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Solar still desalination systems: a comparative study and proposition of a new design based on the Internet of Things technique

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ABSTRACT

Solar still is the simplest form of solar desalination system, which allows freshwater production from a clean source of energy (solar radiation). Major research in this area focuses on improving the amount of daily production of desalinated water. Thus, a compromise between productivity, simplicity and economic feasibility should be taken into account. This work presents a brief overview of solar desalination systems existing in the literature, followed by a comparative study between different solar still designs. A new automatic solar still system is proposed, it consists of using a low-cost microcontroller with the Internet of Things for real-time monitoring of the solar still parameters (such as temperatures, relative humidity, and daily production of distilled water).

Keywords: Hybrid solar stills; Water desalination; Monitoring parameters; Microcontroller; Internet of Things

1. Introduction

Numerous solar desalination systems were developed in the literature. There are basically two processes of solar desalination systems: direct and indirect desalination processes. In fact, solar energy produces thermal energy which is needed for the water desalination process (direct systems) or by producing the electricity required to power the membrane process (indirect systems). Therefore, direct desalination systems use thermal energy to obtain desalinated water directly from solar still, and in indirect desalination systems, there are two units to produce distilled water which are the desalination process and solar collector. Different kinds of solar collectors like an evacuated tube, flat plate, the heat pipe can be used along with the thermal desalination technique such as membrane distillation and vapor compression [1], multi-stage distillation [2,3], multi-effect evaporation [4].

For large-scale production of desalination water up to 1.8 kWh/m^3 [5], reverse osmosis is the largest method used. While, for a small amount of distilled water, the direct system consists of evaporation and condensation in the same unit. There are different kinds of solar such as single and double slope solar still, pyramidal and cone, triangular and spherical still, and others, which are suitable for freshwater production [6].

Various configurations of solar stills were investigated in Al-Hayeka and Badran [7], Fath [8], Tayeb [9], Badran [10], Kabeel et al. [11]. More specifically designs were developed such as hemispherical solar still [12,13], pyramidal [14,15], double, triple and multiple basin [16–23], inverted absorber [24–27], tubular [28,29], compound parabolic concentrator (CPC) solar still [30], weir-type cascade [31], integrated basin using sandy reservoir [32], titled wick-type with reflector [33], active vibratory [34], and a plastic solar still [35]. A study was done to find a relation for

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predicting convective and evaporative heat transfer coefficients for different condensing surfaces under indoor simulation [36]. It was found that a higher yield was obtained with an increase in temperature for a 30° slope compared to the 15° and 45° slopes of the condensing cover. Another work was made to find out the convective heat transfer coefficient for an active solar distillation system [37]. This work studied the effect of different water depths in the basin on the heat and mass transfer coefficients. It was found that the convective heat transfer coefficient between water and inner condensing cover depends significantly on the water depth in the basin. Another work about the evaluation of the internal heat transfer coefficient of solar still was done on single and double-slope passive solar stills in different climatic conditions [38]. A very interesting work about solar distillation systems was given in Tiwari and Sahota [39]. In fact, a good history of passive solar-distillation systems was developed in this work. Recent work was done by Gopal Singh and Tiwari [40] in order to simulate the performance of solar still by using the iteration method for an internal convective heat and evaporative (mass) transfer coefficient which are used in basic energy balance equations.

The main objective of this paper is to present a brief overview of different solar still available in the literature and to make a comparison with the proposed new smart solar still system using the Internet of Things (IoT) technique to control and manage the still system. The different goals are as follow:

- Investigating the use of renewable energy systems in a water desalination plants.
- Design of a smart solar still water desalination prototype.
- Monitoring system for controlling online performance.
- Collecting data using the Internet of Things technique (IoT) via a web page for users.
- Controlling the quality of the water.

This paper is organized as follows: The principle of solar still desalination with different types of still systems is given and presented in Section 2. In Section 3, a new design of solar still using a smart monitoring system based on the Internet of Things (IoT) technique is proposed. The different factors influencing the performance of solar stills are given in Section 4. Section 5 presents the yearly cost of freshwater production and a comparison between the existing solar still and the new still proposed in this work. Conclusion and outlook are presented in the last Section 6.

2. Principle of solar still desalination

Solar desalination systems consist of two processes, direct and indirect processes as illustrated in Fig. 1.

In this work, the direct processes of different solar still designs are presented. Regarding the direct process, the same unit called solar still allows evaporation and condensation. Such units are more applicable to produce a small amount of distilled water per day. The others type of solar still such as single and double slope are suitable to meet freshwater demand. The simplicity in the design of solar stills and their low cost do not need high energy as illustrated in Fig. 2 [41].

Different solar desalination designs were made using the same principle. Solar energy is transferred to thermal energy by global warming and then the salt water is heated until evaporation. This allows increasing the density of water vapor which is condensed at the inner surface of the cover, and then due to the gravity, the condensed

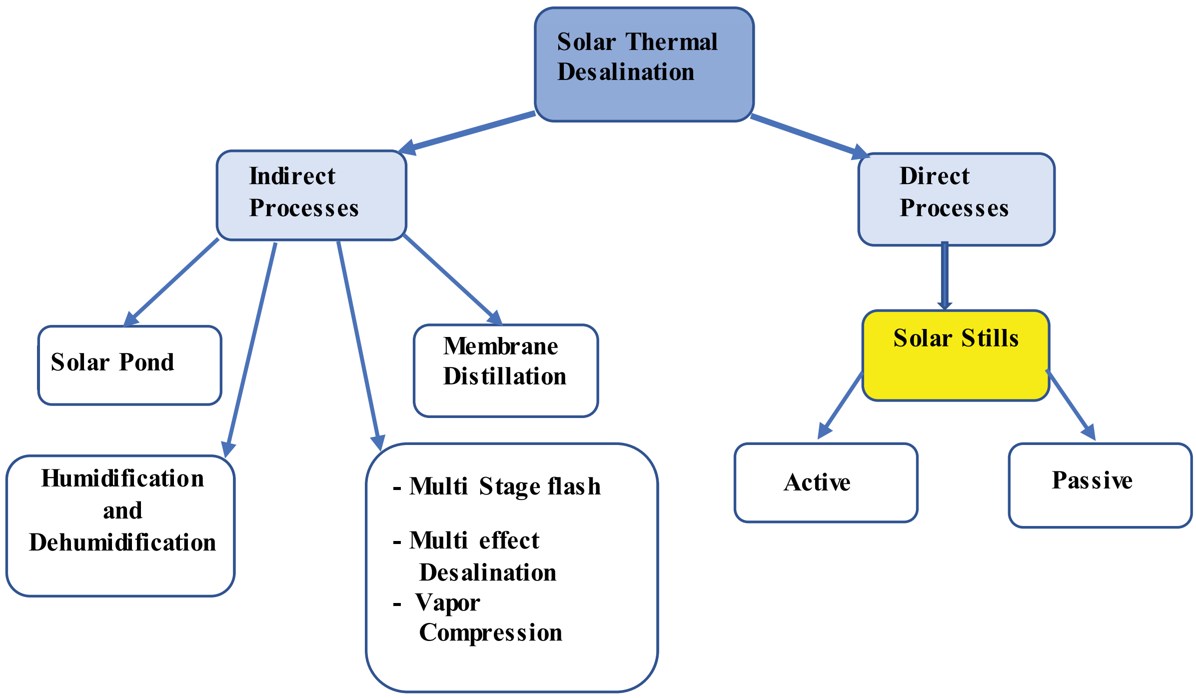

Fig. 1. Solar thermal water desalination processes.

water trickles down and is collected in a metric recipient in order to calculate the amount of distilled water per day [42].

The main advantages of solar stills consist of their simplicity and their low cost. They can be used for water desalination for different sources of saline water like sea water, brackish water and groundwater for drinking and irrigation purposes.

To increase the efficiency of stills [44], many techniques were proposed for this purpose such as the use of reflectors, concentrators and preheating the saline water. In fact, different methods can be realized to preheat the salted water using a flat plate collector or other techniques.

2.1. Types of solar still

A solar still is constituted by a saline water basin which is covered with a tilted glass sheet as indicated in Fig. 3 [43]. Solar irradiation heats the salt water in the basin and allows evaporation of water. The water vapor condenses at the inner side of the cover glass and is then collected into a condensate channel. The black liner of the basin absorbs more solar irradiation and then improves the heating of the solar still and allows evaporation of salt water.

There are two kinds of solar stills: active and passive stills. The passive stills are based only on solar thermal [20]. The active stills use external energy sources in order

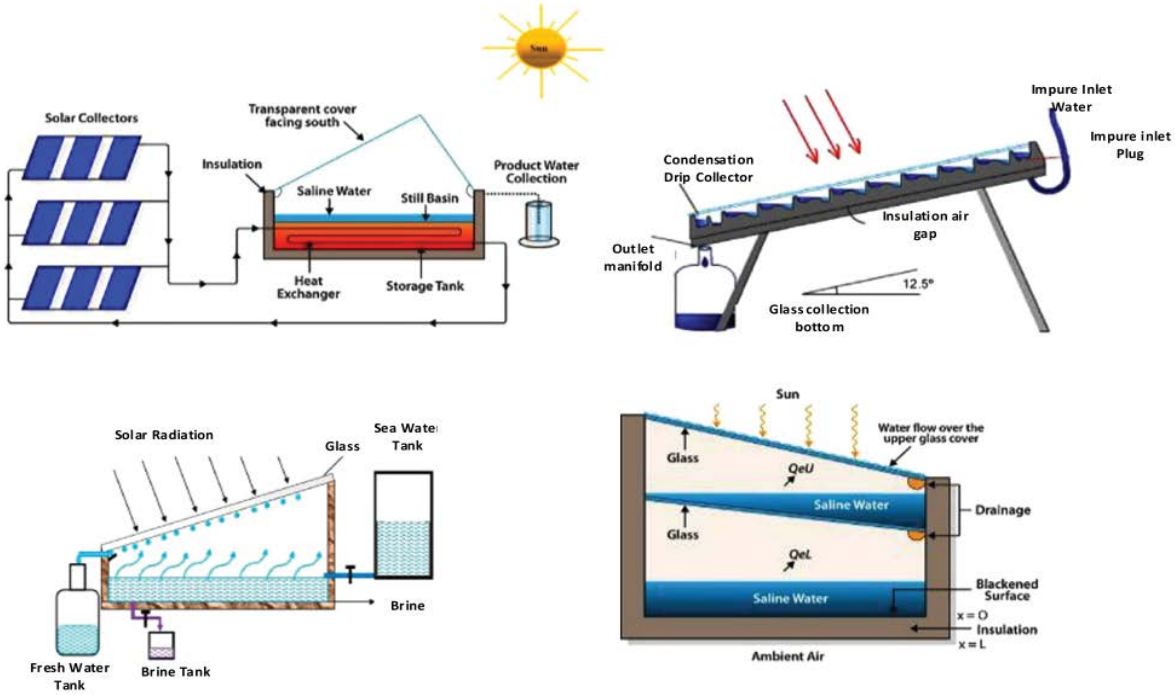

Fig. 2. Simple solar still architectures [41].

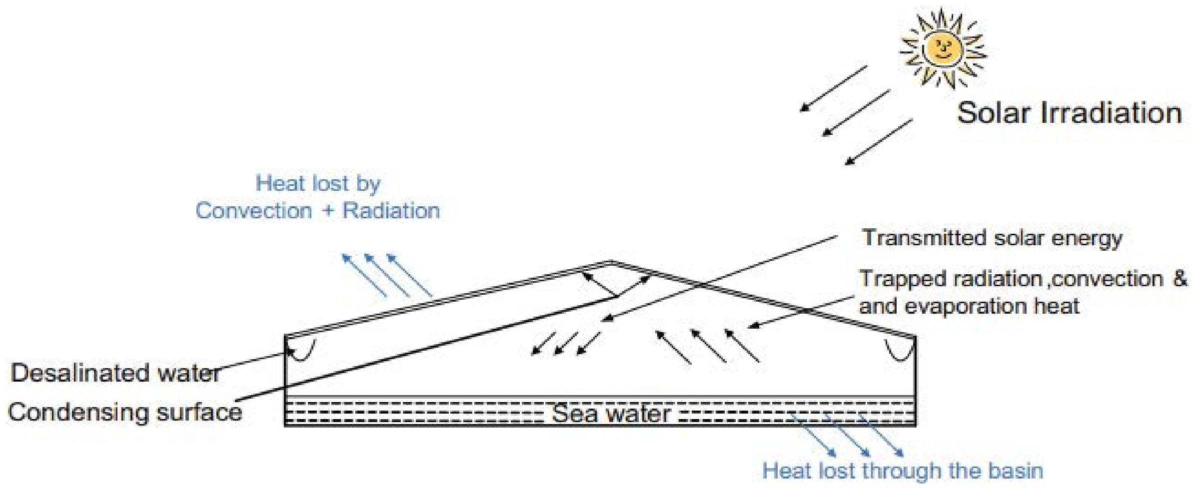

Fig. 3. Double slope solar still.

to upgrade the heating inside the still. The solar concentrator allows a higher heat inside the solar still [21], waste thermal energy [22], or a conventional boiler. A conventional still can be classified by its design: single slope [23], double slope [24] as indicated in Fig. 3, vertical and conical [25,26]. There are other geometric forms such as inverted absorber [27] and multiple-effect horizontal and vertical form [28]. The efficiency of a two-basin solar still is about 50%. Another type is called multistage solar collector is based on a solar collector and a pump to increase heating [23,26,28].

The use of simple heat and mass balances [28] allows modeling a multistage solar still. Different design is used to get the best efficacy of solar still like sponge cubes [29] wicks [30]. Other works show that due to the higher solar absorption, the distiller water product is augmented. In fact, the efficiency is about 15% in the case of charcoal particles as absorber [31], or also using violet dye in the water to get 27% efficiency. In addition, to get the best increase in water product, the energy storage units are added to the still.

A new solar still based on a heat exchanger has been proposed for economic considerations [34]. In fact, in order to enhance the distilled water product, a solar heater has been used to heat the oil, and then transferred to the heat exchanger situated in the still for more heat of saline water. A reflecting surface has been used to increase the intensity of solar irradiation into the still [32]. A new design based on cascaded-type of solar desalination [33] has been proposed. Modeling has been proposed [34] to estimate the heat flux and evaporation, using a semi-empirical equation [30].

It should be noted that passive still desalination is used for small water demand, such as solar stills. Solar still design can be divided into four types which are: basin still, tilted wick solar still, concentrating mirror and multiple trays tilted still. The size of the solar still prototype and the incident solar irradiation affect directly the outcome of fresh water produced per day.

The principle of a solar still desalination system is very simple, it is based on the greenhouse effect, so the sunlight increases the inside temperature and then allows evaporating of water inside a solar still. The salty water is introduced on a black plate of the solar still. The solar irradiance allows the evaporation of water to produce distilled droplets of water.

2.1.1. Solar still in a spherical design

Recently, a new type of solar still has been realized in the form of a sphere having an area of 0.28 m^2 [12]. The basin with a capacity of 16 L and 60 cm of diameter has been made in steel. To ensure good absorption, the circular basin has been painted in black and fixed at the middle of the solar still which has a radial height of 28 cm and a total height of 63 cm as shown in Fig. 4. A gap of 3 cm is fixed between the cover and circular basin. Due to the gravity, the condensed evaporated water drips to the collector as shown in Fig. 4 [41].

2.1.2. Pyramidal solar still

Another type of solar still has been made in form of a pyramid having a square surface of 110 cm × 110 cm as shown in Fig. 5 [14,15,41]. The salted water has been

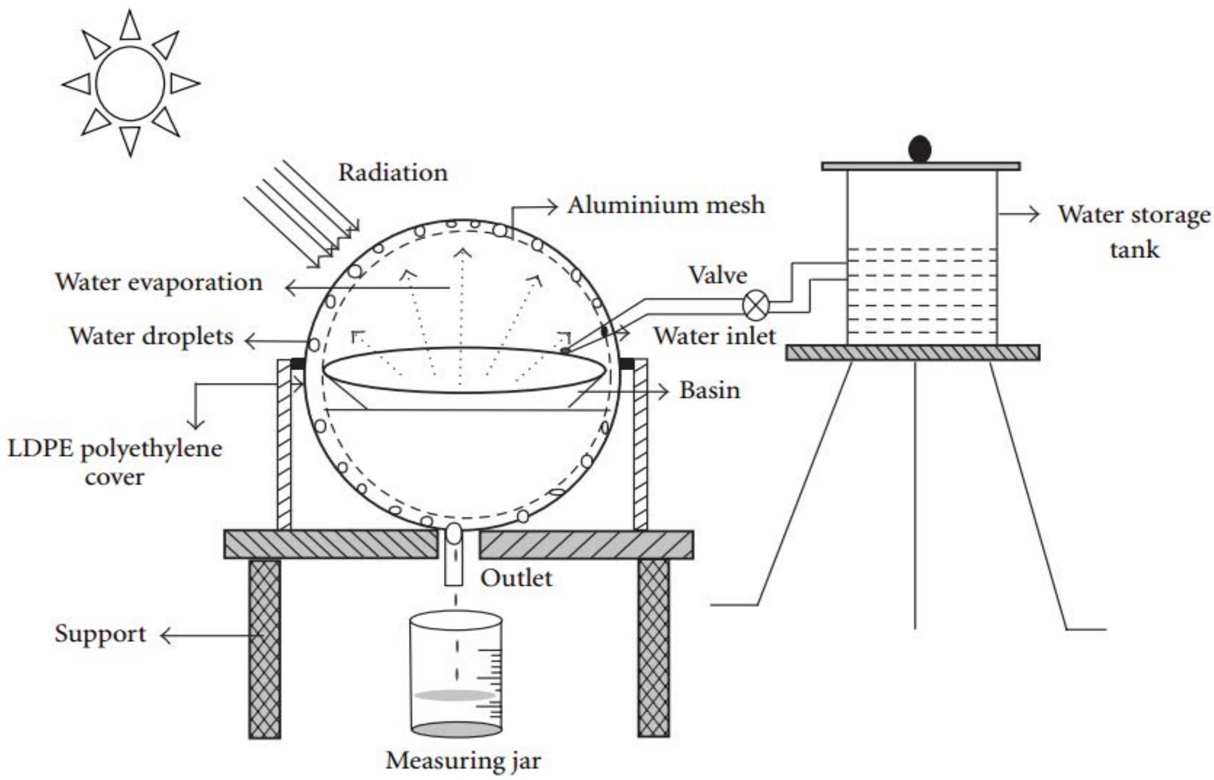

Fig. 4. Schematic of spherical design [41].

introduced inside the still until a 5 cm height. In order to get the low cost of produced distilled water, the solar still was fabricated using an insulating material such as sawdust which is a good substitute for glass wool.

2.1.3. Hemisphere solar still

This kind of solar still has been designed using mild steel of 95 cm as diameter and 10 cm height as illustrated in Fig. 6 [13,41]. To get the full absorption of solar irradiation, the basin has been coated in black and filled with 5 cm of salted water. In this design, the cover of 94.5 cm of diameter with 20 cm height has been made using a transparent acrylic sheet of 3 mm thick and 88% of solar transmittance.

The external box of the still is made of wood 4 mm thick and size 1.10 m × 1.10 m × 0.25 m. The bottom of the basin is made using sawdust insulation with 15 cm height. The glass wool was used for the sides.

2.1.4. Solar still with double basin

A design was made using a double basin [18] as illustrated in Fig. 7 [41]. The sizes of the basins are

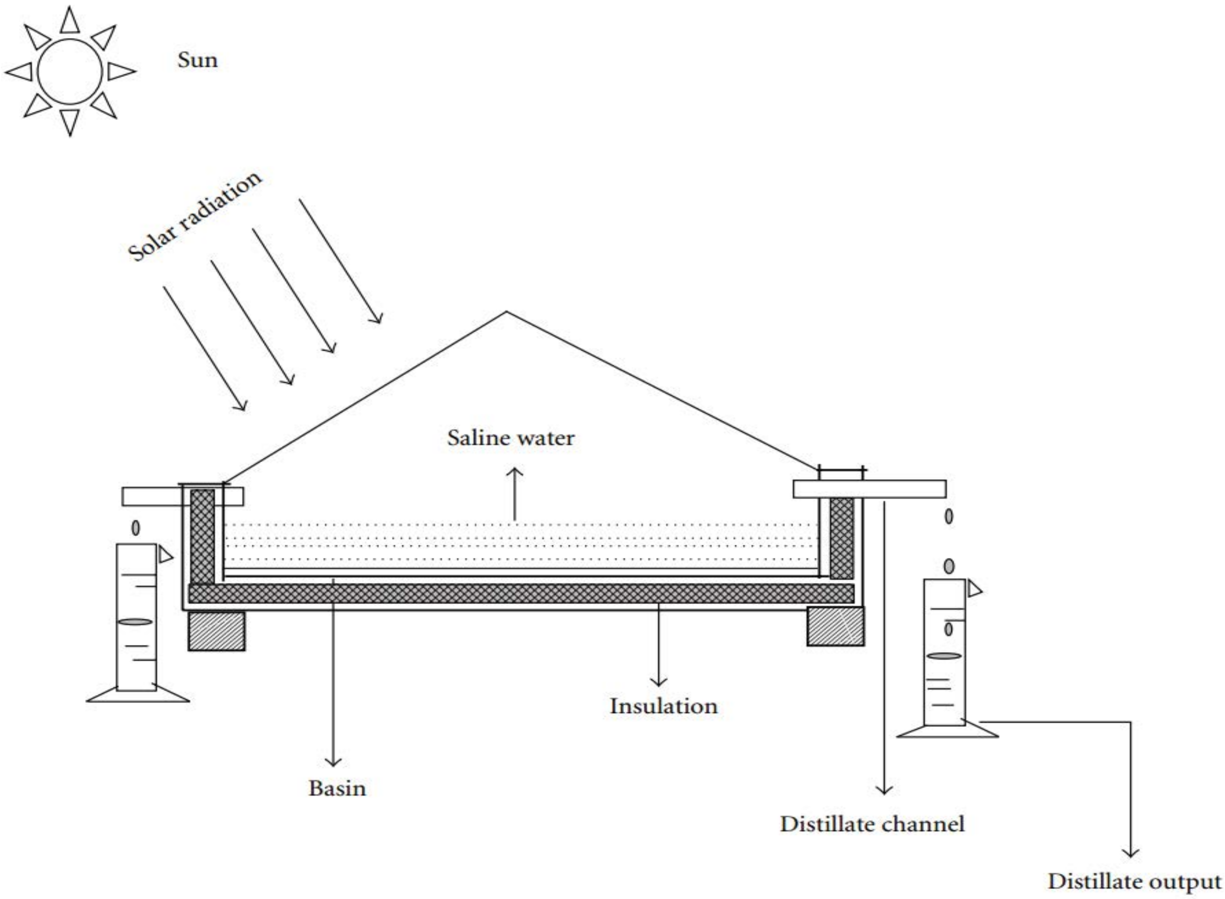

Fig. 5. Pyramid solar still [41].

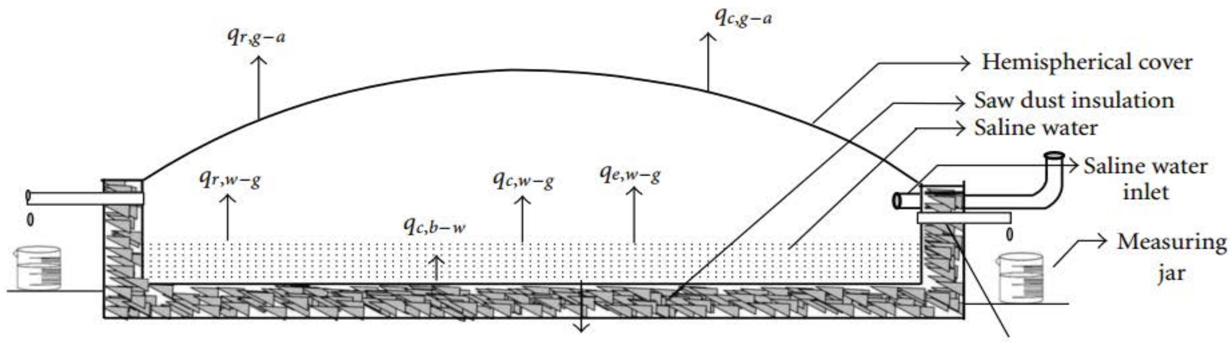

Fig. 6. Hemispherical solar still [13].

59 cm × 44 cm × 44 cm and 60 cm × 46 cm × 46 cm respectively. The top cover of the still has 3 mm of thickness. The inclination of each side is 17°.

To avoid the apparition of a dry spot on the top cover, the upper basin has been divided into four basins as shown in Fig. 7. The design allowed the insertion of a thermocouple for temperature measurement without any loses of heat or water vapor by using an insulating material.

2.1.5. Tubular solar still

Another design of solar still was elaborated [29] which is call tubular still having a rectangular absorber as illustrated in Fig. 8 [29,41]. The size of this prototype is about 2 m × 3 cm × 2.5 cm which is coated in black by spray method.

The rapid evaporation allows the apparition of a dry spot and then the water level decreased. So, by using a

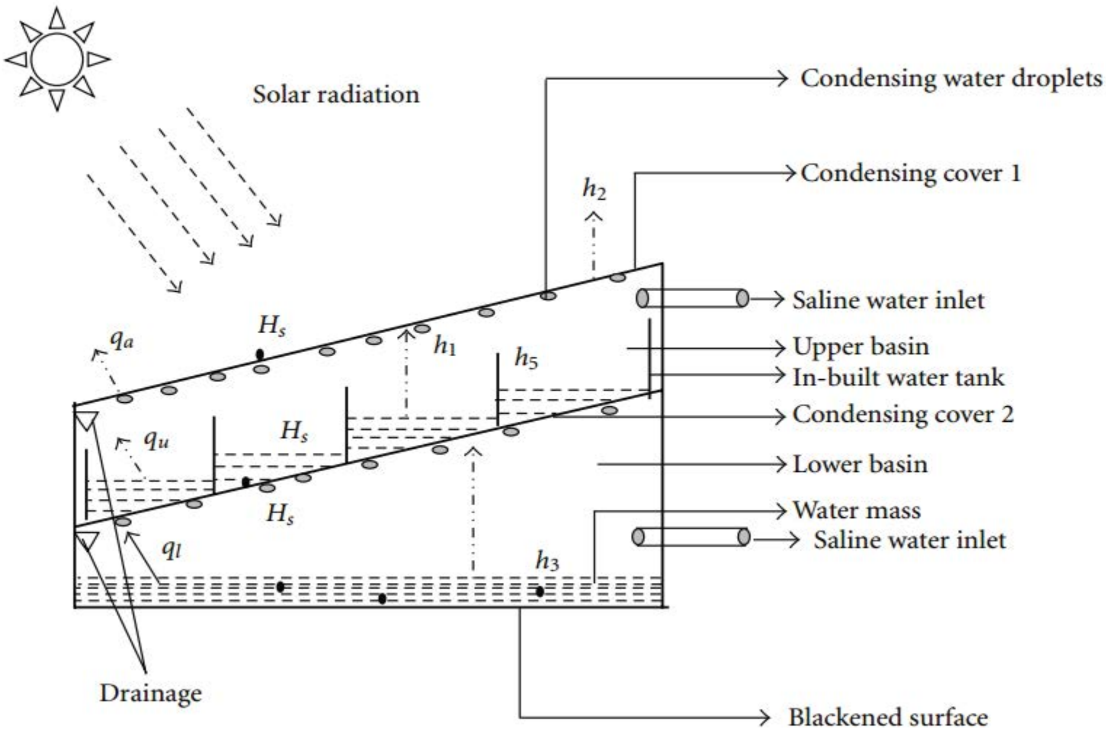

Fig. 7. Double-basin glass solar still [41].

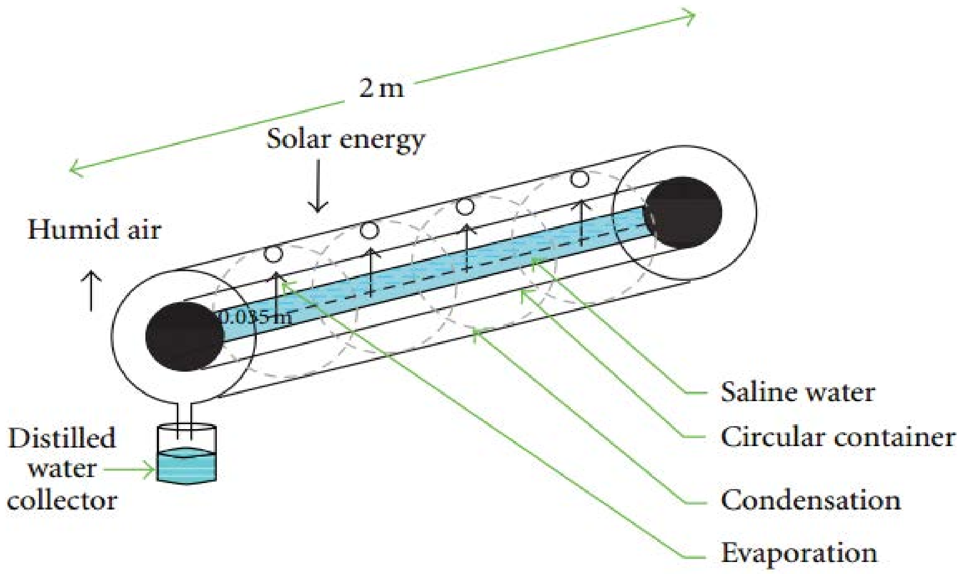

Fig. 8. Tubular solar still [41].

graduated tube, the water inside still is filling continuously. The advantage of this process is to keep the same quantity of water in the basin even if the evaporation is faster. For this, a water tank is used to fill water continuously inside the still.

2.1.6. Tubular – pyramid solar still

A design was developed using tubular – pyramid solar still with area of 1 m × 1 m [14,46]. A basin with 2 m length and 3.5 cm of diameter has been coated using black paint. In order to minimize the cost of produced distilled water, the solar still is made using insulated with saw dust. A tubular solar still is joined with pyramid solar still and the flow rate has been measured using a graduated jar as shown in Fig. 9 [41].

2.1.7. Hemispherical concentrator solar still

Hemispherical concentrator solar still has been designed using a single slope solar still [39]. The used basin is made with copper of 4 mm thick and the absorber has a diameter of 22 cm as indicated in Fig. 10. To ensure a good absorption of solar radiation, a black paint has been used to coat the inner surfaces. Thermocouples has been inserting through a 6 mm hole in order to measure inside temperature of the fabricated still. The slope of 16° tilted is made by a transparent glass with 2 mm thick with a dimension of 30 cm × 30 cm.

2.2. Discussion

Experimental setups have been done to study the behaviors of different types of solar still during clear sky conditions [41]. The same setup has been respected for different cases starting by filling the basins with salted water, the collected data has been done every half an hour. The average of daily water obtained is represented in Table 1 Due to the large surface in the design of spherical solar still, a big amount of water vapor is condensed and then the average distillates yield is around 2.3 L/m^2/d [39].

- The double basin still gave good results than a single slope still [41]. In fact, the average distillates yield is 2.90 L/m^2/d.
- The average distillates yield is around 3.3 and 3.66 L/m^2/d obtained from hemispherical and pyramid solar still respectively [41]. Different factors affect the achievement of solar still such as the surface of the solar still.
- The obtained amount for the distilled water in the case of the concentrator with single slope still is 2.6 L/m^2/d. The average distillates yield is around 4.50 L/m^2/d for tubular still and around 6.93 L/m^2/d for tubular associated with pyramid solar still [41].

Therefore, the best achievement has been obtained by increasing the distilled yield. The temperature difference inside a solar still, the surface and the design of still play a principal role to increase the yield rate of distillate water.

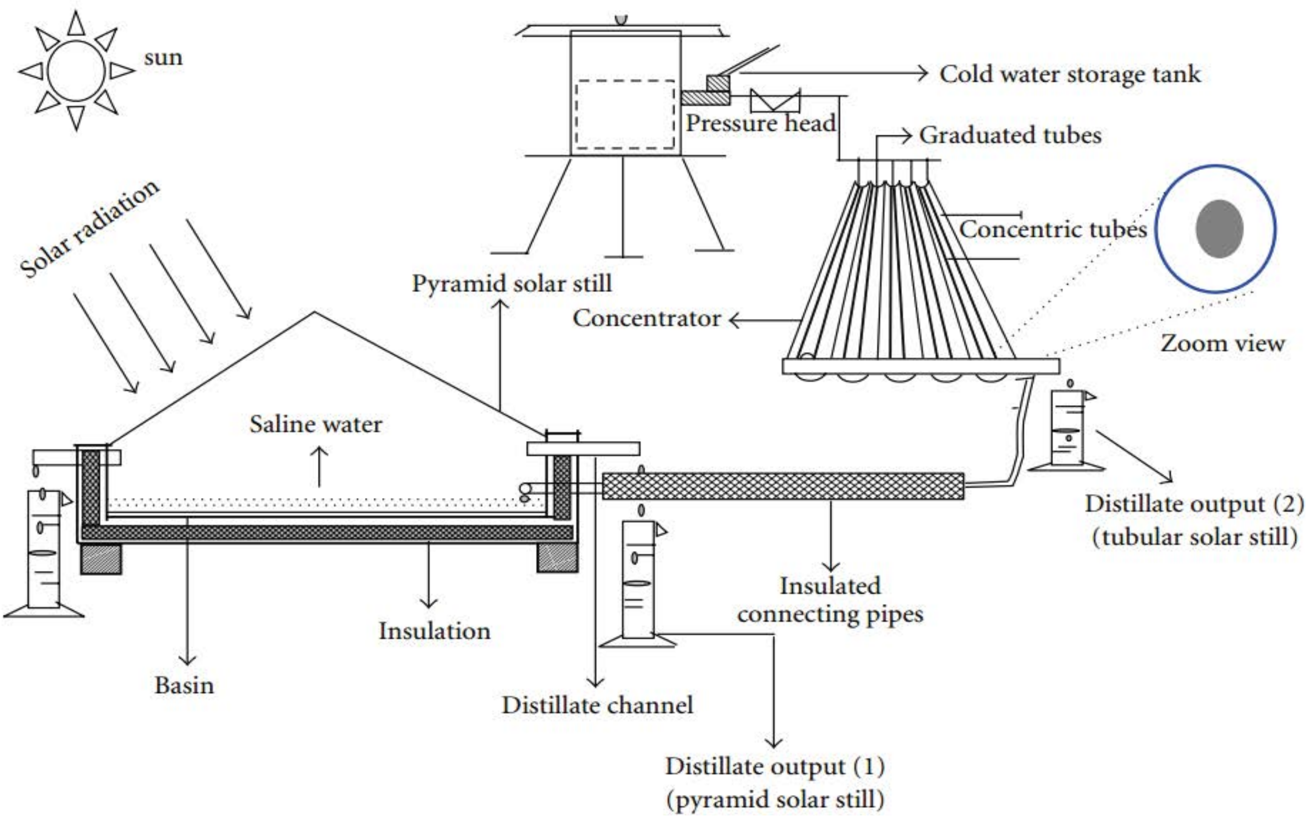

Fig. 9. Hybrid tubular-pyramid solar still [41].

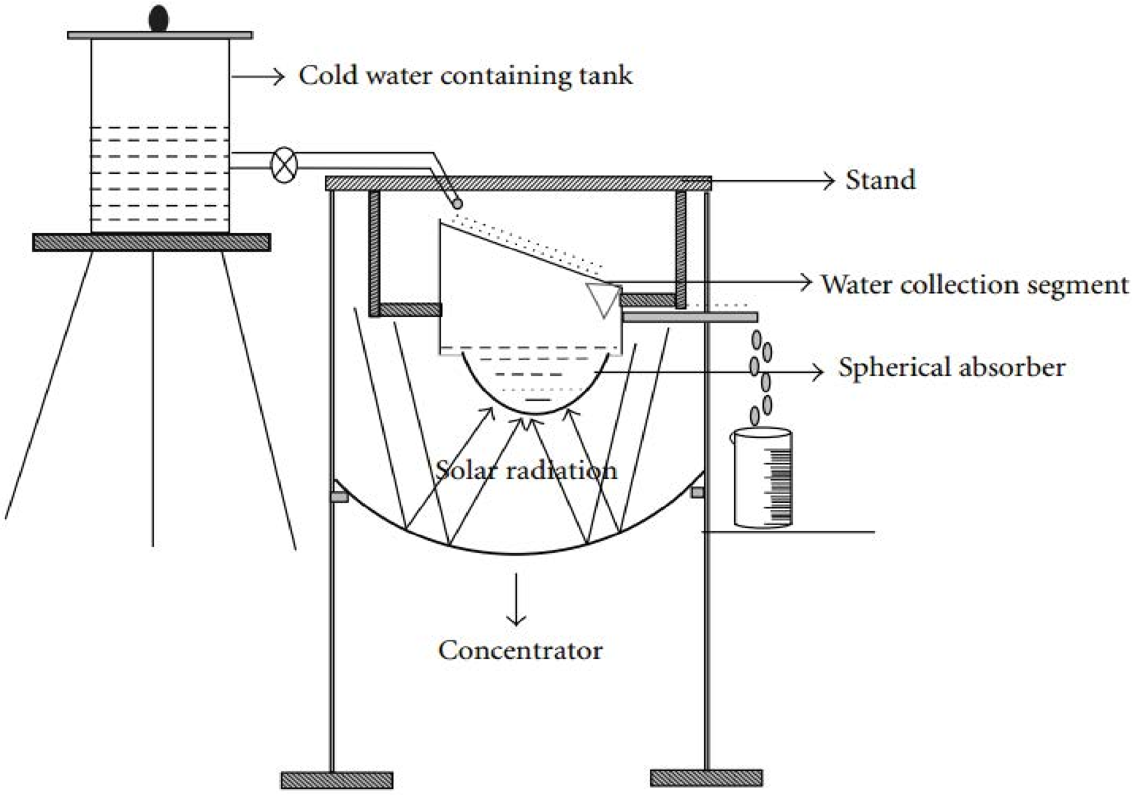

Fig. 10. Spherical basin solar still [41].

Table 1
Productivity of various designs of solar stills

Different designs of solar stills	Yield (mL/m^2/d)
Spherical solar still (SSS)	2,300
Concentrator coupled single slope solar still (CCSSS)	2,600
Double-basin glass solar still (DBGSS)	2,900
Pyramid solar still (PSS)	3,300
Hemispherical solar still (HSS)	3,659
Tubular solar still (TSS)	4,500
Tubular solar still coupled with pyramid solar still (TSS – PSS)	6,928

These results [36] confirmed that the higher distilled yield is obtained by using the tubular solar still joined with pyramid solar still. All, researches in this field focus on producing a low-cost design of solar stills for acquiring high quality distilled water.

3. A new hybrid solar still-solar heater desalination system

As reported in the previous section, the performance of solar stills system is affected by numerous operating factors and design configuration [32]. Thus, to obtain the best the performances of the investigated solar still system some steps should be taken in consideration for this work, which can be summarized as follows: Best absorption of solar radiation; great surface area; using a heat recovery system to increase the condensing surface temperature [33]. The two slopes solar still is designed with inner dimensions of 1 m × 1 m and the glass cover is tilted at 25° (latitude of the location). In this work, the effect of water capacity in the basin on the internal and external heat transfer has been studied. The average yield of distilled water produced by solar still is 10 L/m^2/d. So, to get the best performances, a combination between the two slopes still and solar heater has been done in order to preheat the salted water before injecting it in basin as shown in Fig. 11.

The proposed hybrid system (solar still – solar heater) allows the fast evaporation of water vapor. The average yield of distilled water produced reaches the value of 12 L/m^2/d. In order to test and control the proposed prototype, a smart data acquisition system based on microcontroller Mega Arduino and IoT technique has been designed.

The different data are as follow: solar radiation, ambient temperature, relative humidity, Input water temperature to the heater, output water temperature from the heater, temperature inside the heater, water temperature inside basin, relative humidity inside basin, the amount (L/h) of output distilled water, Salinity of desalinated water and the daily average yield of distilled water (L/d).

Fig. 12 illustrates the prototype of the proposed smart hybrid solar still system based IoT technique. In addition, the integration of small photovoltaic system has contributed to power the designed circuits corresponding to the different sensors. The salty water is introduced first in a solar heater designed also in this work. The heated water

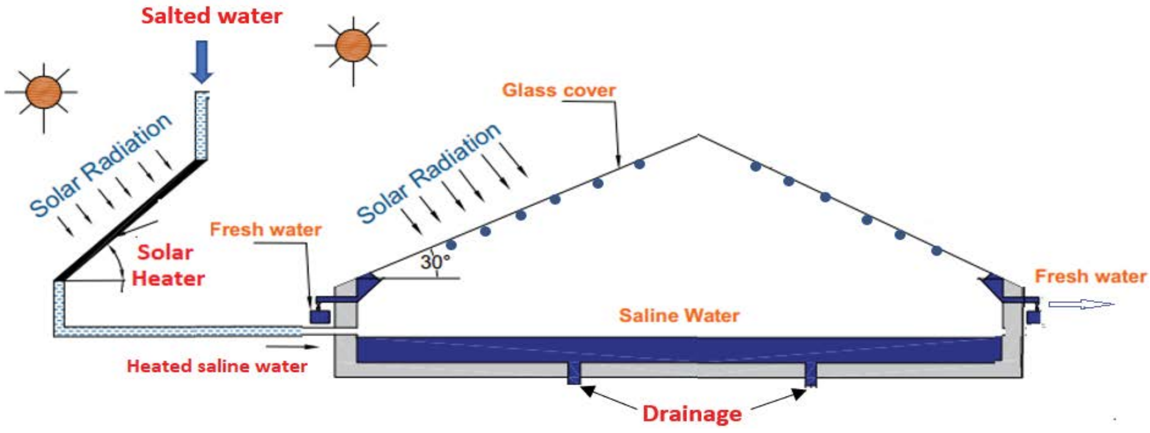

Fig. 11. Hybrid solar still – solar heater water desalination system.

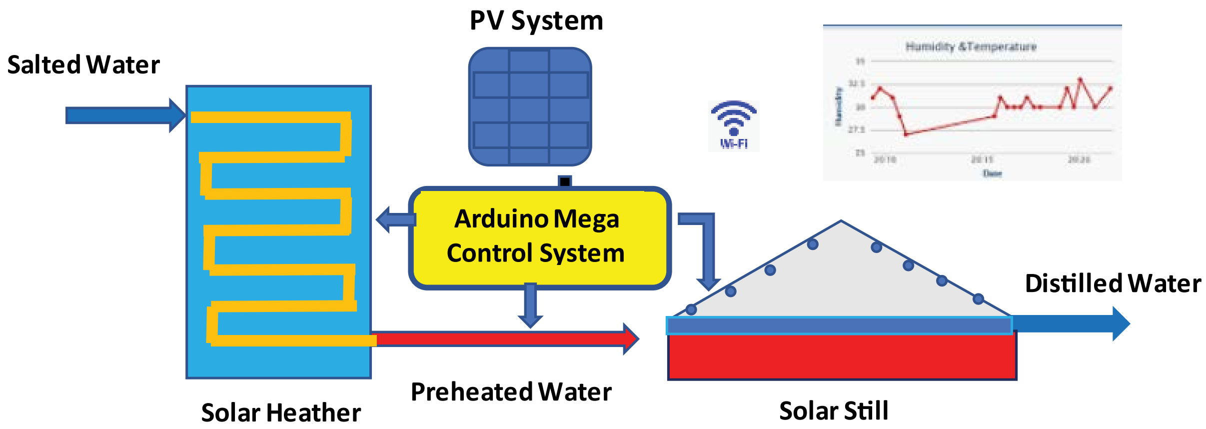

Fig. 12. Smart hybrid system (solar heater – solar still) based on microcontroller and IoT technique.

is introduced on a black plate of the solar still. The solar irradiance allows the fast evaporation of the heated water to produce distilled droplets of water. The droplets slide down, due to the gravity, until a special channel of colleting water. Measured data by the system can be uploaded on a website for eventual online visualization and monitoring.

Figs. 13a, 13c and 13b show scheme and the photos of experimental designed hybrid solar still.

A low-cost smart water desalination system powered by solar energy has been designed and verified experimentally. The solar panel inserted between solar heater and solar still in Fig. 13b allows powering the designed data acquisition system-based Arduino mega board (Fig. 13c) which collect different data described above. A monitoring system has been integrated to the designed solar still using Internet of Things (IoT) in order to control the evolution of the system in real time.

4. Factors influencing the performance of solar stills

The major parameters which influence on the performances of solar stills are: Solar radiation intensity, the temperature difference between glass cover plate and water, basin water depth, thickness of glass cover plate and wind velocity.

4.1. Solar radiation intensity

In [69] the authors concluded that the productivity of solar still increase with the increase of solar radiation intensity.

4.2. Temperature difference of glass cover plate and water

It has been concluded that the productivity of distilled water is improving when the temperature difference between the water and glass cover plate is high [70].

4.3. Basin water depth

Many research works [71–74] have studied the effect of basin water depth and they concluded that the productivity of water increase with the decrease of basin water depth.

4.4. Thickness of glass cover plate

The effect of thickness of glass cover on the productivity of distilled water were studied deeply [75–77]. It was found that the minimum thickness around 3 mm of glass cover give the best productivity compared with glass cover thickness of 4 mm, 5 mm and 6 mm [75–77].

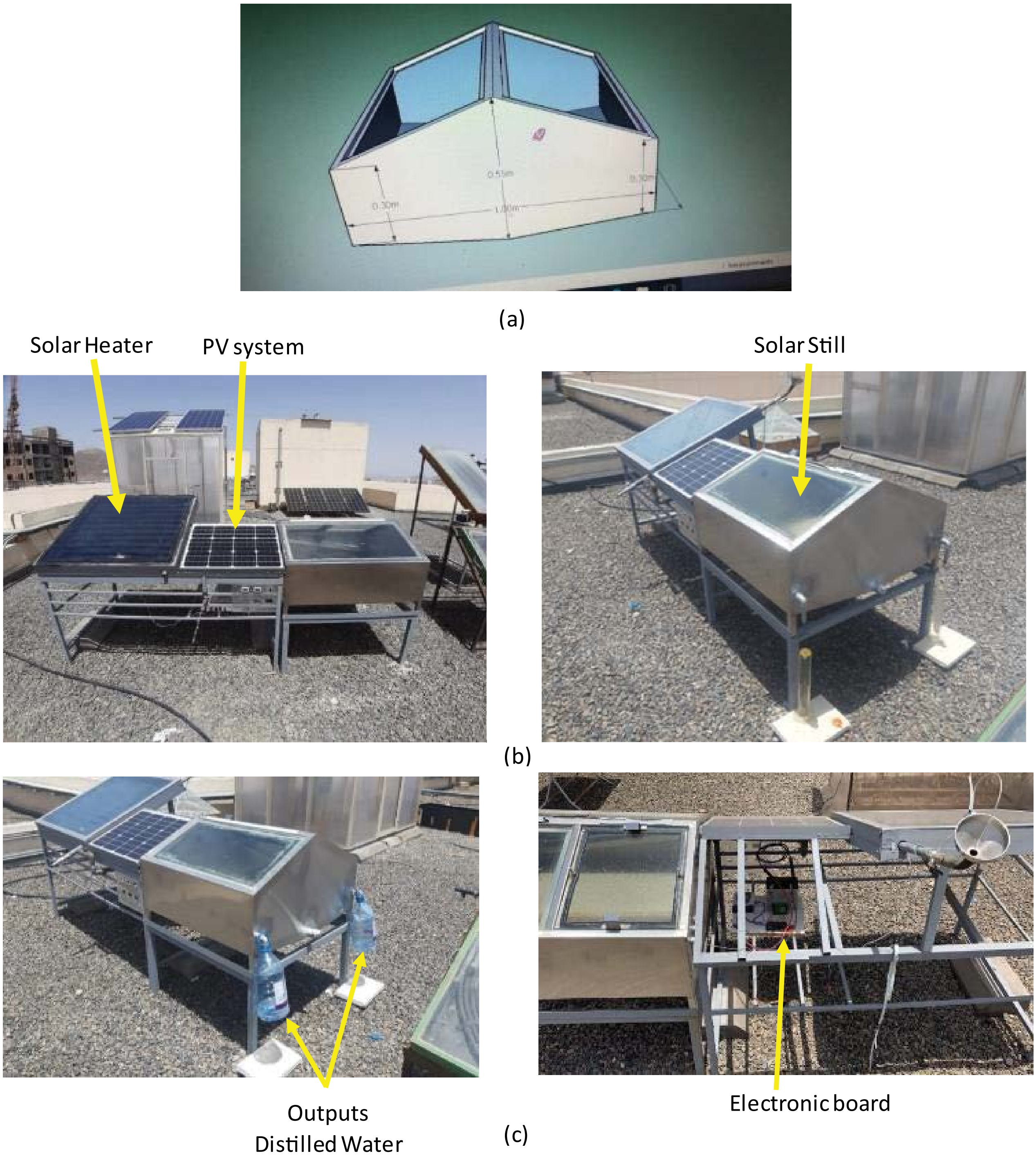

Fig. 13. Designed solar still (a), experimental photos of the hybrid solar heather – solar still (b), and photo of Arduino Mega Board for controlling and collecting data (c).

4.5. Wind velocity

It has been concluded that the daily productivity of distilled water increases to a typical value with the increase of wind speed which allow the convective heat transfer between glass and ambient which improve the condensation of solar still [78,79].

- Three parameters influence the outcomes of the solar stills, like operation factors [48], environmental parameters [50,51] and design [47,54] as illustrated in Table 2 and Fig. 14. Also, there are others parameters which can affect directly the performance of solar stills but these parameters cannot be controlled such as the incident global irradiation, air temperature, relative humidity and wind velocity [52–55].

- The evaporation area and water depth are two factors which affect directly the outcomes of the solar stills. In fact, to get higher performance, the minimum water depth in basins should be ensured to increase the evaporation heat transfer.
- The intrinsic parameters of saline water such as salt concentration, mineral layers on solar stills basins and sometimes algae apparition on water, influence the outcomes of solar stills.
- The major parameter which affects directly the production of distilled water is the incident solar radiation on the location of solar stills [54–57].
- The design of solar stills (thickness of insulation and angle of cover) affects the daily production of fresh water.
- The achievement of solar stills is affected by the latent heat on the cover and this gives low water productivity around 4 L/m^2 [58].

5. Yearly cost of freshwater production

As any system production, the final cost of water desalination system depends on the first investment cost, maintenance and operational cost and energy cost. To achieve the total cost, it is necessary to consider which type of energy is needed for operation in such systems. In fact, there are two kind of energy such as thermal energy, using solar heater for increasing the water temperature for fast evaporation and photovoltaic (PV) system for generating electricity for powering the pumps, solar instruments, etc.

The final cost of distilled water production depends principally on the present capital cost (P) and the annual yield (M) which correspond to the daily average productivity. Many studies [45,56] confirm that lowest cost per liter of solar stills is single basin solar still merged to tube collector, stepped solar still using reflectors and elliptical solar still. In Saudi markets, the production cost of distillate water, using solar desalinations systems, were economical [56]. Table 3 presents the annual cost (average yield per liter) of distillate water production corresponding to 260 d.

From Table 3, it is noted that the elliptical solar still gave more water production (5,229 L) than the others solar stills and the corresponding total cost of water production (34.51 USD) is almost the same with the others solar stills which gave lowest water production. So, large scale production of distillate water using these kinds of solar stills can be applicable for rural regions with few populations. Table 4 shows the average daily production and outcomes of different research works including our present work. The cost of water production from solar stills is affected by different parameters as follow [49]:

- The amortization budget factor,
- The interest per year almost 12%,
- Life time of the solar stills which is assumed 10 y,
- Capital recovery factor,
- Constant yearly cost,
- Actual capital cost (P),

Table 2
Factors influencing the performance of solar stills

Factor	Outcome
Incident solar irradiation	Proportional directly
Wind	Proportional
Air temperature	Proportional with water production
Polystyrene insulation	Output increasing (15%)
Thermal loss	Reduces yield

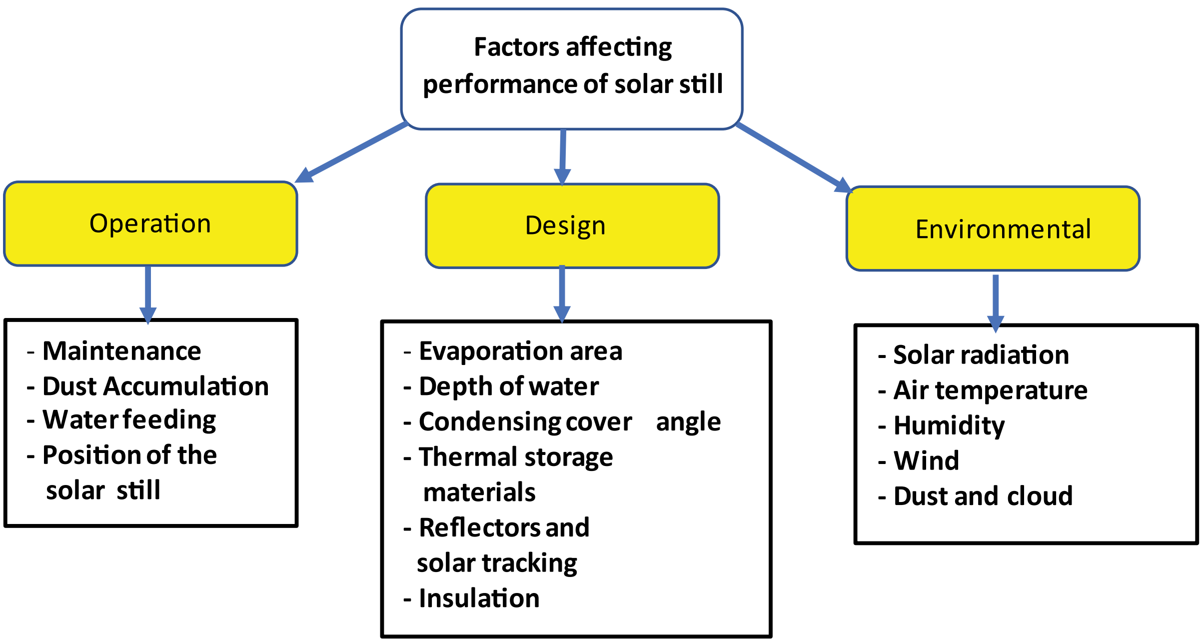

Fig. 14. Factors affecting the productivity of solar stills [51].

Table 3
Annual cost of water solar still production

Solar stills	Initial investment (USD)	Daily average yield (L)	Annual average yield (L)	Annual cost of yield per liter (USD)	Total cost for water production per year (USD)
Single basin still using collector	160	6.35	1,651	0.0186	30.71
Stepped solar still using reflectors	160	6	1,560	0.0197	30.73
Elliptical solar still	180	20.11	5,229	0.0066	34.51

Table 4
Outcomes of researches work with average daily production

Solar stills with low cost	Average water production (L/d)	Daylight (h)	Country
Bucket defluoridator [59]	32	8–10	Tanzania
Elliptical type [60]	20.11	8	Libya
Pyramidal type [61]	4.15	7–8	Oman
Triangular type [62]	1.55	7–17	Malaysia
Still coupled with Evacuated Tube Collector [63]	6.35	8	Iran
Solar still of type stepped [64]	6	8	Egypt
Cone still [65]	1.6	7–8	Germany
Still in V-type with waterflow on Cotton Gauze Top Cover Cooling [66]	4.3	9–17	India
Still in V-type with water and airflow on Cotton Gauze Top Cover Cooling [66]	4.6	9–17	India
Solar water purifier [67,68]	15	7–10	India
Hybrid two slopes solar still-solar heater (present work)	12	10–12	Saudi Arabia

- Yearly maintenance cost about 10% of present cost,
- The yearly salvage value cost,
- The yearly cost of fresh water per liter and the yearly yield (M).

6. Conclusion and outlook

In this work, different designs of direct process desalination systems have been reviewed. A comparison has been made between the existing solar stills in literature by presenting the performance of each system in point of view simplicity of fabrication, fresh water productivity and annual average cost. The following points can be highlighted:

- The best performance was obtained by the tubular solar still associated with pyramid solar still, due the concentrator effect.
- The daily average production of fresh water depends on the operation factors, environmental parameters and design of the solar stills.
- The best technique to increase the water temperature is the use of concentrator effect.

In fact, the temperature reached the value of 95°C compared with others solar stills presented in this manuscript.

- The proposed solar still preheated by a solar heater gives a good amount of distilled water production in comparison with the previous solar still systems.
- This hybrid system allows fast evaporation of water inside the solar still and the average yield of distilled water produced reaches the value of 12 L/m^2/d.

As future direction in this field, the integration of smart monitoring systems based on the IoT technique in these solar still systems will help users to monitor their systems easily. Android App could be also integrated for remote monitoring of different parameters inside the solar still such as temperature, humidity, water quality, and possible identification of faults.

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