Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27063

222 (2021) 23–35
May

Challenges and progress made toward the improvement of a multistage solar still desalination system

Mfanafuthi Mthandeni Mkhize, Velaphi Msomi*

Cape Peninsula University of Technology, Faculty of Engineering and the Built Environment, Mechanical Engineering Department, P.O. Box: 1906, Bellville 7535, South Africa, emails: msomiv@gmail.com (V. Msomi), sggamkhize@gmail.com (M.M. Mkhize)

Received 31 July 2020; Accepted 24 January 2021

ABSTRACT

The shortage of potable water has been a growing concern globally. This concern has led to the development of systems and devices that can be used to produce freshwater from seawater or any contaminated water. Solar still is one of the devices that was developed mostly for seawater purification. This device works with the principle of evaporation and condensation for freshwater production. Solar still can be categorized as single-stage or multistage depending on the design. This paper reviews briefly the various designs of multistage solar stills with stacked stages. The current work found that the evacuated system with flowing waterbed achieved the highest distillate output of 28.04 and 53.21 kg/m^2/d at atmospheric pressure and 0.03 bar vacuum pressure, respectively. However, a standalone multistage system produced on average about 7.36 L/m^2/d with flat plate solar collector (FPSC) and 16 L/m^2/d with evacuated tube solar collector (ETSC), respectively. The approximated cost of producing distillate per gallon (CPG) ranges from 0.00182993–0.3631 $/gal. The challenges that are associated with each design are also reviewed. Recommendations and future outlook which would guides the future researches has also been presented.

Keywords: Multistage; Stagnant waterbed; Flowing waterbed; Solar still; Stacked trays; Seawater desalination

---

1. Introduction

Access to clean and uncontaminated freshwater is a necessity for a healthy life and some processes are involved in obtaining water fit for human consumption [1]. There are various ways of producing fresh and healthy water and one of them is through solar still systems. Solar still and renewable energy applications have been observed for centuries [2]. Solar stills have become progressively popular in recent years and more so in the 20th and 21st centuries [3]. This is partly, if not entirely, due to the need to invent new alternative means to produce fresh drinking water [4]. The solar stills have evolved from simple solar stills which were mainly passive and to more complex active solar stills [2]. In achieving the active and sophisticated solar still, solar panels and collectors have played a great role in facilitating their advancements. Many researchers have explored the active solar still concept, either for small-scale or large-scale water production.

However, these explorations have not come without setbacks. This is because, in designing, constructing, and commissioning a solar still there are some costs attached to the process. Due to these costs, one must minimize the cost of building such a system to avoid making the design incredibly unattractive. Some of the costs attached to the life of a solar still are operational costs such as regular filling of saline water and testing of the distillate quality. Maintenance costs are the removal of salt deposits, maintenance of vacuum pumps, electric controls, fans, and others [5]. However, the cost of constructing a multistage solar still is not considered steep compared to other forms of water desalination systems [6].

---

* Corresponding author.

1944-3994/1944-3986

Economically exploited conventional energy resources have become increasingly limited because of their natural limitations. Their use is also questioned by large population groups, especially in industrialized countries. They are questioned due to their adverse impact on the environment and their contribution to global climate change. Solar still as an alternative to fossil fuels has been improved in different ways over the years. Many modifications to improve the performance of solar still have been made. These include linking the desalination process with the solar energy collectors, incorporating several effects to recover the latent heat of condensation, improving the configurations and flow patterns to increase the heat transfer rate, and using low-cost material in construction to reduce the costs [7].

The demand for renewable energy resources comes as fossil fuels have reached their natural limitation, growing population, urbanization, automation, and other contributing factors [8]. There are many renewable energy processes for water desalination. These processes include but are not limited to electrodialysis for saline water desalination discussed in a detailed assessment study by Campoine et al. [9] and Alkhadra et al. [10]. Seawater reverse osmosis (SWRO) coupled with wind, solar, and other types of renewable energy are pursued by some researchers such as Penate and Garcia-Rodriguez [11]. Renewable energies, like any other systems, are faced with challenges of their own. The state of renewable energy technologies and the guidelines on the selection of renewable energy-powered desalination processes, as well as the costs coupled with them, is reported by Eltawil et al. [12]. Desalination systems that are coupled with renewable energy sources instead of fossil fuels as a source of energy are viewed as attractive because of the renewable energy aspect [13]. However, some costs may be reduced through the use of locally available material for the construction of a solar still [14]. A review study on the global applicability of renewable energy processes was conducted by Pugsley et al. [15]. In addition, renewable energy has become a formidable competitor to fossil fuels and solar energy could replace fossil fuels entirely in water purification processes [16]. Various studies have been performed in analyzing the feasibility of using renewable energy as a source of energy for desalination systems [17–26].

There are different ways of water desalination, but the literature surveyed has been narrowed to solar still desalination systems. The operation of a simple basin type solar still is explained by Li et al. [27], in a review study. Simple solar stills are cheap and easy to construct; however, the multistage system is relatively expensive compared to simple solar stills [28]. The solar still systems are mainly dependent on weather conditions [29]. Solar radiation plays an important role in the production of distillate [30]. A desalination system with improved configuration to recover the latent heat was studied by Liu et al. [31]. According to the study, the heat recovery process is most effective on a sunny day when the solar intensity is higher and the rate at which the heat is recovered and re-used is higher compared to a cloudy day. Solar stills have enough water for few people on a small scale but crucial techniques that can be employed to improve solar desalination systems were reported by Sivakumar and Sundaram [32].

One such solar system was reported in the literature as an adaptable wind/solar-powered hybrid system [33]. The design produces 17.4 kg/m^2/d of freshwater and the study acknowledges the need to find alternative means to produce fresh drinking water as most regions are water-scarce. In light of an adaptable hybrid system studied by Soni et al. [33], the reduction in environmental-polluting resources can be implemented. A system coupled with an evacuated tube solar collector (ETSC), flat plate solar collector (FPSC), and/or photovoltaic panels is said to be active [34]. Active stills are known to yield more distillate than passive solar stills. Their capital costs per liter of distillate yield per day are relatively lower. The high costs of active solar still are as a result of the upkeep of the system which is fixed [35,36].

The purpose of this paper is to mainly review the improvement made towards the multistage solar still system with stacked stages. There are various reviews found in the literature that deal with many types of solar thermal systems [12,37,30,16,32,38]. However, the current review work solely deals with the solar thermal desalination process of a multistage with stacked stage systems. This work takes a closer look at the historical development of the multistage and how it has evolved. One aspect that is of interest in this study is the nature of heat transfer within the multistage tower. Amongst the three modes of heat transfer, namely conduction, convection, and radiation. Convection, which involves a bulk fluid motion has a high rate of heat exchange [39]. Therefore, the productivity of the multistage stills is compared based on the nature of the waterbed (i.e., stagnant and flowing waterbed) in the stages. The vapor generation and freshwater capturing on each reviewed design are also discussed. This review is also attempting at discussing the challenges that are faced with each design. It is anticipated that this review assists in understanding the most performing multistage solar still and the challenges associated with it.

2. Multistage solar still with waterbed

This section reviews the different types of multistage solar stills with stack stages and a stagnant waterbed. A waterbed is defined as the seawater or saline that is fed on the stages before the operation of the system. There two types of waterbed-based multistage solar still, that is, stagnant waterbed-based and flowing waterbed-based multistage solar still. The following sections review the status of the improvement made on these two types of settings in the solar stills.

2.1. Stagnant waterbed

Adhikari et al. [40] conducted a simulation study on a multistage solar still with stack stages. The multistage solar still used for this simulation was coupled with an auxiliary immersion electric heater. The simulated system used gravity for water circulation in the system. Various temperature values were used in conducting the performance of the system. The temperature values used for analysis were based on those obtained from the experimental setup used to validate the numerical analysis. The simulated system used mixed shapes for the stage trays, that is, rectangular and V-shaped stages. Stage one tray was rectangular except for the intermediate stage trays. The maximum depth of seawater in each stage was kept at 5 cm. Jubran et al. [41] developed the mathematical model to be used in analyzing the performance of the multistage solar still.

The system used for the analysis comprised of three stages. The developed system used the heat recovery principle and the expansion nozzle as a way of enhancing the performance of the system. Fig. 1 shows a redrawn representation of a multistage with an expansion nozzle to enhance the productivity of the solar still. The stage trays were all designed to be inclined which is different from the above-mentioned system. The solar panel was used as the source of energy to drive the heat exchanger located at the bottom stage. The heat input values used for the numerical analysis were based on the daily average solar intensity for the Middle East and this location was chosen because the system was proposed for such areas. The simulation results were found to be higher compared to the experimental results tested under similar conditions. The same conditions produced the distillate efficiency of about 87%.

Schwarzer et al. [6] conducted a study of a new standalone multistage solar still with stack stages that can operate using solar energy only. Four multistage solar stills were tested in different locations. A multistage solar still consisted of between 5 and 7 stages stacked on top of each other with a heat recovery process. The multistage solar still had removable stages that can be removed, cleaned, and replaced. Since only solar energy was required to supply thermal energy to the solar still, the multistage solar still was, therefore, suitable for remote areas. Furthermore, the parameters such as depth of water in the stage, number of stages, tilt angle of the stage trays, area of each tray, and others were also studied. However, the findings of the parameters were not reported in the study. The four multistage solar still prototypes were divided into two systems and were tested simultaneously, one system was coupled with an FPSC and the other coupled with ETSC. When testing drinking water, 32–60 L of distillate was produced, and when the seawater was tested 20% reduction in the distillate yield.

Ahmed et al. [42] conducted a study on the characteristics of an evacuated multistage solar still. Multistage solar still was coupled with a vacuum pump to enhance the distillate yield. Each stage was maintained at a pressure below atmospheric pressure. The pressure gradient $P_1 > P_2 > P_3$ was maintained in the stages, that is, the pressure in stage two was lower than the pressure in stage one. Saline water was supplied from the tank positioned at the top of the stacked stages. The thermal energy was supplied to the system through circulating water between the collector and the heat exchanger. The study was experimentally conducted in an actual setting with solar radiation as a heat supplier and a solar panel as a collector. To enhance the productivity of a multistage system, the study employed the use of a vacuum pump to remove incondensable gases and reduce the pressure in each stage. The distillate yield of the system at 0.7 and 0.5 bar was reported to have increased by 20% and 45%, respectively compared to the atmospheric conditions of 1 bar. The maximum distillate production was achieved at the lowest pressure of 0.5 bar. Fig. 2 shows a redrawn representation of a typical multistage solar still with a waterbed in the stages. One stage of the still was modeled on a computer software FLUENT to determine the influence of varying heights of a solar still. It was reported that the height of the system has some profound influence on the productivity of the solar still. Increasing the height reduces the still's productivity. Finally, the conclusion was that the distillate yield of a multistage solar still is approximately three times that of the basin type solar still. However, it is

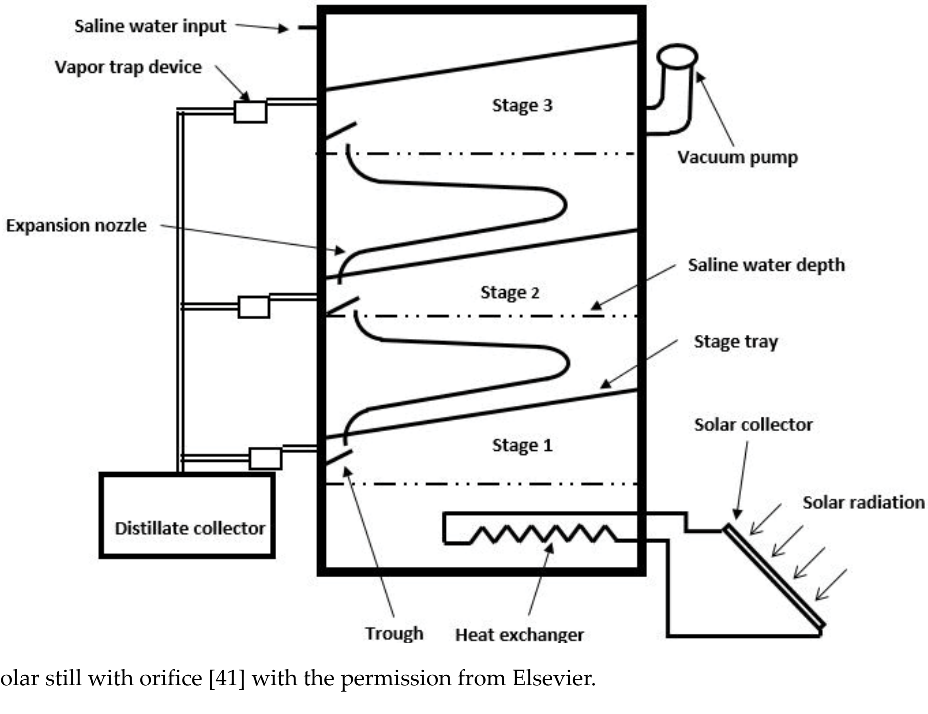

Fig. 1. Multistage solar still with orifice [41] with the permission from Elsevier.

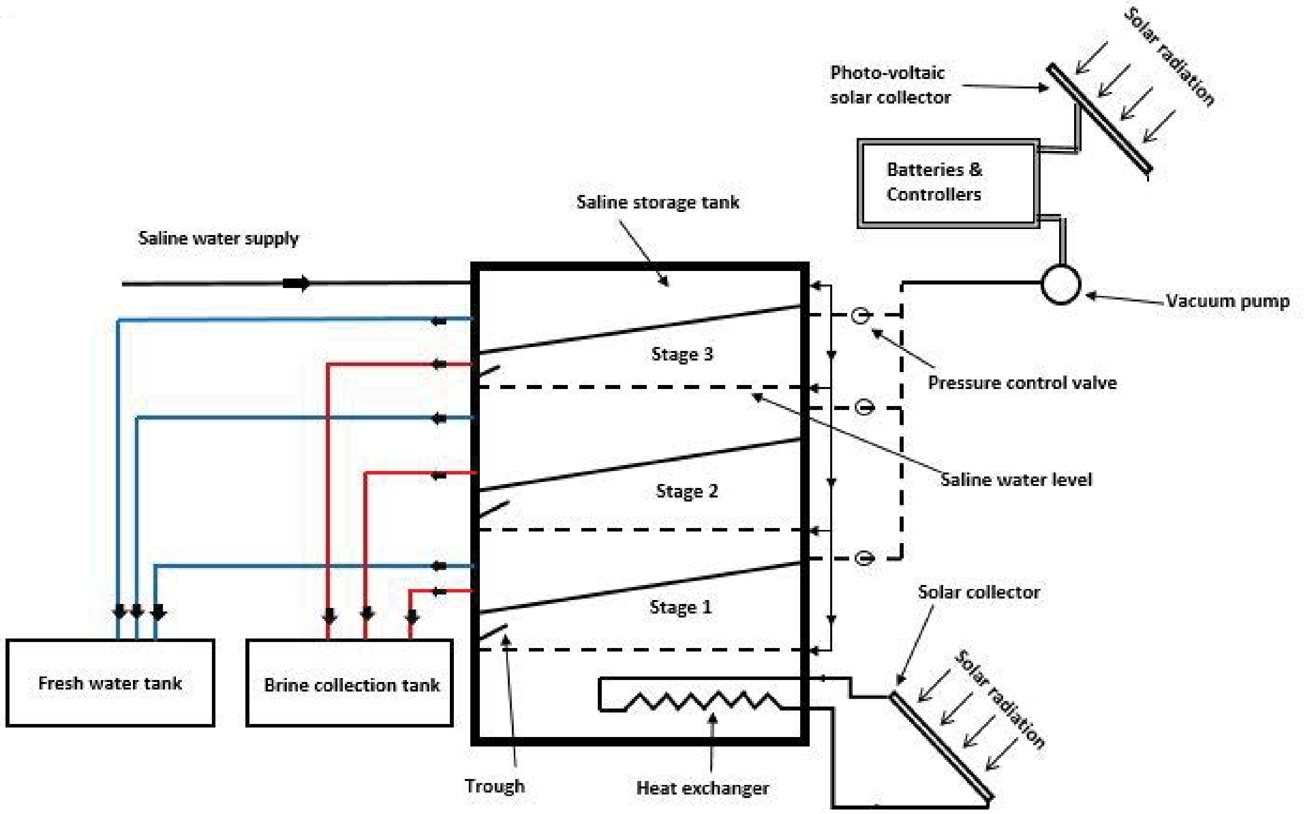

Fig. 2. Multistage solar still with stacked stages and waterbed [42] with the permission from Elsevier.

not clear whether the comparison was made between multistage solar still and a passive basin type solar still or an active one. The cost analysis of the study stated that 1 gallon would cost 0.02544 $, 1 gallon is equivalent to 3.785 L.

Shatat and Mahkamov [43] conducted a study to determine the rational design parameters of a multistage solar still using transient mathematical modeling. The system was tested in a simulated environment using prepared synthetic brackish water and an electric heater (floodlights). A prototype consists of a multistage and an ETSC with a closed-loop thermosiphon circuit. The intermittency and the pattern of solar radiation were taken into account during the tests. It was reported that for a given solar collector and a fully insulated solar still, the system reaches a condition referred to as "thermal damage". The thermal damage is when the condensing trays reach a temperature above the evaporation surface which stops the distillation process altogether. The first and second stages reached temperatures of 99°C–100°C, while the fourth reached 80°C. When the system was partially insulated with only the top tray left un-insulated, the system functioned well without reaching thermal damage. In the analysis of the quality of distilled water, it was reported that the distilled water far exceeds the satisfactory limit determined by the World Health Organization (WHO). Furthermore, the optimum number of stages was determined to be 4 or 5 for stage trays with 1 m^2 dimension and an ETSC of 1.7 m^2.

Singh et al. [44] conducted a performance evaluation of low inertia multistage solar still. The stack trays of the system were corrugated as opposed to a flat surface. The trays of a multistage were a series of small inclined surfaces at 15° to ensure that each "V" shape incline holds a minimal amount of saline water. The downward-facing "A" shape surfaces are used to collect the condensate. It was reported that distillate yield on lower stages is higher due to high water temperatures and temperature differences during the day. The upper stages yield more distillate at night-time due to high-temperature difference in those stages. The maximum distillate yield occurred at 1.5 m^2 of the evaporation area of the stage trays. The annual distillate yield was found to be 2,223 L/m^2. On average, 2,223 L/m^2/y for 300 d amounts to 7.41 L/m^2/d. Theoretical distillate yield was found to be 10% higher than experimental distillate yield. Therefore, less than 10% is 6.669 L/m^2/d for the experimental distillate yield.

Estahbanati et al. [45] conducted an experimental investigation study on the effect of the number of stages on a multistage solar still. Saline water was supplied from the saline water tank positioned on top of the stack stages of the system. Thermal energy was supplied to the system through heat transfer oil heated up by the electric heater. The energy input into the system was modeled in accordance with solar radiation. Furthermore, distillate yield was experimentally tested under two modes, continuous and non-continuous mode. The study was simulated indoors and an electric heater was used in place of a solar collector. It was reported that for optimum distillate collection, the stage trays are positioned at a certain angle. An angle of 8°

was used after a 5° angle was experimentally determined. Fig. 3 shows a representation of a typical stage of a multistage solar still with stacked trays inclined at an angle.

The non-continuous mode was experimentally tested for a period of 24 h. During a non-continuous mode, brackish water was fed to the system only once at the beginning of an experiment. It was reported that the non-continuous mode experienced some delays in producing the distillate. This was because of the thermal energy dissipation from the saline water over a period of 24 h. Furthermore, feeding relatively cold brackish water after 24 h, meant a delay in the production of the distillate. The delay was due to the heat supplied from the bottom of the system and the upper stages took a while to receive the thermal energy and start the evaporation process.

However, the continuous mode was tested continuously with the saline water maintained at its level. It thus did not experience a similar delay because of the heat stored in the saline water. The lower stages produced more distillate during the daytime while the upper stages produced more at night-time. The productivity patterns of lower and upper stages during day and night time are similar to the trend reported by Singh et al. [44]. Adding more than one stage increases the distillate output more on a continuous mode than a non-continuous mode. Furthermore, adding up to 10 stages in a continuous mode increases each stage output by 1 kg. However, a non-continuous mode with six stages only produces about 23.8 kg/d. It was reported that the overall distillate output of the still is increased by adding additional stages.

Comparing the continuous and the non-continuous mode in terms of the distillate yield. The continuous mode shows that by adding the 4th stage on a three-stage system, the distillate yield improves dramatically to 27.1 kg/d. However, the non-continuous mode shows a slight increase to 22.9 kg/d in the distillate produced when the fourth stage is added. Finally, according to the study, the cost of producing the distillate is 0.2 $/stage which amounts to 0.8 $ in total for a four-stage system.

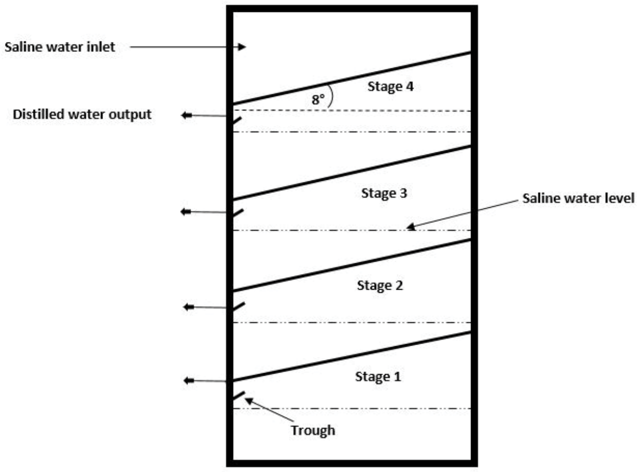

Fig. 3. Stage trays at 8° from the horizontal [45] with the permission from Elsevier.

Feilizadeh et al. [46] conducted a study on the same system studied by Estahbanati et al. [45]. However, Feilizadeh et al. [46] studied experimentally the effect of amount and mode of input energy on the performance of a multistage solar still. An electric heater that simulated solar radiation was used in an experimental study. Varying distillate yield over different collector over basin (CBA) ratios was determined. The distillate production was found to be a quadratic function of the CBA ratio. Also, thermal energy storage (TES) improved system productivity by 5%–10% in terms of its productivity. When the installation cost is considered, it was suggested that only when the CBA is higher, that is, if the area of a collector is much larger than that of a basin and the system cannot operate at high temperatures, the TES can be augmented.

The TES can then be used to store thermal energy. Furthermore, feeding the energy impulsively to the system results in a sudden increase in temperatures in the stages as well as distillate production. It was reported that the distillate produced varies under different modes of energy feeding to the system. Also, distillate yield variation follows the temperature variation in the stages. In addition to the above, distillate production increases with the increase in energy input. The lower stage (stage one) produced more distillate than the rest of the stages above and the impulse mode of energy input increased the still's productivity by a small margin. A similar trend was observed in the study by Singh et al. [44], and Estahbanati et al. [45], distillate yield is higher in the lower stages.

Bait and Si-Ameur [47] conducted a numerical investigation on multistage solar still, the effect of solar radiation term on mass and heat energy balance was investigated. The numerical study was simulated based on the fluctuation of the solar radiation of a local area where the study was conducted. It was reported that the FPSC should be inclined at an angle equal to the latitude of the area for optimum operation. A closed-loop thermosiphon cycle was used to supply the thermal energy to the system under natural mode. The stages were designed into "V" shaped trays to collect the condensate. A multistage system could operate at a temperature of 80.96°C. The bottom trays of the first stage were varied to study the effect of different areas on evaporation.

Enhanced evaporation was achieved on the largest area of 1.2×0.4 m^2. It was reported, as reported by all the studies above, that lower stages generate more distillate than the upper stages. The study reported that the evaporation area in the basin of the system affects the distillate yield. The proposed system was similar to the one studied by Adhikari et al. [40] in terms of the main components of the system. However, the numerical analysis predicted results based on actual settings and thus, the distillate yield estimated is lower.

Chen et al. [48] studied a multistage solar still with stack stages intending to analyze the heat and mass transfer mechanism in a system. Also, the study experimentally analyzed the performance of the still as well. The stage trays were corrugated along the surface as described by Singh et al. [44]. A multistage system was designed in such a way that stage trays were stack on top of one another and the last stage was constructed in the shape of a basin-type solar still with a single slope.

The last stage had a transparent glass to receive direct solar radiation directly from the sun rays. It was reported that the distillate produced in the third (last tray) stage was more than that of the first stage. During the simulation, an electric heater was used to simulate the heat supplied by the solar collector on the first experiment. Under actual weather conditions, an ETSC with an aperture area of 0.9 m^2 was used as a source of thermal energy. Due to the adverse effects boiling of saline water has, the temperature of the system was maintained below 100°C. It was reported that temperatures beyond boiling point reduce the production rate of the distillate. This study was different in that, the ETSC was inserted directly into the first stage of the system. Therefore, a natural convection mode was used to pre-heat and evaporate the saline water in the basin.

Soni et al. [33] studied a wind-solar hybrid system for wastewater treatment. The system was described as self-sustaining and it can be installed in a household. Wind energy was used to pump wastewater from the ground up to the roof where desalination takes place. The system was operated under partial vacuum conditions created by a vacuum pump in the stages. The last stage was exposed to the sun's rays to heat the saline water in this stage directly from the sun as done by Shatat and Mahkamov [43] and Chen et al. [48]. The vacuum pressure is such that $P_1 > P_2 > P_3 > P_4$ as described by Jubran et al. [41]. The study stated that cleaning of the stage trays has to be done daily due to foreign and contaminating residue on the trays left by wastewater.

A solar collector that supplies heat to the bottom stage of the multistage solar still was operated with a thermosiphon cycle under natural circulation. According to the study, the system was operated under a constant solar flux and it did not simulate the variation of solar radiation. It was reported that increasing the number of stages beyond four has an insignificant effect on the productivity of the still. Thus, increasing the stages is not economically justifiable. It was reported that a 50 kg/m^2/d wastewater circulation and a depth of 5 cm be maintained in the system as recommended by Adhikari et al. [40]. The wastewater used was from the household and therefore, the salt content is relatively lower compared to brackish and seawater obtained from the ocean.

Abdessemed et al. [49] conducted a study on the design of stage trays. The "V" and "A" shaped trays are shown in Figs. 4 and 5. The figures are a redrawn representation of the multistage studied. It was reported that the "V" shaped trays are more effective and they produced about 1,370 mL of freshwater. This shape yields more distillate per unit of energy used. On the other hand, the second set of trays called "A" shaped tray yielded less distillate per unit of thermal energy used at 1,020 mL. It was reported that in both cases of two different types of trays, the lower stages produce more distillate than the upper stages because of an elevated temperature in the lower stages. It was further reported that the saline water in the "A" shaped trays are in constant contact with the thin outer walls and thus heat is lost to the surrounding through conduction.

In the "V" shaped trays, the saline water is concentrated in the middle of the tray where the temperature is maximum, and thus more evaporation occurs, and a minimal heat lost through the thin outer wall of the still was observed. Also, the "A" shaped trays have two distillate collectors which increase the loss of distillate. However, further details on how the distillate collector (trough) increases the loss of the distillate are not discussed in detail. In all the studies reviewed above, their maintenance and operational costs are higher compared to the passive or active single slope basin type solar still. However, El-Bailey et al. [24] conducted the cost analysis review study and concluded that active solar still is more expensive than passive solar still.

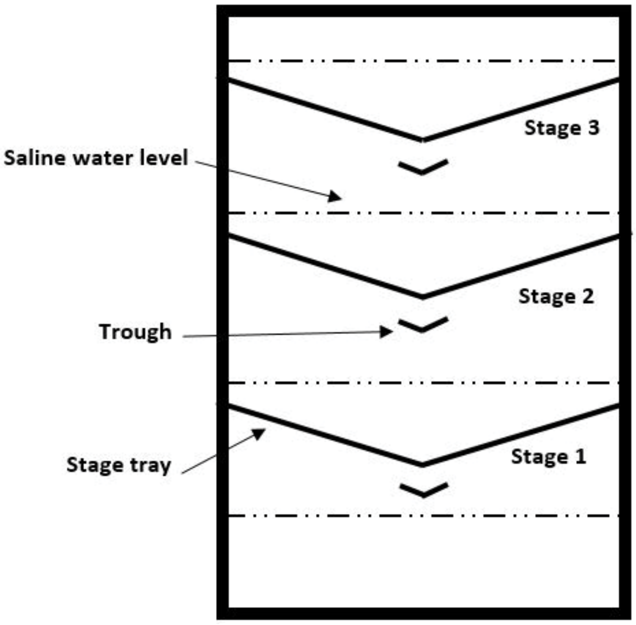

Fig. 4. "V" shaped trays [49] with the permission from Elsevier.

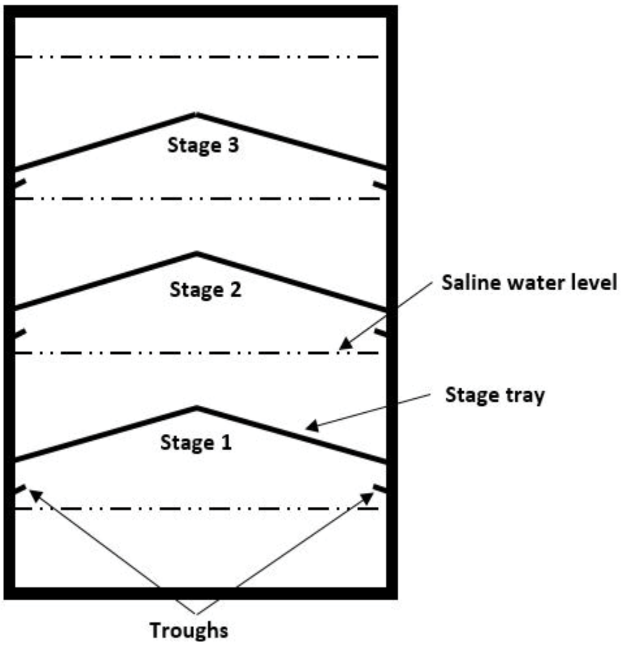

Fig. 5. "A" shaped trays [49] with the permission from Elsevier.

The concentration techniques such as ETSC, FPSC, etc., should be used as this results in improved distillate output per day with relatively low capital costs. Even though their costs are higher but their advantage is high distillate output compared to passive or active basin type solar still. There are other factors that should be considered when selecting a type of energy source as locally available and cheap source reduces the cost of producing distilled water [14]. Table 1 summarizes the performance of the various solar still system. It should be noted that there's very little work performed recently under a similar subject hence limited literature.

2.2. Flowing waterbed

This section reviews the different types of multi-stage solar stills with stack stages and flowing waterbeds. The waterbed is defined as the seawater or saline that is fed on the stages before the operation of the system. The flowing waterbed in a stage is a flow rate of saline water maintained over the surface of the trays for the duration of experimental testing. The following section reviews the status of the improvement made on these types of setting in the solar stills. The chronological order of the year the systems were studied is followed to track the improvement over the years. The advantage of heat transfer through a fluid with bulk motion is described by Cengel [39].

Franco and Saravia [50], introduced a new design on multistage solar still with stack stages. The study was conducted through experimental tests as well as numerical calculations for comparison. The trays of the stages were inclined at an angle to allow the saline fed from the top to flow down under the influence of gravity. The trays were at an angle of 25° and the cotton fabric was used on the surface of the trays to ensure the distribution of saline water over the entire surface of the tray as it flows down. Fig. 6 shows a redrawn representation of stage trays and the saline direction of flow only. Saline water was fed from the last tray of the stack stages and allowed to flow under the influence of gravity until it reached the bottom tray. The heat is transferred through the stages is in a similar fashion as in a system with a stagnant waterbed. The only difference is that the cold saline water is poured from the top stage. Experiments were done using an electric heater to supply thermal energy in the lower stage. Varying saline water flow and temperatures were used in determining the distillate yield of the system. It was stated that the increase in saline water flow through the system does not have a significant effect on the overall distillate output. However, there are some noticeable increases in distillate produced in individual stages.

The decrease in tray temperature decreases the distillate output. Furthermore, the excess heat was removed by ejecting warm brine from the tray and a minimum water depth of flow rate was recommended. According to the study, a prototype showed a distillate yield of 5 L per hour per square meter. Also, decreasing the number of stages

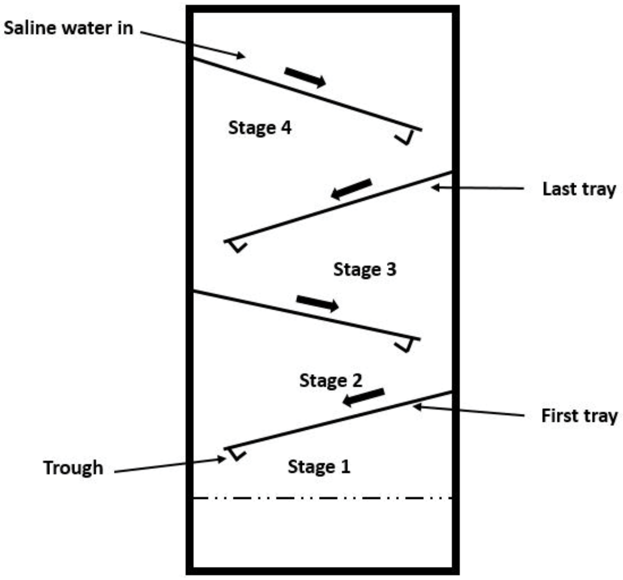

Fig. 6. Inclined stage trays [50] with the permission from Elsevier.

Table 1
Multistage solar still performance

System type	Energy type	No. of stages	Output	Author(s)
Multistage	Auxiliary immersion heater	3	2 kg/h	Adhikari et al. [40]
Multistage	Solar panel	3	9 kg/m^2/d	Jubran et al. [41]
Multistage	FPSC and ETSC	5–7	15–18 L/d	Schwarzer et al. [6]
Multistage	Solar collector	3	14.2 kg/m^2/d	Ahmed et al. [42]
Multistage	ETSC	4–5	9 kg/d	Shatat and Mahkamov [43]
Multistage	FPSC	5	7.41 kg/m^2/d	Singh et al. [44]
Multistage	Solar collector	4	27.1 kg/d	Estahbanati et al. [45]
Multistage	Solar collector	4	9.54 kg/d	Feilizadeh et al. [46]
Multistage	FPSC	4	8.88 kg/d	Bait and Si-Ameur [47]
Multistage	ETSC	4	7.29 kg/d	Chen et al. [48]
Multistage	FPSC	4	17.4 kg/m^2/d	Soni et al. [33]
Multistage	Electric heater	4	1,370 mL	Abdessemed et al. [49]

increases the distillate yield while the performance ratio decreases.

Schwarzer et al. [51] developed an enhanced solar thermal desalination system through the incorporation of the heat recovery system. Before the construction of the multistage system, the single-stage unit was constructed and tested using controlled conditions. The single-stage unit was used to determine the number of parameters required for the construction of the main system. The performance of the main system was tested using the actual field conditions. The main system was designed such that the latent heat from the condensation process is used to heat the next stages. The flat plate and vacuum tube collectors were used as the mode of water heating mechanism. The stages of this system were designed on the A-shaped type. A maximum of seven stages was built for the tested systems. The gravity was used to feed seawater to the stages. It was discovered that the performance of the system during the night is not far off from the day production. The performance of this system was found to be 3–5 times more than a similar system without the heat recovery mechanism.

Reddy et al. [34] conducted an elaborate analysis on an evacuated multistage system with series and parallel connections of the FPSCs. The distillate yield from freshwater, saline water, brackish water, and brine water was analyzed. The stage trays were inclined at an angle of 16° and their surfaces were covered with a porous silk cloth. A saline water tank was situated at the top of the stack stages and the saline water was supplied through the parallel or series configured FPSC. The stages of the system were maintained at lower pressure through the process of evacuating the stages as done by Soni et al. [33], Jubran et al. [41], and Ahmed et al. [42]. The series connection was reported to yield less distillate compared to a parallel connection due to heat losses between the collectors. It was stated that the heat loss in the series connection is higher than that of the parallel connection which results in a parallel connection yielding more distillate than the series connection. Therefore, parallel-connected collectors were further analyzed.

The effect on the number of stages was computed on a stage(s) operated at atmospheric pressure. The analysis found that for maximum year-round performance the optimum number of stages is 4. It was also reported that varying saline water mass flow rate affects the distillate yield of the system. Decreasing it from 150 to 55 kg/d, enhanced the distillate yield but decreasing any further to 30 kg/d, also decreases the distillate yield. Furthermore, an optimum gap between the stage trays was found to be 100 mm for that system, as a reduction of the gap to 100 mm also increased the distillate yield. It was further reported that increasing the number of stages beyond five stages has no effect on the distillate yield and this is the case throughout the year.

Furthermore, the vacuum pressure in the stages can only be reduced to a certain pressure and not beyond that. This is because the temperature difference between the stages decrease causing the vapor condensation to slow down and thus decreasing the distillate output. Finally, it was reported that the salt content in the water reduces evaporation by as much as 20%. Table 2 summarizes the performance of the various solar still system. It should be noted that there's very little work performed recently under a similar subject hence limited literature.

3. Challenges faced by a multistage solar still with a waterbed in the stages

This section discusses the challenges and the factors affecting a multistage solar still with stack stages and waterbed in the stage. This applies to both systems with a stagnant and flowing waterbed in the stages.

3.1. Salt content and other related contaminants

According to Soni et al [33], Adhikari et al. [40], and Schwarzer et al. [51], seawater (saline water), brackish water, or wastewater comes into contact with the stage trays and contaminates the trays. The saltwater residue clogs the lining of the stages over time due to impurities contained in seawater and regular maintenance and cleaning are required. Depending on the method used to clean the stages, structural integrity, and vapor tightness may be affected. The stagnant waterbed also means that the salt deposits accumulate in the stage over time. The higher the salinity concentration and the bigger the size of the pool of water (waterbed), the less evaporation rate [52].

3.2. Stack stages dependency

A multistage solar still whether with a stagnant or flowing waterbed in the stage is faced with similar challenges. Those challenges are the dependency of their stacked stages on one another. In other words, the stages above stage one, (stage two) depend on it (stage one) to supply the thermal energy through the latent heat of condensation to function and produce the distillate [34,40]. Since the system has a heating source at the base and waterbed in the stages, heat is transferred through latent heat of condensation to the rest of the stacked stages. The base of the system receives its thermal energy from a solar collector, this type of heating is referred to as indirect heating [40]. The stage dependency is such that, should one of the lower

Table 2
Distillate yield from the water with different salinity levels

System type	Energy type	No. of stages	Output	Author(s)
Multistage	Electric heater	4	5 L/m^2/d	Franco and Saravia [50]
Multistage	FPSC	5	25 L/m^2/d	Schwarzer et al. [51]
Multistage	Solar panel	4	28.04 kg/m^2/d	Reddy et al. [34]

stages fails or experience any problem, the heat will not be transferred effectively further up the stacked stages. The failure of one of the bottom trays of the system means that the rest of the upper stage will not yield any distillate.

3.3. Trough or condensate collector

When the condensate is formed at the bottom of the trays, it is collected and stored in a distillate collecting tank. However, not all droplets formed as a result of condensation are collected. Abdessemed et al. [49] reported that due to the design of the trough, some droplets trickle back into the pool of saline water in the stage. This is not a problem of one specific system but all the systems discussed in section two have a similar design. Whether the trough is positioned along with an inclined tray [47], or at the bottom of an inclined tray [45]. However, the exception is with designs such as those studied by Singh et al. [44] and Chen et al. [48] corrugated trays have better condensate collection rates compared to the other designs. Soni et al. [33] reported that the condensing surface of a tray must be at an angle such that the condensate does not fall back into the pool of saline water but is collected by the trough.

3.4. Stagnant waterbed on an inclined stage tray

A system with a stagnant waterbed in the stage means that an even or leveled saline water depth cannot be maintained as the saline water is shallow on the upper end of an inclined tray and deeper on the lower end of the tray. Fig. 7 shows a redrawn representation of a multistage solar still with a stagnant waterbed in the stages only. The depth of water at the lower end of the upper stage tray is directly proportional to the angle of the tray. That is, the higher the tray's angle, the deeper the saline water at this point. A 5 cm saline water depth recommended by Adhikari et al. [40], cannot be maintained.

3.5. Trend of distillate output from individual stages

A system with a waterbed whether stagnant or flowing waterbed in the stages shows a trend that lower stages yield more distillate than the upper stages. Table 3 shows evidence that the lower stages yield more distillate than the upper stages [46,47]. However, multistage solar still such as those studied by Reddy et al. [34] and Chen et al. [48] show a different trend as the last stage was producing more distillate. In the literature surveyed, some studies presented a cumulative distillate yield and each stage was not reported based on their individual yield.

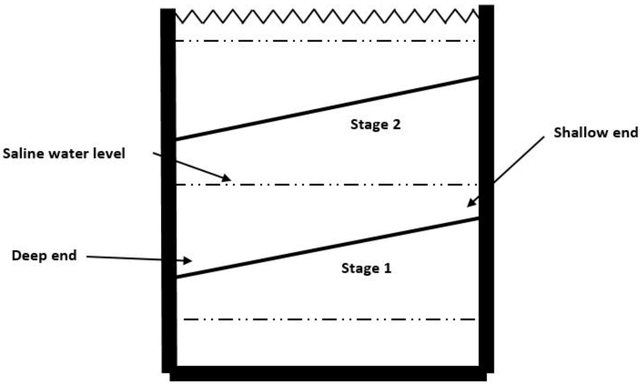

Fig. 7. Stage trays with unequal saline water depth [42] with the permission from Elsevier.

Table 4 shows the distillate yield in the study conducted by Abdessemed et al. [49]. It can be seen from the table that lower stages produce more distillate. The production decreases as the stages increase in an upward direction.

Table 5 shows the results of different distillate yields from individual stages of the evacuated multistage solar still. The results show that the uppermost stage produces the most distillate while the first stage yields less. Furthermore, Table 6 shows the total accumulative distillate yield at different feed water and pressures. The data shows that decreasing the pressure in the stages below atmospheric pressure enhanced distillate yield in the stages. The percentage increase refers to the comparison of the distillate yield at atmospheric and vacuum pressures.

4. Economics and costs related to multistage solar still

This section presents a brief economic analysis of multistage solar stills. Unless stated otherwise, these analyses are based on the studies conducted by El-Baily et al. [24], Fath et al. [53], and Adhikari et al. [54]. The salvage value (S) is an estimated value of the equipment (solar

Table 3
Distillate yield of each tray of a multistage solar still with stacked trays and a flowing waterbed

Description	Distillate per stage (kg/h)	Temperature per stage (°C)
Stage 1	0.3	82.2
Stage 2	0.27	70.5
Stage 3	0.22	53.2
Stage 4	0.14	27
Total	0.93	
Author(s)	Franco and Saravia [50]	

Table 4
Distillate yield of each stage of multistage solar still with stacked trays and a stagnant waterbed

Description	Distillate per stage (kg/h)	Temperature per stage (°C)
Stage 1	310	53.7
Stage 2	235	50.9
Stage 3	145	45.3
Stage 4	110	43
Total	1,120	
Author(s)	Abdessemed et al. [49]	

Table 5
Distillate yield of each tray of a multistage solar still with stacked trays and flowing waterbed

Description	Distillate per stage (kg/h)
Stage 1	0.85
Stage 2	4.17
Stage 3	9.45
Stage 4	13.58
Total	28.04
Author(s)	Reddy et al. [34]

still) after depreciation is complete. Present capital cost (*P*), is the total cost required for all the work to be done to complete the solar still from designing to commissioning. Annual cost (AC), is the cost incurred due to ownership, operation, etc. of the solar still annually. Cost of distillate production per gallon (CPG), sinking fund factor (SFF) is used to calculate the future value of the equipment as it depreciates over the months and years. Fixed annual cost (FAC), is the fixed cost that is attached to the equipment and it does not change with varying distillate yields of the still. Capital recovery factor (CRF), is the ratio of constant returns to the value of equipment for a given time. Annual maintenance cost (AMC) is estimated at 15% FAC [53]. Annual interest is represented by *i* (%) and the number of years (*n*) the equipment is productive:

$$\text{CRF} = \frac{i(1+i)^n}{\left[(1+i)^n - 1\right]} \tag{1}$$

$$\text{FAC} = P \times \text{CRF} \tag{2}$$

$$\text{SFF} = \frac{i}{\left[(1+i)^n - 1\right]} \tag{3}$$

$$\text{ASV} = \text{SFFP} \times S \tag{4}$$

$$\text{AC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{5}$$

$$\text{CPG} = \frac{\text{AC}}{M} \tag{6}$$

$$S = 0.2P \tag{7}$$

Schwarzer et al. [6] reported that a system coupled with an ETSC consumed 0.175 kWh/L. For economic and cost consideration, one location (India) on which the systems were tested is chosen. An average rupee to dollar exchange rate in 2009 was $1 = Rs. 75.04669 [55]. Therefore the CPG was determined to be 0.126 $/gallon. For Chen et al. [48], the yuan to dollar exchange rate was approximately 6.70 to one dollar and the electricity tariffs were about 0.13 kWh per unit of electricity in 2015–2016 [56]. Therefore, the CPG is estimated to be 0.3631 $/gallon. The CPG reported by Abdessemed et al. [49] is seemingly lower compared to other systems, however, some of the fundamental costs were not taken into account in the techno-economic analysis of that study. The cost comparison between the system with flowing and stagnant waterbed was not performed. This was due to the unavailability of data in some of the studies and existing reviews in the literature. However, amongst those that were analyzed, Chen et al. [48] had the highest CPG at 0.3631 $/gal. The costs of the multistage solar stills are comparatively higher than those of the passive systems [12,24,37]. These costs are justified by the enhanced distillate output relative to passive systems. Table 7 shows distillate cost per gallon of distillate water produced of that system with available data for economic analysis.

5. Recommendations and future outlook

It is recommended that the hot saline water be recirculated as far as possible before it is disposed off for the multistage system, especially in the systems with flowing waterbed. When the brine is rejected from the system, it should be stored in a tank where the feed water (saline water) is stored. This will allow the transfer of heat from the heated brine to the feed water. The feed water and the brine should be separated by a thin layer of material, preferably an aluminum sheet. This will ensure that the feedwater enters the system at a pre-heated temperature. According to Morad et al. [57], saline water have different salinities, therefore, a study to determine the limiting levels of salinity in the brine in the system would assist is in determining an estimated brine disposal period. It is also recommended that pumps that require electricity should not be used in circulating/recirculating the saline water. This would reduce the fixed cost and thereby reducing the CPG as well. Amongst the systems found in the literature, the stage dependency on each other within the multistage has

Table 6
Total cumulative distillate yields from varying feed water and pressures below atmospheric pressure

Pressure (bar)	Feedwater	Distillate per stage (kg/m²/d)	Percentage increase (%)	Author(s)
0.03	Freshwater	53.21	96.75	Reddy et al. [34]
0.02	Brackish water	42.04	76.44	
0.02	Saline water	40.26	73.13	
0.02	Brine solution	33.05	60.09	

Table 7
Cost associated with the production of the distillate

Total distillate cost/L ($/gallon)	Author(s)
0.0256	Jubran et al. [41]
0.02544	Ahmed et al. [42]
0.1063	Estahbanati et al. [45]
0.126	Schwarzer et al. [6]
0.05139	Bait and Si-Ameur [47]
0.3631	Chen et al. [48]
0.0284–0.06813	Soni et al. [33]
0.00182993–0.002665	Abdessemed et al. [49]

not evolved with time and thus a different approach may yield different results. Despite the condensing tower being insulated, these systems have a large body area exposed to convective heat loss by ambient air. Therefore, the height of these systems should be reduced to make them more compact and easy to carry [Reddy et al. [34], Ahmed et al. [42]. Harnessing the thermal energy and using to perform other function (i.e., circulation of saline water within the system) can be an added advantage to the multistage.

Even though these systems generally produce small quantities of clean water, there is a promising future for the multistage system with stacked stages. These systems can be driven by any energy source and they have the potential to be self-sufficient. In addition, they have the advantage of requiring less infrastructure Eltawil et al. [12], which requires less maintenance and upkeep. They can be completely independent of the traditional electrical grid as presented by Schwarzer et al. [51]. Since their stages are stacked on top of the other, they are compact and occupy less floor space compared to basin solar still with the same collecting area. As far as heat transfer is concerned, there are limitless methods, flow patterns, configurations that can be employed to recover latent and sensible heat and reuse it as seen in the literature. A waterless stage (no waterbed) is one method that can be adapted to eradicate the need to open and clean the vapor-tight trays which may affect the vapor tightness and the integrity of the system. The waterless stage would also help in reducing the gap between the stages which will reduce the overall height of the system. These systems are small-scale and decentralized compared to the traditional desalination systems. Therefore, when commercialized, they can locally produce fresh water for a typical household continuously and with fewer maintenance costs in remote areas.

6. Concluding remarks

The current work has reviewed the multistage system with stacked stages. A multistage solar still with stack stages and waterbed in the stages have been studied over the years. Despite the limited literature on the subject, some advancements have been made such as:

- Evacuating the condensing tower to enhance evaporation.
- Incorporating expansion nozzles to enhance heat transfer in the stages.
- Enlarging the solar energy collection area by series and parallel connection of the collectors.
- Employing various stage tray shapes (designs) and orientation to enhance distillate collection.
- Exposing the last stage (top stage) to solar radiation for direct heating by the sun rays.

A multistage solar still with stack stages and waterbed in the stages have been studied over the years. Different researchers have contributed to the improvement of the system by introducing new configurations, vapor flow patterns, coupling the still with solar collector, pumps, and other equipment. The analysis of different aspects of the system has been carried out to better understand the workings of the still and thereby enhancing distillate yield from the system. The recently developed evacuated multistage systems with flowing waterbed is relatively higher at 53.21 kg/m^2/d than that of the stagnant waterbed at 16 L/m^2/d. The higher cost per distillate yield can be justified by the higher yield compared to a passive still. Furthermore, it is a view of this study that the improvements are limitless and new configurations can still be introduced to enhance distillate output, contribute to ease of operation, and minimize maintenance as well as operational costs. The costs associated with the construction, maintenance, and operation of the system throughout its life are relatively higher than that of a passive still. These costs are substantially increased when additional equipment (i.e., pumps) are integrated into the multistage. The CPG of the reviewed multistage systems has been found to range from 0.00182993 to 0.3631 $/gal.

Data availability statement

The data supporting this review are from previously reported studies and datasets, which have been cited. The processed data are available from the corresponding author upon request.

Funding

Thuthuka Grant from National Research Foundation [118046].

Acknowledgments

The authors would like to thank the Cape Peninsula University of Technology (CPUT) Mechanical Engineering workshop staff for their continued support.

References

[1] A. Gadgil, Drinking water in developing countries, Annu. Rev. Energy Environ., 23 (1998) 253–286.
[2] E. Delyannis, Historical background of desalination and renewable energies, Sol. Energy, 75 (2003) 358–366.
[3] P.J.K. Mbadinga, A Solar Water Purification System for Rural Areas, South Africa, MTech Thesis, Cape Peninsula University of Technology, Cape Town, 2015.
[4] L. Furter, Solar Distillation Solves Rural Water Problem: Consulting, Vol. 29, IMIESA, 2004, 59 p.
[5] A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills, Desalination, 276 (2011) 1–12.

[6] K. Schwarzer, E.V. da Silva, B. Hoffschmidt, T.A. Schwarzer, A new solar desalination system with heat recovery for decentralized drinking water production, Desalination, 248 (2009) 204–211.
[7] J. Bundschuh, J. Hoinkis, Renewable Energy Applications for Freshwater Production, 2nd ed., CRC Press/Balkema, London, 2012, 6 p.
[8] F. Trieb, H. Muller-Steinhagen, Concentrating solar power for seawater desalination in the Middle East and North Africa, Desalination, 220 (2008) 165–183.
[9] A.L. Campoine, M. Gurreri, G. Ciafalo, A. Micale, T.A. Cipollina, Electrodialysis for water desalination: a critical assessment of recent developments on process fundamentals, models and applications, Desalination, 434 (2018) 121–160.
[10] M.A. Alkhadra, T. Gao, K.M. Conforti, H. Tian, M.Z. Bazant, Small-scale desalination of seawater by shock electrodialysis, Desalination, 476 (2020) 114219, doi: 10.1016/j.desal.2019.114219.
[11] B. Penate, L. Garcia-Rodriguez, Current trends and future prospects in the design of seawater reverse osmosis desalination technology, Desalination, 284 (2011) 1–8.
[12] M.A. Eltawil, Z. Zhengming, L. Yuan, A review of renewable energy technologies integrated with desalination system, Renewable Sustainable Energy Rev., 13 (2009) 2245–2262.
[13] J.H. Rief, W. Alhalabi, Solar-powered desalination: its significant challenges and potential, Renewable Sustainable Energy Rev., 48 (2015) 152–165.
[14] A.A. Badran, A.A. Al-Hallaq, I.A.E. Salman, M.Z. Odat, A solar still augmented with a flat plate collector, Desalination, 172 (2004) 227–234.
[15] A. Pugsley, A. Zacharopoulos, J.D. Mondol, M. Smyth, Global applicability of solar desalination, Renewable Energy, 88 (2015)200–219.
[16] M. Thirugnanasambandam, S. Iniyan, R. Goic, A review of solar thermal technologies, Renewable Sustainable Energy Rev., 14 (2010) 312–322.
[17] E. Chafik, A new type of seawater desalination plants using solar energy, Desalination, 156 (2003) 333–348.
[18] B.A. Shaffi, S.J. Mamouri, M.M. Lotfi, H.J. Mosleh, A modified solar desalination system using evacuated tube collector, Desalination, 396 (2016) 30–38.
[19] S.W. Sharshir, G. Peng, N. Yang, M.A. Eltawil, M.K.A. Ali, A.E. Kabeel, A hybrid desalination system using humidification-dehumidification and solar still integrated with evacuated solar water heater, Energy Convers. Manage., 124 (2016) 287–296.
[20] Z.H. Liu, R.L. Hu, L. Lu, F. Zhao, H.S. Xiao, Thermal performance of an open thermosyphon using nano fluid for evacuated tubular high temperature air solar collector, Energy Convers. Manage., 73 (2013) 135–143.
[21] Z. Xu, L. Zhang, L. Zhao, B. Li, B. Bhatia, C. Wang, K.L. Wilke, Y. Song, O. Labban, J.H. Lienhard, R. Wang, E.N. Wang, Ultrahigh-efficiency desalination via a thermally-localized multistage solar still, Energy Environ. Sci., 13 (2020) 830–839.
[22] L. Garcia-Rodriguez, Seawater desalination driven by renewable energies: a review, Desalination, 143 (2002) 103–113.
[23] G. Xiao, X. Wang, M. Ni, F. Wang, W. Zhu, Z. Lou, K. Cen, A review on solar stills for brine desalination, Appl. Energy, 103 (2012) 642–652.
[24] E. El-Baily, S.M. Shalaby, A.E. Kabeel, A.M. Fathy, Cost analysis for several solar desalination systems, Desalination, 384 (2016) 12–30.
[25] S.W. Sharshir, G. Peng, L. Wu, N. Yang, F.A. Essa, A.H. Elsheikh, S.I.T. Mohamed, A.E. Kabeel, Enhancing the solar still performance using nanofluid and glass cover cooling: experimental study, Appl. Therm. Eng., 113 (2016) 684–693.
[26] E. Sartori, Solar still versus solar evaporation: a comparative study between their thermal behaviors, Sol. Energy, 56 (1996) 199–206.
[27] C. Li, Y. Goswami, E. Stefanakos, Solar assisted seawater desalination: a review, Renewable Sust. Energy Rev., 19 (2012) 136–163.
[28] R.A. Van Steenderen, Studies on the efficiency of solar desalination still for supplementing drinking water supplies is southwest Africa, Water SA, 3 (1977) 1–4.
[29] H.E.S. Fath, Solar distillation: a promising alternative for water provision with free energy, simple technology and clean environment, Desalination, 116 (1998) 45–56.
[30] H.N. Panchal, S. Patel, An extensive review on different design and climatic parameters to increase distillate output of a solar still, Renewable Sustainable Energy Rev., 69 (2016) 750–758.
[31] Z.H. Liu, H.Y. Guan, G.S. Wang, Performance optimization study on an integrated solar desalination system with multi-stage evaporation/heat recovery processes, Energy, 76 (2014) 1001–1010.
[32] V. Sivakumar, E.G. Sundaram, Improvement techniques of solar still efficiency: a review, Renewable Sustainable Energy Rev., 28 (2013) 246–264.
[33] A. Soni, J.A. Stagner, D.S.K. Ting, Adaptable wind/solar powered hybrid system for household wastewater treatment, Sustainable Energy Technol. Assess., 24 (2017) 8–18.
[34] K.S. Reddy, K.R. Kumar, T.S. O'Donovan, T.K. Mallick, Performance analysis of an evacuated multi-stage solar desalination system, Desalination, 288 (2012) 80–92.
[35] O.O. Badran, H.A. Al-Tahaineh, The effect of coupling a flat-plate collector on a solar still productivity, Desalination, 183 (2005) 137–142.
[36] E.C. Joubert, S. Hess, J.L. Van Niekerk, Large-scale solar water heating in South Africa: status, barriers and recommendations, Renewable Energy, 97 (2016) 809–822.
[37] H. Sharon, K.S. Reddy, A review of solar energy driven desalination technologies, Renewable Sustainable Energy Rev., 41 (2014) 1080–1118.
[38] Z.M. Omara, A.E. Kabeel, A.S. Abdullah, A review of solar still performance with reflectors, Renewable Sustainable Energy Rev., 68 (2016) 638–649.
[39] Y.A. Cengel, Heat and Mass Transfer: A Practical Approach, 2nd ed., McGraw-Hill, New York, NY, USA, 2003, pp. 334–343.
[40] R.S. Adhikari, A. Kumar, G.D. Sootha, Simulation studies on a multi-stage stacked tray solar still, Sol. Energy, 54 (1995) 317–325.
[41] B.A. Jubran, M.I. Ahmed, A.F. Ismail, Y.A. Abakar, Numerical modelling of a multi-stage solar still, Energy Conserv. Manage., 41 (2000) 1107–1121.
[42] M.I. Ahmed, M. Hrairi, A.F. Ismail, On the characteristics of multistage evacuated solar distillation, Renewable Energy, 34 (2008) 1471–1478.
[43] M.I.M. Shatat, K. Mahkamov, Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling, Renewable Energy, 35 (2009) 52–61.
[44] P. Singh, P. Singh, J. Singh, R.I. Singh, K. Kundu, Performance Evaluation of Low Inertia Multi-Stage Solar Still, Proceeding of the International Multi Conference of Engineers and Computers Scientists, Hong Kong, China, 2012.
[45] M.R.K. Estahbanati, M. Feilizadeh, K. Jafarpur, M. Feilizadeh, M.R. Rahimpour, Experimental investigation of a multi-effect active solar still: the effect of the number of stages, Appl. Energy, 137 (2014) 46–55.
[46] M. Feilizadeh, M.R.K. Estahbanati, A.S. Ardekani, S.M.E. Zakeri, K. Jafapur, Effects of amount and mode of input energy on the performance of a multi-stage solar still: an experimental study, Desalination, 375 (2015) 108–115.
[47] O. Bait, M. Si-Ameur, Numerical investigation of a multi-stage solar still under Batna climatic conditions: effect of radiation term on mass and heat energy balances, Energy, 98 (2016) 308–323.
[48] Z. Chen, J. Peng, G. Chen, L. Hou, T. Yu, Y. Yao, H. Zheng, Analysis of heat and mass transferring mechanism of multi-stage stacked-tray solar seawater desalination still and experimental research on its performance, Sol. Energy, 142 (2016) 278–287.
[49] A. Abdessemed, C. Bougriou, D. Guerraiche, R. Abachi, Effects of tray shape of a multi-stage solar still coupled to a parabolic concentrating solar collector in Algeria, Renewable Energy, 132 (2019) 1134–1140.
[50] J. Franco, L. Saravia, A new design for a passive atmospheric multistage still, Renewable Energy, 4 (1994) 119–122.

[51] K. Schwarzer, M.E. Vieira, F. Faber, C. Müller, Solar thermal desalination system with heat recovery, Desalination, 137 (2001) 23–29.

[52] P.K. Abdenacer, S. Nafila, Impact of temperature difference (water-solar collector) on solar-still global efficiency, Desalination, 209 (2007) 298–305.

[53] H.E.S. Fath, M. El-Samanoudy, K. Fahmy, A. Hassabou, Thermal-economic analysis and comparison between pyramid-shape and single-slope solar still configurations, Desalination, 159 (2003) 69–79.

[54] R.S. Adhikari, A. Kumar, H.P. Garg, Techno-economic analysis of a multi-stage stacked tray (MSST) solar still, Desalination, 127 (2000) 19–26.

[55] Average Exchange Rate: March 2009 – September 2009 and Inflation Rates of GEF Donors. Available at: https://www.thegef.org/sites/default/files/council-meeting-documents/GEF_R5_Inf15_Rev1_Average_Exchange_Rates_and_Inflation_Rates_of_ GEF_Donors_5.pdf (accessed November 27, 2020).

[56] S. Han, B. Zhang, X. Sun, S. Han, M. HÖÖk, China's energy transition in the power and transport sectors from a substitution perspective, Energy, 10 (2017) 1–25.

[57] M.M. Morad, H.A.M. El-Maghawry, K.I. Wasfy, A developed solar powered desalination system for enhancing freshwater productivity, Sol. Energy, 146 (2017) 20–29.