on the productivity of the system. The phase change materials tested were palmitic acid, white beeswax and stearic acid. The system recorded freshwater yields of 2.234L/m^2, 2.382L/m^2, 2.424L/m^2 and 2.082 L/m^2 for white beeswax, palmitic acid, stearic acid and without PCM respectively. The result represented an increase of 7.3%, 14.41% and 16.43%, respectively for the solar still with white beeswax, palmitic acid and stearic acid over that without PCM. Gnanaraj et.al. [68] evaluated the performance of a basin-type solar still with fins, reflectors and thermal energy storage material. The solar still had an absorber area of 0.44m^2. Results obtained showed that with only the fins, freshwater yield of 2.25 liters and efficiency of 45% were achieved. When coal which served as an energy storage material was introduced, freshwater yield and efficiency increased to 2.55 liters and 51%, respectively. With the introduction of mirrors, freshwater yield increased to 2.8 liters while the efficiency increased to 56%. Jenis et.al. [69] used palmitic acid as a phase change material in a single slope solar still and obtained an improvement in freshwater yield of 80.54% over a similar solar still without a phase change material. An analytical study conducted by El-Sebaii et.al. [70] showed that for 30kg of steric acid in a single slope solar still, the freshwater yield of the system improved by 84.3%.

2.2 Multi-effect solar distillation systems.

This group of solar stills is characterized by more than one condensing cover layer over the saline water surface. Suneja and Tiwari [71] compared the performances of an inverted absorber-triple effect solar still and a conventional triple effect solar still. Using energy equations developed for each component of the system and solved using Laplace transform technique, they observed that the inverted absorber type performed better by 30%. Also, the lowest basin produced the highest freshwater yield and the daily yield improved with the number of effects. Madhlopa [72] worked on a passive triple effect solar still. The system had a separate evaporator and two condenser chambers. The evaporator chamber housed basin 1 while the condenser chambers housed basin 2 and 3 as depicted in Fig.13. The system achieved a freshwater yield of 4.599 kg/m^2 which represented a 22% improvement in performance over a single basin solar still. From the total yield, the first effect contributed 88%, the second effect contributed 11% while the third effect contributed 1%. Overall, the system produced an efficiency of 39%.

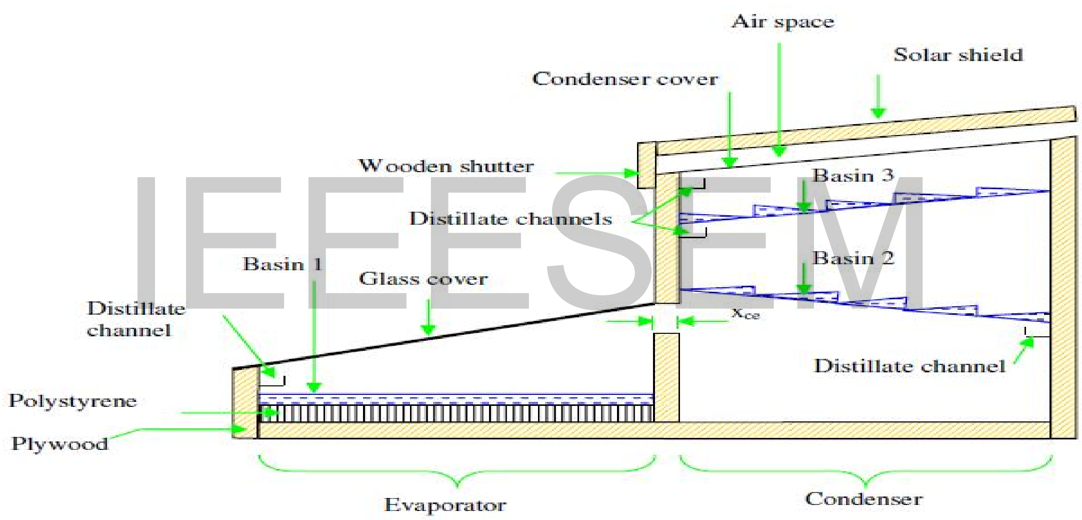

Fig.13: Schematic diagram of a triple effect solar still built and tested by Madhlopa [72]

Hashim [73] compared the performances of a double basin solar still and a single basin solar still. The double basin solar still comprised a horizontal and a vertical basin with the sum of the absorber areas of both basins equivalent to that of the single basin solar still. His results showed that the double basin solar still performed better than the single basin solar still by 11%. With the addition of external reflectors, the performance of the system improved by 32%. The performance of a double effect solar still coupled to a compound parabolic concentrator (CPC) under forced circulation was analyzed by Prasad and Tiwari [74]. They observed an improvement in the overall freshwater yield due to the exploitation of the latent heat of condensation by the upper basin. Ahmed et.al. [75] designed a three-stage evacuated solar still with the stages arranged adjacent to each other. The solar still chamber was evacuated with the aid of a solar powered vacuum pump. The system achieved a daily freshwater yield of 6kg/m^2, 4.3kg/m^2 and 2kg/m^2 for the first, second and third stages respectively at a pressure of 0.5bar. With the increment in pressure, a marked reduction in freshwater yield was observed. Similarly, working with a double basin solar still coupled to vacuum tubes, Panchal [76] recorded a 56% improvement in freshwater yield. With the introduction of an energy storage material made from black granite gravel, the yield further improved by 9%, making it a total of 65% performance improvement. Rajaseenivasan et.al. [77] compared the performances of a double effect-double slope and a single effect-double slope solar stills of equivalent absorber area. The system recorded freshwater yields of 1.61 liters/day and 2.99 liters/day for the single effect and double effect solar stills respectively. With the introduction of mild steel pieces as an energy storage material, the freshwater yields increased to1.94 liters/day and 3.58 liters/day for the single effect and double effect solar stills respectively. Similar work done by Kaliappan et.al. [78] recorded freshwater yields of 0.58 liters/day and 1.02 liters/day for the single effect and double effect solar stills respectively. With the introduction of mild steel pieces, the yield increased to 0.695 liters/day and 1.22 liters/day for the single effect and double effect solar stills respectively. Comparing this result with the work of Rajaseenivasan et al [77], showed that the double slope performed better than the single slope. Working with a double basin solar still coupled to a liquid flat plate collector, Nithin and Hraiharan [79] recorded a daily freshwater yield of 5.2 kg/m^2. In general, multi-effect solar stills have shown to exhibit significant performance when compared to singe effect solar stills and other design configurations. This fact is corroborated by the list of efficiencies of various solar still designs shown in Table 1.0 [80].

Table 1.0: Efficiencies of various solar still configurations by Bhattacharyya [80]

Type of solar still	Output efficiency
Simple basin type solar still	30%
Single slope solar still	23% to 31%
Double slope solar still	25% to 34%
Multiple wick solar still	34%
Low cost thermoformed solar still	39%
Double effect multi wick solar still	50% to 60%
Capillary film distiller (one stage)	50% to 55%
Tilted wick type solar still	53%

2.3 Solar Still Parametric Studies

The rate of distillate yield is an important performance parameter. It is a function of the temperature differential between the saline water interface and the condensing cover. The magnitude of this differential is the driving force for distillate production. In order to maximize this factor, the saline water temperature should be maintained as high as possible and the condensing cover temperature, as low as possible. This has led to various solar still configurations with variation of design parameters. Patil et.al. [81] reviewed the factors that affect solar still performance. They concluded that basin area, water depth, inlet saline water temperature, condensing cover inclination and temperature difference in the solar still cavity are possible factors to consider for improved solar still productivity. Panchal [82] observed that reduction in basin water depth with improved absorptivity of the absorbing surface, increased the freshwater yield of a double slope solar still. Working with a single basin solar still using Matlab Simulink, Kumar et.al. [83] investigated the effect of saline water depth and condensing cover inclination on the freshwater yield. The system recorded an optimized performance at an inclination of 30^o while the freshwater yield decreased with increase in saline water depth. Shankar et.al. [84] studied the effect of colour of the internal walls of a solar distillation system on its productivity. The setup had two configurations: a control solar still with black interior and a modified solar still with white interior walls as shown in Fig.14. Aluminum oxide (Al_2O_3) nanoparticles were used in both solar stills to improve the heat transfer properties inside the system.

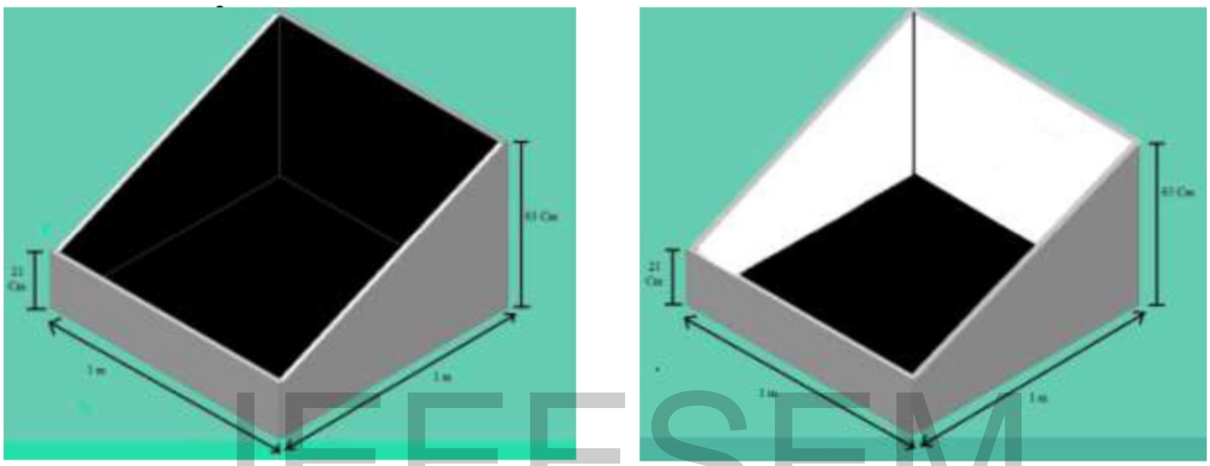

Fig.14: Perspective view of conventional and modified solar stills by Shankar et.al. [84]

The modified solar still produced 3.258L/m^2 of freshwater while the control solar still produced 2.605L/m^2 of freshwater. This represents 25% improvement in performance and is attributed to the reflection of radiation by the white interior walls to the absorber thus, increase in evaporation rate in the modified solar still. Alvarado-Juarez et.al. [85] reported that the aspect ratio (length/height) and the condensing cover angle of a solar distillation system significantly affect the distillate yield. Using model equations solved by the forward time step marching discretization technique with codes written in FORTRAN, Ambarita [86] concluded that varying the temperature of the heat source in vacuum desalination, produced better performance when compared to constant temperature of the heat source. Malaeb et.al. [87] concluded from their work that the condensing cover geometry of a solar still does not significantly affect its performance. Zedan and Eldin [88] reported that preheating the inlet saline water could increase the distillate production by 27.7 – 29.3%.

3.0 Rural potable water supply

The term potable water, is referred to water suitable for drinking. This is accomplished by detailed laboratory test by a competent health official. On the other hand, clean water is referred to as water devoid of dirt and other visible contaminants [89]. Water with high bacteria content that are not visible to the eyes could be seen as clean water. Thus, there is a thin difference between potable and clean as properties of drinking water. Rural communities especially in developing countries are bedeviled with scarcity of potable water supply. The common water supply sources in rural areas are: rainwater, wells and streams. These water sources, in their present form are not suitable for drinking due to the level of contaminants. According to Howard and Bartram [90], there is an established link between water supply, hygiene and disease. Water-borne diseases like diarrhoeal, infectious hepatitis, typhoid, and guinea worm are caused by consumption of contaminated water. Thus, there is need for adequate potable water supply in our rural communities. Several researchers have made effort in resolving the problem of limited supply of potable water in remote areas. Jasrotia et.al. [91] implemented the design of a solar powered distillation pilot system for the provision of potable water in an Arsenic affected rural village of Kaudikasa, India. The process diagram of the saline water treatment and potable water supply is shown Fig.15.

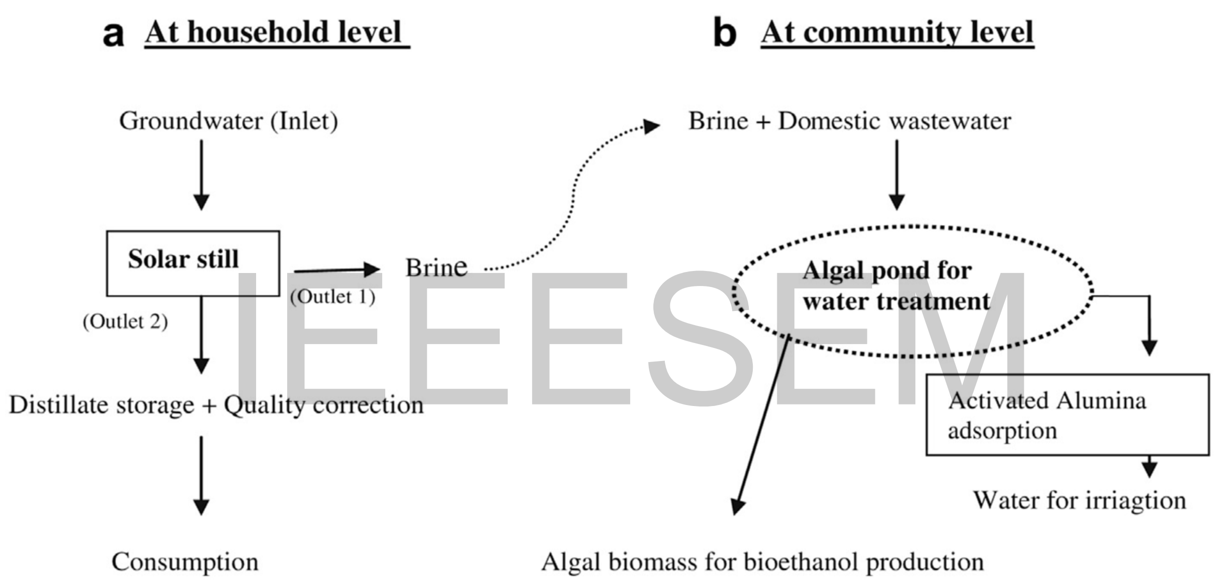

Fig.15: Scheme for treatment and supply of potable water in an Arsenic affected village by Jasrotia et.al. [91]

The treatment process was accomplished at two distinct levels. At the household level, the solar still was used for saline water treatment and potable water supply. At the community level, an algal pond was used for co-treatment of solar still brine and domestic wastewater. The treated water from the algal pond was used for irrigation and other agricultural purposes. The total Arsenic concentration present in the effluent after the algal pond treatment was recorded as 0.1mg/L. The total Arsenic contaminants removed daily was recorded as 40mg. The system produced a daily freshwater yield of 3L/m^2. In order to meet the WHO standard of 1.5mg/L of fluoride concentration in potable water, some fluoride salts were added to the freshwater yield. The authors suggested that an average family would need a solar still area of 16 square meters to meet their daily potable water requirement. The installation cost for a square meter of the solar still was estimated as USD400. Karima and Islam [92], designed a low-cost tubular solar still (TSS) for the supply of potable water in the costal belt of southwest region of Bangladesh. The groundwater sources in this region are contaminated with high level of arsenic concentration. The solar still recorded a maximum daily production of 3.83L/m^2. They concluded that the desalination system was capable of meeting the potable water demand of a single household in the coastal area. The cost of production of the distilled water was estimated as 0.0046 USD per liter. Bala et.al. [93] constructed a solar still-solar water heater hybrid system for the provision of potable water in rural areas. The system recorded a daily production of 440ml for an area of 0.276m^2. Madhlopa and Johnstone [94] designed a solar powered water distillation system for the provision of potable water in the rural areas of Malawi. The system had a daily freshwater yield of 2.5kgm^{-2}.

Fiestas et.al. [95] implemented the design of a solar powered distillation pilot scheme for the supply of potable water for the rural areas of Sechura. The system comprised raw water storage tank, photovoltaic pump, water distilling panels, support structures and distilled water storage tank. The schematic diagram of the plant and the installed distilling panels are shown in Fig.16a and Fig.16b respectively.

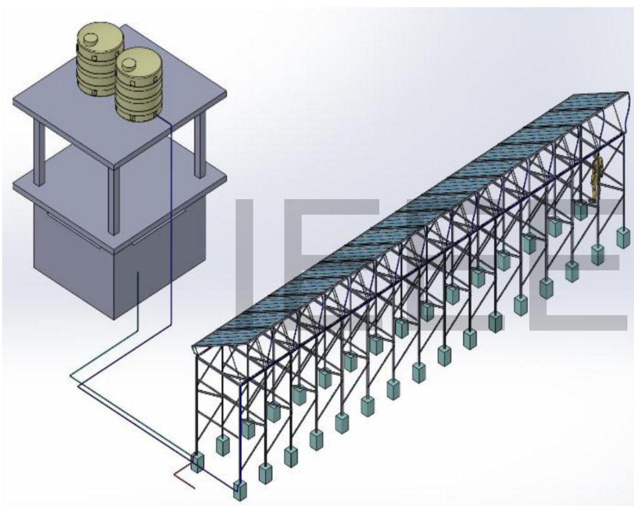
Fig16a Pilot plant scheme from Fiestas et.al. [95]


Fig16b Installed distilling panels by Fiestas et.al. [95]

The plant had a total of 15 distilling panels with a total production capacity of 300 liters per day operating for eight hours. Each distilling panel had an effective area of 3m^2 thus, the total daily production capacity is expressed as 6.67 L/m^2. They argued that the quality of the produced water met the recommended standard established for potable water. Pasache et.al. [96] caried out an assessment on bottling of water from the initiative of the pilot plant scheme of Fiestas et.al.[95]. The results showed that their proposal was encouraging especially for the rural communities in the north of Peru. Foster et.al. [97] applied some cost-shared solar distillation systems along the U.S./Mexico border to meet the potable water demands in low-income colonias communities plagued with high level of arsenic and fluoride concentrations. This project was done in conjunction with El Paso Solar Energy Association (EPSEA). The cost-shared solar distillers were distributed to forty households by EPSEA. The project was adjudged by the participating households to be successful. Solar distillation technology has been shown to have the capacity to provide potable water for households especially, for those in rural areas without grid connected electricity. This technology has been proven to be capable of removing 99.96% of viable bacteria per liter of impure water [97]. A test carried out at the New Mexico State University (NMSU) shows the effectiveness of solar still in providing potable water and the results are shown in Table 2 [97].

Table 2. NMSU water quality test by Foster et.al. [97]

Sample	Conductivity μS/cm	$CaCO_3$ Mg/L	Fluoride Mg/L	PH
Input	1190	260	6.2	7.9
Output	4.8	4	0.1	9.2
Input	1180	250	8.2	7.4
Output	1.8	0	0.1	9.1

4.0: Constraints and prospects of solar still technology

4.1: Field experience and commercial solar still

The utilization of solar distillation systems in different parts of the globe shows that they have huge potentials of reducing the over dependence on conventional energy sources for the provision of potable water for domestic and commercial consumption. The results obtained from test running the system in several locations are required to establish a trend, system reliability as well as provide operational data for further research. Kopperdal [98] built and tested a prototype solar still in Kabul, Afghanistan with a daily production capacity of 1.9L/m^2. Al Faruq et.al. [99] carried out a field evaluation of a basin-type solar still in Khulna, Bangladesh from June 2011 to June 2012. The system recorded a maximum yield of 3.76L/m^2 in July, 2011 and a minimum yield of 0.21L/m^2 in December, 2012. The average yield was recorded as 1.8L/m^2. Kemp [100] reported an innovative solar distillation system built by KII. Inc./Suns River. The system was tested at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, USA. The system had two condensation effects and an absorber area of 1.4m^2. It had two production cycles: diurnal and nocturnal, with the nocturnal cycle used as the next day's cooling water for the condenser. Fig.17 shows a home-sized solar still tested at BGNDRF.

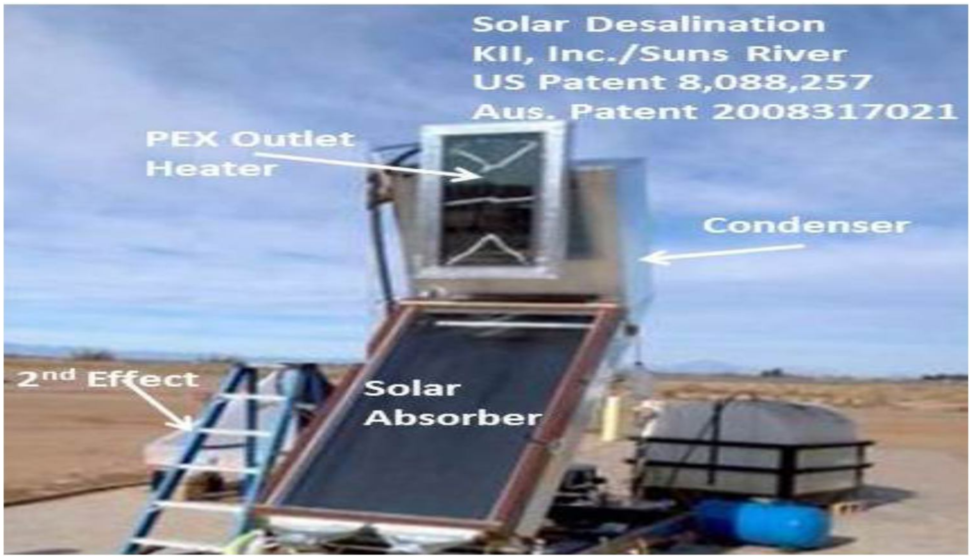

Fig.17: Home-sized solar still at BGNDRF by Kemp [100]

For an absorber area of 1.4m^2, the system recorded an average freshwater yield of 37 L per day. This translates to a daily production capacity of 26.43L/m^2. With this value, the author argued that the daily portable water need of one family was met. The freshwater cost from this system was projected to be in the range of $4 - $7 per 1000 gallons.

Markham [101] reported the invention of Watercone® solar still by Stephan Augstin in Germany. It had a basin diameter of 60 – 80 cm and a freshwater yield of 1.5 L/day with an estimated cost of €20.00. Gan et.al. [19] produced a cost effective solar still with a production capacity of 1.28kg$(m^2h)^{-1}$ and an estimated material cost of $1.6 per square meter. They argued that their product had addressed the challenge of production cost. They founded a company; Sunny clean water- for the purpose of commercializing the new technology. Other commercial solar stills that have enjoyed reasonable market penetration are: The Aquadome; this is a simple technology manufactured by speed plastics limited. It is mostly used in survival situations to provide short to medium term source of freshwater from seawater, lakes and ponds. The product is estimated to cost US$ 246.95 with a production rate of 300 ml/h [102]. The Cleardome solar still is a combination of a solar still and a pasteurizer measuring 8 × 17 × 48 inches with an estimated cost of US$30.00 [103]. About one-quarter of the freshwater production is recorded during nighttime due to the utilization of the stored heat inside the solar still cavity. Rainmaker™ 500 is a solar distiller manufactured by SolAqua. It has an absorber area of 0.93m^2 and a production capacity of 6L/day in summer and 3L/day in winter [104]. The setup of this system is shown in Fig.18.

Fig.18: Rainmaker 550 solar distiller [104]

With a thermal efficiency of 60%, the performance of the system is expressed as 0.8 liters per sun hour [104]. The cost of system is estimated at US$569.95. Rainkit™ 990 is another product of SolAqua. It is a do-it-yourself solar distiller kit for persons with basic technical skills. It comprises a construction plan and components for easy assembly. It has a basin area of 1.7 m^2, production capacity of 11 liter/day and an estimated cost of US$245.00 [105]. The Eliodomestico solar still is made from ceramic material. It has a production capacity of 5 liter/day and an estimated cost of US$50.00 [106]. African's climate and in particular Nigeria, has the capacity to support the utilization of solar powered desalination systems. Extended testing and long-term performance are necessary for the development of standards and characterization of solar stills, which will in turn aid the improvement of this technology.

4.2: Constraints

Solar powered desalination systems are increasingly gaining awareness due to high cost of fossil fuels and the need to use clean and environmentally friendly energy sources. Despite these gains, the usage and acceptability of solar stills is very limited. The factors responsible for the poor level of acceptance and usage differs from geographical area and broadly can be grouped as economic and technical constraints.

4.2.1: Economic constraints.

Several economic factors and government policies have hampered the successful commercialization of some solar powered desalination systems. Some of these factors include; low-income level, poor energy policies, poor awareness level, lack of research grant and the provision of little or no subsidy on the part of government. These factors are however, more pronounced in developing countries. In developed countries, the major constraints are, the lack of promotion of solar stills and poor acceptability by customers due to low efficiency. One of government's responsibility is the provision of conducive environment for businesses to thrive. This is equally applicable to solar still technology. Government and corporate organizations have to encourage indigenous researchers by providing grants and other necessary assistance. This is to enable them come up with better and cost-effective materials that can improve the productivity and efficiency of solar distillation systems. Moreover, the improvement in living standard of the people, provision of direct subsidy and financing scheme will also aid in mitigating this constraint. Lack of awareness can be overcome through public enlightenment campaign in the form of advertorials, or sponsored programs on green energy sources.

4.2.2: Technical constraints

Most of the reviewed solar stills have their technical limitations. Some of the technical constraints associated with solar powered desalination systems are: lack of standard methods for performance evaluation, high nocturnal energy losses, low yield rate and poor capability to harvest solar energy. Most of the technical shortcomings identified in this section can be overcome if ways of improving the existing designs are sought. These ways include, reduction of the thermal capacity of saline water by using shallow basins, use of glazing materials with better greenhouse effect, increasing the absorber area by use of fins and absorber materials with good capillary property, use of energy storage, utilization of latent heat of condensation etc. Combination of these methods can significantly improve the performance of existing solar stills.

5.0 Conclusion

Freshwater demand is on a steady increase due to rapid population growth and advances in industrial and technological activities. Solar desalination is found to be an economical and environmentally friendly approach of distilling saline water. This review has presented the different designs of various solar stills. It has also considered different operational parameters that affect freshwater yield. The following conclusions are drawn from this review.

- One of the major setbacks associated with passive solar stills is their low freshwater yield. This can be improved by augmenting the heat transfer processes inside the solar still chamber.
- Solar stills with multi-effect condensation produce better performance compared to solar stills with single-effect condensation. This is due to the application of the latent heat of condensation in the subsequent effects.
- Parameters like basin water depth, condensing cover temperature, inlet water temperature, water-glazing temperature difference, glazing angle, absorber area etc., were identified as factors affecting the amount of freshwater production. Improvement in productivity and efficiency of solar stills are achieved by varying these parameters.

- Solar still technology has been proven as a viable tool for the provision of potable water for households. With proper design, this system can be deployed on a large scale to provide potable water for commercial application.

REFERENCES

[1] WHO/UNICEF joint monitoring program. Progress on drinking water and sanitation: special focus on sanitation. Geneva: WHO/UNICEF, 2008.

[2] B. Baker, C. Aldridge and A. Omer. Water: Availability and use. Mississippi state university extension service, 2016.

[3] R. Clayton. Desalination for water supply, 3rd edition. Foundation for water research, 2015.

[4] L. Ramulongo, N.S. Nethengwe and A. Musyoki. The nature of urban household water demand and consumption in makhado local municipality: A case study of makhado newton. Procedia environmental sciences, 2017, 37, pp.182-194.

[5] WHO/UNICEF joint monitoring program. Global water supply and sanitation assessment report. Geneva: WHO/UNICEF, 2000.

[6] V. Narula, M.F. Khan and S. Bahuguna. Recent developments in solar water distillation Designs. The engineering journal of application and scopes, 2017, 2(1).

[7] J. Krishna. Introduction to desalination technologies. Texas water development board. 2004 [online] Available from: https://texaswater.tamu.edu/readings/desal/introtodesal.pdf. [Accessed 10 Dec 2020]

[8] S.W. Sharshir, N. Yang, G. Peng and A.E. Kabeel. Factors affecting solar stills productivity and improvement techniques: A detailed review. Applied thermal engineering, 2016, 100, pp.267-284.

[9] J.A. Duffie and W.A. Beckman. Solar engineering of thermal processes, 4th edition. New Jersey: John Wiley & Sons Inc., 2013.

[10] N. Suresh, R. Jayaprakash and S. Dhanabagyam. Water distillation by single slope solar still. International journal of current multidisciplinary studies, 2015, 1(1), pp.1-4.

[11] A. Mehta, A. Vyas, N. Bodar and D. Lathiya. Design of solar distillation system. International journal of advanced science and technology, 2011, Vol. 29.

[12] J. Eze and O. Ojike. Comparative evaluation of rectangular and pyramidal shaped solar stills using saline water. International journal of the physical sciences, 2012, 7(31), pp 5202-5208.

[13] E. Ugwuoke, J. Eneh, H. Edeh, R. Ochu and B. Onyia. Purification of brackish water by solar water distillation process. International journal of research in advanced engineering and technology, 2016, 2(5), pp.1-5.

[14] A. Badusha and V. Arjunan. Performance analysis of single slope solar still. International journal of mechanical engineering and robotics research, 2013, 2(4).

[15] J.T. Mahdi, B.E. Smith and A.O. Sharif. An experimental wick-type solar still system: Design and construction. Desalination, 2011, 267, pp.233-238.

[16] S.H. Sengar, A.G. Mohod, Y.P. Khandetod, S.P. Modak and D.K. Gupta. Design and development of wick type solar distillation system. Journal of soil science and environmental management, 2011, 2(7), pp.125-133.

[17] P.U. Suneesh, R. Jayaprakash, T. Namshad and S. Kumar. Performance of corrugated wick in "V" type solar still. Smart grid and renewable energy, 2013, 4, pp. 483-487.

[18] A. Prakash, R. Jayaprakash and S. Kumar. Experimental analysis of pyramid wick-type solar still. International journal of scientific and engineering research, 2016, 7(4), ISSN: 2229-5518

[19] Q. Gan, Z. Liu, H. Song, D. Ji, C. Li, A. Cheney, Y. Liu, N. Zhang, X. Zeng, B. Chen, J. Gao, Y. Li, X. Liu, D. Aga, S. Jiang and Z. Yu. Extremely cost-effective and efficient solar vapour generation under nonconcentrated illumination using thermally isolated black paper. Global challenges, 2017.

[20] H. Hammadi, H. Al-Shamkhee and A. Jabar. Experimental study of the performance of tubular solar still in Najaf city. International journal of energy and environment, 2015, 6(6), pp.587-596.

[21] K.M.S. Islam and T. Fukuhara. Production analysis of a tubular solar still. Doboku gakkaironbunshuu B, 2007, 63(2), pp.108-119.

[22] H.N. Panchal and P.K. Shah. Experimental and ANSYS CFD simulation analysis of hemispherical solar still. International journal of renewable energy, 2013, 8(1).

[23] J. Eze, Onyekwere, Ojike and I. Ejilah. Solar powered distillation of Lagos bar beach water. Global journal of science frontier research, 2011, 11(6), ISSN: 0975-5896

[24] M. Afrand, R. Kalbasi, A. Karimipour and S. Wongwises. Experimental investigation on a thermal model for a basin solar still with an external reflector. Energies, 2017, 10(18).

[25] A. Khalifa, A.S. Al-Jubouri and M.K. Abed. An experimental study on modified simple solar stills. Energy conversion and management, 1999, 40(17), pp.1835-1847.

[26] N. Bao. The mathematical model of basin-type solar distillation systems. Intechopen, 2019.

[27] K. Srithar. Performance analysis of vapour adsorption solar still integrated with mini-solar pond for effluent treatment. International journal of chemical engineering and applications, 2010, 1(4), ISSN: 2010-0221.

[28] K. Shanmugasundaram and B. Janarthanan. Performance analysis of the single basin double slope solar still integrated with shallow solar pond. International journal of innovative research in sciences, engineering and technology, 2013, 2(10), ISSN: 2319-8753

[29] N. Panchal, I. Patel, B. Patel, R. Goswami and M. Doshi. A comparative analysis of single slope solar still coupled with flat plate collector and passive solar still. IJRRAS, 2011, 7(2).

[30] M. Abdullah, A. Shabibi and M. Tahat. Thermal performance of a single slope solar water still with enhanced solar heating system. Renewable energy and power quality journal, 2015, 1(13), ISSN: 2172-038.

[31] A. Alaudeen, K. Johnson, P. Ganasundar, A. Abuthahir and K. Srithar. Study on stepped type basin in a solar still. Journal of king saud university – engineering sciences, 2013, 26, pp.176-183.

[32] H.B. Halima, N. Frikha and R.B. Slama. Numerical investigation of a simple solar still coupled to a compression heat pump. Desalination, 2014, 337, pp.60-66.

[33] M. Boubekri and A. Chaker. Yield of an improved solar still: Numerical approach. Energy procedia, 2011, 6, pp.610-617.

[34] J. Sharma and K. Modi. Techniques to improve productivity of spherical solar still. IJARIIE, 2016, 2(3).

[35] T. Arunkumar, K. Vinothkumar, A. Ashan, R. Jayaprakash and S. Kumar. Experimental study on various solar still designs. ISRN Renewable energy, 2012. Vol: 2012, Article ID: 569381.

[36] T. Arunkumar, K. Vinothkumar, A. Ashan, R. Jayaprakash and S. Kumar. Experimental study on a compound parabolic concentrator tubular solar still tied with pyramid solar still. 2012. [online] Available from: http://dx.doi.org/10.5772/49995. [Accessed 7 August 2017].

[37] T. Arunkumar. Compound parabolic concentrator-tubular solar still coupled with single slope solar still. Journal of environmental research and development, 2013, 7(4).

[38] S. Solanki, R. Soni, and P. Patel. Comparative study on hemispherical solar still with black ink added. International journal of engineering research and general science, 2014, 2(3), ISSN: 2091-2730

[39] H.J. Mosleh, S.J. Mamouri, M.B. Shafii and A.H. Sima. A new desalination system using a combination of heat pipe, evacuated tube and parabolic trough collector. Energy conversion and management, 2015, 99, pp.141-150.

[40] K. Chaithanya, V. Rajesh and R. Suresh. Experimental analysis of desalination unit coupled with solar water lens concentrator. IOP conf. series: materials science and engineering, 2016, 149.

[41] B. Chaouchi, A. Zrelli and S. Gabsi. Desalination of brackish water by means of a parabolic solar concentrator. Desalination, 2007, 217, pp.118-26.

[42] S.A. Abdul-Wahab and Y.Y. Al-Hatmi. Study of the performance of the inverted solar still integrated with a refrigeration cycle. Procedia engineering, 2012, 33, pp.424-434.

[43] T. Arunkumar and A. Ahsan. Effect of water flow on the concentrator coupled hemispherical basin solar still. International journal of applied and natural sciences, 2013,.2(1).

[44] T. Arunkumar, R. Velraj, D. Denkenberger, R. Sathyamurthy, K. Kumar and A. Ahsan. Productivity enhancements of compound parabolic concentrator tubular solar stills. Renewable energy, 2015, 88, pp.391-400.

[45] A.E. Kabeel, H.A. Edin and A. Alghrubah. Enhancing the performance of solar still using a solar dish concentrator under Egyptian conditions. Nineteenth international water technology conference, 2016, pp.21-23.

[46] M. Gnanadason, P. Kumar, V. Wilson, G. Hariharan and N. Vinayagamoorthi. Design and performance analysis of an innovative single basin solar nanostill. Smart grid and renewable energy, 2012, 4, pp.88-98.

[47] B. Panitapu, V. Koneru, S. Sagi and A. Parik. Solar distillation using nano-material. International journal of scientific engineering and technology, 2014,.3(5), pp.583-587.

[48] A. Singh and K. Singh. Performance evaluation of solar still with and without nanofluid. International journal of science, engineering and technology, 2015, 3(4).

[49] K. Sain and G. Kumawat. Performance enhancement of single slope solar still using nanoparticles mixed black paint. Advanced nanoscience and technology, 2015, 1(1).

[50] S. Sharshir, G. Peng, L. Wu, N. Yang, F. Essa, A. Elsheikh, S. Mohamed and A. Kabeel. Enhancing the solar still performance using nanofluids and glass cover cooling: experimental study. Applied thermal engineering, 2016, 113, pp.684-693.

[51] A.E. Kabeel, Z.M. Omara and F.A. Essa. Numerical investigation of modified solar still using nanofluids and external condenser. Journal of the Taiwan institute of chemical engineers, 2017, 75, pp.77-86.

[52] J. Navale, R. Kumbhar and K. Bhojawani. Experimental study of masonic solar still by using nanofluid. International engineering research journal, 2016, pp.984-987.

[53] T. Chaichan and A. Kazem. Water solar distiller productivity enhancement using concentrating solar water heater and phase change material (PCM). Case studies in thermal engineering, 2015, 5, pp.151-159.

[54] F. Al-hamadani and S. Shukla. Water distillation using solar energy system with lauric acid as storage medium. International journal of energy engineering, 2011, 1, pp.1-8.

[55] M. Gowtham, M. Chander, S. Mallikarujanan and N. Karthikeyan. Concentrated parabolic solar distiller with latent heat storage capacity. International journal of chemical engineering and applications, 2011, 2(3).

[56] D.C. Kantesh. Design of solar still using phase changing material as a storage medium. International journal of scientific and engineering research, 2012, 3(12).

[57] H.N. Panchal, M. Doshi, P. Chavda and R. Goswami. Effect of cow dung cakes inside basin on heat transfer coefficients and productivity of single basin single slope solar still. International journal of applied engineering research, 2011, 1(4).

[58] S. Ramasamy and B. Sivaraman. Heat transfer enhancement of solar still using phase change materials (PCMs). International journal of engineering and advanced technology, 2013, 2, pp.2249-8958.

[59] N. Sarada, H. Bindu, R. Devi and R. Gugulothu. Solar water distillation using two different phase change materials. Applied mechanics and materials, 2014, pp.2409-2415.

[60] N. Somanchi, S. Sagi, A. Kumar, D. Kakarlamudi and A. Parik. Modelling and analysis of single slope solar still at different water depth. International conference on water resources, coastal and ocean engineering, 2015, 4, pp.1477-1482.

[61] M. Khan and I. Nwaz. Analysis and modelling of single slope solar still at different water depth. Journal of energy technologies and policy, 2016, 6(9).

[62] S. Agrawal. Distillation of water using solar energy with phase change materials. International journal of engineering research and applications, 2015.

[63] D. Sonawane O. Jadhav, M. Patil and V. Jambuti. Research paper on enhancing solar still productivity by optimizing angle of PCM embedded absorber surface. International journal of science technology and engineering, 2015, 2.

[64] A. Kuhe and A. Edeoja. Distillate yield improvement using a parabolic dish reflector coupled single slope basin solar still with thermal energy storage using beeswax. Leonardo electronic journal of practices and technologies, 2016, 28, pp.137-146.

[65] T. Arunkumar, D. Denkenberger, R. Velraj, R. Sathyamurthy, H. Tanaka and K. Vinothkumar. Experimental study on a parabolic concentrator assisted solar desalting system. Energy conversion and management, 2015, 105, pp.665-674.

[66] B. Hari and J. Kishore. Evacuated stepped basin solar still with PCM and intermittent water collector. International journal for research in applied science and engineering technology, 2015, 3(8).

[67] M. Kumar, S. Kumar and H. Manchanda. Design, fabrication and thermal analysis of a stepped solar still with phase change materials. International journal for scientific research and development, 2016, 4(5).

[68] P. Gnanaraj, S. Ramachandran and G. Mageshwaran. Experimental analysis of single basin solar still with internal reflector and sensible heat storage medium. International journal of chem tech research, 2016, 9(8), pp.328-337.

[69] B.A Jenis, D. Lawrence and S. Jayabal. Effective design of solar still by using phase change material. American-eurasian network for scientific information, 2016, 10(6), pp.110-114.

[70] A.A. El-Sebaii, A.A. Al-Ghamdi and F.S. Al-Hazmi. Thermal performance of a single basin solar still with PCM as a storage medium. Applied energy, 2009, 86, pp.1187-1195.

[71] S. Suneja and G.N. Tiwari. Parametric study of an inverted absorber triple effect solar still. New Delhi: Centre for energy studies, 1999.

[72] A. Madhlopa. Development of an advanced passive solar still with separate condenser. Ph.D. dissertation, University of Strathclyde: Energy systems research unit, Glasgow, 2009.

[73] A.Y. Hashim. A new design of a single slope double-basin solar still (SSDBS). Journal of basrah researches (sciences), 2011, 37(2).

[74] B. Prasad and G.N. Tiwari. Analysis of double effect active solar distillation. Energy conversion and management, 1996, 37.

[75] M.I. Ahmed, M. Hrairi and A.F. Ismail. On the characteristic of multistage evacuated solar distillation. Renewable energy, 2009, 34.

[76] N. Panchal. Enhancement of distillate output of double basin solar still with vacuum tubes. Journal of king saud university – engineering sciences, 2013, 27, pp.170-175.

[77] T. Rajaseenivasan, T. Elango and K.K. Murugavel. Comparative study of double basin and single basin solar stills. Desalination, 2013, 309, pp.27-31.

[78] S.I. Kaliappan, M.D. Rajkamal, V.G. Ganesan and P. Manikadan. Experimental investigation on single basin and double basin solar desalination. Int J Chem Sci, 2016, 14(2), pp.1121-1132.

[79] P.K. Nithin and R. Hraiharan. Experimental analysis of double effect type solar still integrated with liquid flat plate collector. International journal of emerging engineering research and technology, 2014, 2(7).

[80] A. Bhattacharyya. Solar stills for desalination of water in rural households. International journal of environment and sustainability, 2013, 2(1), pp.21-30.

[81] L. Patil, A. Hole and S. Wankhede. Parameters affecting productivity of solar still and improvement techniques: a detailed review. International journal of engineering technology, management and applied sciences, 2017, 5(2).

[82] N. Panchal. Effect of different parameters on double slope solar still productivity. International journal of advances in engineering sciences, 2011, 1(2).

[83] D. Kumar, P. Himanshu and Z. Ahmad. Performance analysis of single slope solar still. International journal of emerging technology and advanced engineering, 2013, 3(3).

[84] P. Shankar, R. Sharma, B. Gupta and H. Parmar. Effect of colour and Al_2O_3 nanoparticles on efficiency of the solar still. SSRG international journal of thermal engineering, 2015, 1(5).

[85] R. Alvarado-juarez, J. Xaman, G. Alvarez and I. Hernandez-Lopez. Numerical study of heat and mass transfer in a solar still device: effect of the glass cover. Desalination, 2014, 359, pp.200-211.

[86] H. Ambarita, I. Abdullah, C.A. Siregar, R.E.T. Siregar and A.D. Ronowikarto. Experimental study on melting and solidification of phase change material thermal storage. IOP Conf series – material science and engineering, 2017.

[87] L. Malaeb, M. Ayoub and M. Al-hindi. The effect of cover geometry on the productivity of a modified solar still desalination unit. Energy procedia, 2014, 50, pp.406-413.

[88] S. Zedan and S. Eldin. An experimental investigation of the factors which affect the performance of a single basin typical double slope solar still for water desalination. Energy and power engineering, 2015, 7, pp.270-277.

[89] E.C. Nnamani. Lack of access to potable water supply and its impact on the Nigerian rural communities. 2018. [online] Available from: https://www.researchgate.net/publication/328389481. [Accessed 10 January 2021]

[90] G. Howard and J. Bartram. Domestic water quantity, service, level and health. Geneva: WHO document production services, 2003.

[91] S. Jasrotia, A. Kansal and V.V.N. Kishore. Application of solar energy for water supply and sanitation in arsenic affected rural areas: A study for kaudikasa village, India. Journal of cleaner production, 2013, 60, pp.102-106.

[92] A. Karima and S. Islam. Drinking water desalination using low-cost tubular solar still. Applied water science, 2019, 10(4).

[93] M.S. Bala, S. Aminu, U. Sadik, A.A. Safana and A.I. Usman. Design and construction of solar still-solar water heater hybrid for small scale application. Journal of alternate energy sources and technologies, 2018, 8(2).

[94] A. Madhlopa and C. Johnstone. Potential for water distillation by using solar energy in Malawi. Glasgow: Energy systems research unit, university of Strathclyde, 2008.

[95] H. Fiestas, E.A. Sanchez, M. Quinde and A.M. Cumpa. Implementation of a pilot plant for distilling water using solar energy. Proceedings of the world congress on engineering and computer science, San Francisco. 2016, 2.

[96] M.B. Pasache, H. Fiestas and E.A. Sanchez. Assessment of bottled water for the province of sechura(peru) from initiative of a pilot plant that purifies the water from a spring using solar energy. Universidad de piura, 2018.

[97] R.E. Foster, M. Romero, G.R. Vogel, M. Cormier, W. Amos, S. Eby-Martin and V. Gupta. Solar distillation providing potable water for border colonias. Nevada: America solar energy society, 2002.

[98] H.H. Kopperdal. Design, prototyping and field testing of solar stills in remote areas in Afghanistan. Norwegian university of life science, 2015.

[99] A. Al Faruq, S. Akter, Alamin and Z. Islam. Desalination of water using conventional basin type solar still. Global journal of researches in engineering, 2013, 13(3).

[100] H. Kemp. The suns river solar still. Desalination and water purification research and development program report, 2013, 168.

[101] D. Markham. The watercone: A simple, effective solar still. Water for life, 2009. [online] Available from: https://insteading.com/blog/the-watercone-a-simple-effective-solar-still/ [Accessed 7 June 2020]

[102] Aquadome Solar Water Still: Using the sun's energy to distill impure water. [online] Available from: https://www.speedplastics.co.uk/aquadome-solar-water-still/ [Accessed 17 January 2021].

[103] ClearDome Solar Thermal Pure Water Pasteurizer and Cooker. [online] Available from: http://cleardomesolar.com/solarpurewaterstill.html [Accessed 17 January 2021].

[104] Rainmaker 550 Solar Distiller. [online] Available from: https://readymaderesources.com/product/rainmaker-550-solar-distiller-free-shipping/ [Accessed 17 January 2021].

[105] SolAqua: Rainkit 990 and DIY kit plan. [online] Available from: http://www.solaqua.com/solaquakit2.html?viewfullsite=1 [Accessed 17 January 2021].

[106] ''Eliodomestico: Solar Terracotta Water Filter Distills 5 Liters of Water a Day,'' last modified January 17, 2021, https://inhabitat.com/eliodomestico-solar-terracotta-water-filter-distills-5-liters-of-water-a-day/