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Experimental study on lens type solar still with single slope and single basin

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ABSTRACT

A basin type single slope active solar still with lenses and external reflectors was constructed and then examined in outdoor experiments in summer in Hangzhou, China. The lens facing the sun was inclined toward the solar still to refract and introduce the sunrays into the solar still. The external reflector was inclined slightly backward to make the reflected sunrays hit the basin liner of the still effectively. Lenses and reflector mirrors were proposed to be attached to the basin type solar still, and an experimental study was conducted to study productivities of different models, such as the solar still with one lens (Model-1), the solar still with two lenses (Model-2), the solar still with three lenses (Model-3), and the solar still with three lenses and one external reflector (Model-4). It was experimentally found that the productivity of Model-1 was almost equal to that of a traditional basin type solar still, and the productivity of Model-2 was 17.46% bigger than that of the traditional basin type solar still. The daily productivity of the basin type still can be increased by 20.32% with a modification using three lenses in Model-3. Model-4 had the maximum distilled water production of about 2.5 kg/m^2/d. Compared with the traditional still, there was about 32% increment in yield through Model-4, and the hourly production reached peak at about 19:00 o'clock. Model-4 has the optimal heating effect, reducing the heating time (from about 38°C to 50°C) by 83.33%. In the range of the testing time, the water temperature in Model-4 was 10°C higher than that of the traditional solar still on average.

Keywords: Saline alkali water; Active solar still; Additional lenses; External reflector; Higher yield; Experimental study

1. Introduction

In China, the region of Southern Xinjiang used to be a part of ancient Mediterrane about one hundred million years ago [1], causing that the salt content of the land is high. Southern Xinjiang is also an extremely arid region in China, which has annual rainfall less than 100 mm [2], with problems of poor water resources, and serious land salinization and desertification. People living in Xinjiang, where freshwater supply by transport is expensive, facing the issue of water shortage every day. Then, there is sufficient sunshine in Southern Xinjiang, and how to use solar thermal energy to effectively separate the saltwater and the freshwater in brackish water will be an important significance to relieve the shortage of water resources. The equipment applied to utilize the solar energy to purify the brackish water must meet the requirements in the following:

- Economic conditions in Xinjiang are poor, so the water production cost of the solar equipment must be low.
- The purified water must meet the demand of drinking water, so additives cannot be introduced to the brackish water.

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- Metallic materials are not allowed in the basin area of the solar equipment, because metals are vulnerable to salt water corrosion, which will cause a secondary pollution.

According to the above requirements, solar stills present specific advantages to be used in Xinjiang due to its easier construction, minimum skills of operation and maintenance requirements, and friendliness to the environment.

A simple solar still uses the heat of the sun to evaporate impure water, and then collects the freshwater without producing harmful gases. In the still, generally there is a blackened basin filled with brackish or saline water up to a certain depth and covered by an inclined glass to facilitate transmission of solar radiation and condensation [3]. In addition, the solar still is the most economical desalination device for providing water to households and small communities with the yield of about 2–4 L/m^2/d. The obtained water is in its pure form, and small volume of minerals and salts can be added to improve the acceptability and particularly to reduce aggressively of material [4]. Kumar and Tiwari [5] considered that a solar distillation plant with a capacity less than 200 kg/d was more economical after life cycle cost analysis of single slope hybrid (PV/T) active solar still. Many attempts have also been made to increase the distillate productivity of a basin type still, and their major types, and their research methods, innovation points and performance are listed in Table 1 to elaborate the present research status. All of these attempts are somewhat expensive, and there is only one way available for the entrance of sunlight.

External reflectors can be a simple and inexpensive way to increase the solar radiation incident on the basin liner as well as the distillate productivity of a basin type still. The external reflectors used in the solar still are made up of highly reflective materials. As such, the diffuse and direct beams

Table 1
The major solar still types and their research methods, innovation points and performance

Solar still type	Research method	Innovation points	Performance
Single slope solar still [6]	Considering the parameters such as water color, reflector, addition of black dye, red dye, charcoal pieces in experiment	Floating surface of different thickness (3, 6, 10 and 15 mm) with different density (24, 20 and 15 kg/m^3) were performed	The dark color of water could absorb more amount of solar radiation which heats up quickly. The maximum yield is obtained with floating sheet of density 20 kg/m^3 with 3 mm thickness
Single axis sun tracking system [7]	An experimental comparison was conducted between fixed and sun tracked solar stills	The sun tracking is more effective than fixed system and it is capable of enhancing the productivity	The production of water of sun tracked solar still was increased for around 22% compared with fixed solar still, due to the increase of overall efficiency by 2%
Conventional double sloped single basin pyramid solar still [8]	A parametric study was conducted	The performance of the still was evaluated under optimum design conditions	The average annual solar yield of conventional double sloped single basin pyramid solar still is approximately 4 L/m^2 d
Point focus elliptical shape solar still with concave mirrors [9]	Design and experimental investigation	Setting concave mirrors to reflect and concentrate the sun-rays on a solar still	The experimental results showed a significant improvement of the productivity of desalinized water, about 303% compared with the other thermal solar stills. Moreover, the increase of the performance ratio is about 900% more than the roof-type desalination solar systems
Innovative desalination system with vacuum created by natural forces [10]	A designed experiment was conducted	Because of the vacuum, the evaporation temperature of water has been lowered so that vapor can be easily achieved from flat plat collector	The latent heat of condensation can be utilized in multi-effect from one stage to evaporate water in the next stage that would increase production working

Table 2
Different designs of solar stills with reflectors in the literature

No.	Solar still type	Authors	Locations (latitude)	Reflector material	Observations in experiment
1	Tilted wick solar still	Tanaka and Nakatake [11]	Kurume, Japan (33°N)	Mirrors	The average daily amount of distillate peaks when the angle of the still is 20° for the still with the reflector, and peaks at 30° for the still without the reflector
2		Tanaka and Nakatake [12]	Kurume, Japan (30°N)	Mirrors	The inclined reflector can increase the distillate productivity of the still at any still's inclination, and the reflector's inclination should be set at about 15° from vertical
3		Tanaka [13]	Kurume, Japan (30°N)	Mirrors	The distillate can be increased by inclining the reflector backwards in winter and forwards in summer, and the inclination angle would be less than 25° throughout the year
4	Conventional still coupled with external stainless steel reflector and outside condenser	E1-Bahi and Inan [14]	Ankara, Turkey (39.6°N)	Stainless steel	The efficiency of the solar still was improved up to more than 70%, and the distilled freshwater was up to 7.0 L/m^2 d
5	Conventional still	Shanmugan et al. [15]	Tamil Nadu, India (11.30°N)	Mirrors	The efficiency of the still was as high as 35%, and increased to 45% with the mirror booster
6	Conventional still with twin reflector	Pankaj and Agrawal [16]	Rewa India (24.32°N)	Mirrors	The twin reflector booster has to be reoriented only once in a day at mid-noon
7	"V" type solar still	Selva Kumar et al. [17]	India (22°N)	Mirrors	The main advantage of "V" type still is due to center collection and all the condensation are easily directed to the outlet
8	Inverted absorber solar still	Dev et al. [18]	Muscat, Oman (23.37°N)	Steel	The maximum optimized water depth can be taken as 0.03 m for the inverted absorber solar still at which the addition of reflector under the basin does not considerably affect its performance
9	Double slope solar still	Al-Garni [19]	Dhahran, Saudi Arabia (26°N)	Mirrors	Four inclined mirrors were placed around the still to reflect extra solar irradiance onto the solar still
10	Stepped solar still (with 5 mm tray depth and 120 mm tray width)	Omara et al. [20]	Kafr El Sheikh, Egypt (31.07°N)	Mirrors	The productivity of the stepped still with top external reflector (ER) and bottom ER are about 33% and 41% higher than that of the conventional still, respectively

(Continued)

Table 2 *(Continued)*

No.	Solar still type	Authors	Locations (latitude)	Reflector material	Observations in experiment
11	Stepped solar still (with 5 mm tray depth and 100 mm tray width)	El-Samadony et al. [21]	Kafr El Sheikh, Egypt (31.07°N)	Mirrors	The productivity of the stepped still with both reflectors and a condenser are 165% higher than that of the conventional still
12	Conventional still (internal and top reflector)	Tanaka [22]	Kurume, Japan (30°N)	Mirrors	A very simple modification using internal and external reflectors (IERs) can increase the daily productivity of a basin type still in winter by about 70%–100%
13		Tanaka and Nakatake [23]	Kurume, Japan (30°N)	Mirrors	Increase in productivity by using IERs is 48% and by adding only internal reflector it was 22%
14		Tanaka [24]	Kurume, Japan (30°N)	Mirrors	The benefit of both the IERs would be considerably less in summer than in winter
16		Khalifa and Ibrahim [25]	Baghdad, Iraq (33.3°N)	Mirrors	The average daily yield is increased by the use of IR and/or ER except for summer where the effect of the reflectors is found to be negative
17		Khalifa and Ibrahim [26]	Baghdad, Iraq (33.3°N)	Mirrors	The daily yield of the still with no reflectors would remain almost the same at any glass cover angle
18		Boubekri and Chaker [27]	Constantine, Algeria (36°N)	Mirrors	The night production of the still increases when the still is coupled with a storage tank out of the sunshine hours. This increase is about 27.54%, 21% and 23.28%, respectively, for winter, spring and summer
19	Portable thermal–electrical solar still	Monowe et al. [28]	Moscow, Russia (55°45′N)	Aluminum foil	Using reflectors and external condenser can increase the daily productivity of a still to 68%

transmitted through the glass cover are improved through light reflection. Many scholars have conducted, thoroughly, the experimental research on different solar stills with reflectors in the terms of daily yield, productivity improvement, efficiency, and innovation. We have exhibited the experimental results of different designs of external reflectors in Table 2.

Installing external reflectors are more practical in places where solar radiation is weak and back external reflectors are the conventional form. In some cases, the external reflector combines with the internal mirror to introduce more solar radiation into the still, but there is no precedent that the external reflector combines with the lens so far. In the literature, almost all academics applied lenses to form high-energy focal plane, rather than change the transmission direction, for example, Wu et al. [29] demonstrated a multi-stage humidification–dehumidification solar desalination system heated directly by a cylindrical Fresnel lens concentrator. The solar radiation was sent directly into desalination unit, namely, the beams were still vertical to the heated surface, which is similar to the traditional solar still. However, Fresnel lenses utilized as the concentrating tool could enhance, sharply, the driving force of evaporation process. Then, researchers are also interested in linear concentrating solar thermal systems, which is a model for a novel linear Fresnel lens collector with dual-axis tracking capability [30]. Most published studies on linear concentrating collectors are related to parabolic trough systems with evacuated tubular absorbers, showing the emphasis on power generating applications [31,32].

In this study, we consider that the external reflector can effectively promote the transmitting of diffuse and direct beams through the glass cover, and then the lens can be utilized to refract direct beams so that the direct beams radiating on the ground can enter the still's side walls. Therefore, contrast experiments have been conducted to analyze the performance of a modified basin type solar still through adding lenses and external reflectors. Then, we present the results of outdoor experiments of the basin type still with one lens, the still with two lenses, the still with three lenses, and the still with three lenses and one mirror during the summer season in Hangzhou, China (30.3°N latitude and 120.2°E longitude).

2. Design concept of a lens type solar still with an external reflector

There is only one way available for the entrance of sunlight in the traditional solar still, and that is why the working efficiency is very low [33], and the net freshwater production is limited. In addition, the traditional solar still is not easy to adjust according to the position of the sun. Therefore, in order to overcome the shortcomings of the traditional solar still, this paper proposes a lens type solar still (LTSS) which has been applied a patent of invention [34]. This utility model not only can greatly improve the working efficiency of the evaporator, but also can freely adjust the incident direction of the sunrays.

The LTSS includes an inlet valve, a water inlet pipe, an evaporation cavity, an inclined glass, a sawtooth type heat collecting plate, three lenses, a mirror, a water collecting groove, a drainage tube, and a plunger. There is a simple display of the components of the LTSS in Fig. 1. The water inlet pipe is communicated with the brackish water collecting tank. Then, there is a sawtooth type heat collecting plate located at the bottom of the evaporator cavity, and the inclined glass is arranged above the evaporator cavity. One lens is placed in the front of the still, and two lenses are arranged on both sides of the still, and one mirror is installed on the back of the still. A water collecting groove linked with a drainage tube is set in the solar still, and the drainage tube is communicated with a water collector. At last, the bottom of the evaporator cavity owns four wheels, so it is easy to move the solar still.

2.1. Lenses' working mechanism to introduce more sunrays into the solar still

2.1.1. The lens in the front of LTSS

China is in the northern hemisphere, so the best orientation of the solar still is southward. In Fig. 2, the inclined glass (ijgh) faces south, and the sun light transmit through it from the sun to the evaporation cavity. Also, the sun light will transmit through the front glass (abij), which is expressed as "aj" in Fig. 2. The area of the front glass for sun light transmission is limited because of the small height (aj), therefore, we propose that the solar still can be installed with a lens in the front to gather more sun light. The mechanism of the lens in the front of solar still can be elaborated as follows.

In Fig. 3, the lens is installed with a support frame standing upright on the ground, and the lens tilts toward the solar still forming an angle γ with the support's leg. Hence, when the solar beams transmit through the front lens, the beams will be refracted to form a high-energy focal plane at F (focal point). Assuming that the length of "ab" equals x, and the height of "aj" equals y ($y < x$), so the area of "abij" is xy. The shape of the lens is square, and the length of a side is bigger than x, so the area of the lens is bigger than x^2, which is far greater than xy. As such, the radiation flux of the front lens is more than that of the front glass because the radiation flux (J/s) is equal to the radiation intensity (W/m^2) multiplied by the area (m^2). In summary, lenses can be utilized to increase the amount of sun light transmitted into the interior of solar still. Due to that the focal length is always less than the side length of the lens, we propose to blacken the front glass to shorten the focal length, and we use "abcd" to express the

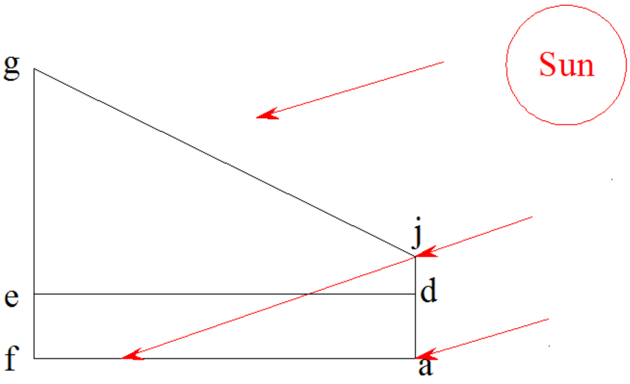

Fig. 2. Left view of the solar still.

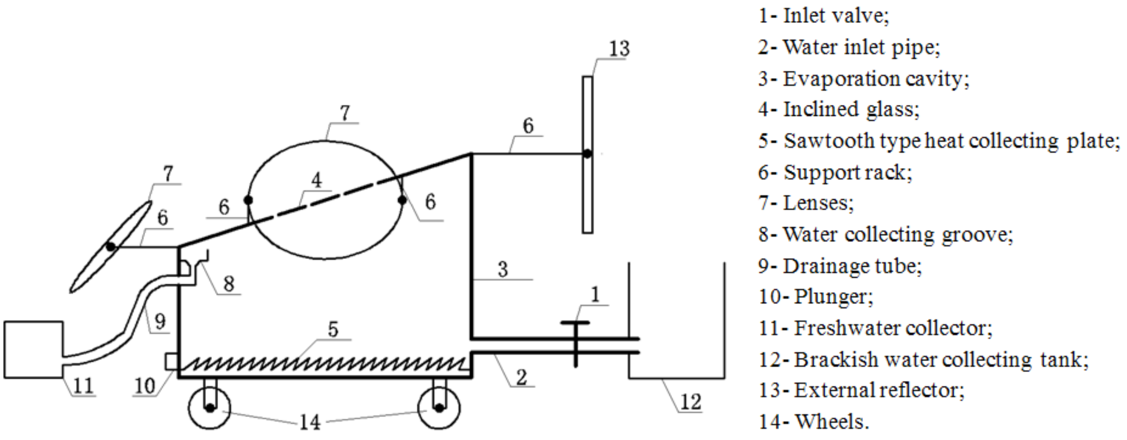

Fig. 1. Schematic diagram of the lens style solar still.

blackened glass. A blackened front glass can better absorb the concentrated solar energy, and the smaller focal length is beneficial for the placement of lenses. As shown in Fig. 4, we can adjust the front lens to achieve the optimum position.

2.1.2. Lenses adjoin to the side walls of LTSS

Besides that the diffusion beams can transmit through the side walls, the direct beams also can pass through the side walls of LTSS if we install lenses on both sides. The mechanism of the lenses on both sides of the solar still can be expressed as follows.

In virtue of Fraunhofer diffraction [35] (shown in Fig. 5), lenses concentrate and focus the rays at the focal point when the rays are perpendicular to its surface, or when the rays are oblique to its surface. Applying this feature of lenses, we propose to install two lenses on both sides of the solar still, and a simple 3D view of the lens on the left side of LTSS is displayed in Fig. 6. The support frames of lenses are vertically placed on the ground, and they are not parallel to the plane "afgj", and there is an angle α between the support frames and the solar still's side surfaces. Then, the lens tilts toward the solar still forming an angle β with the support's leg, and this is used to adjust the focal plane on the side walls. The front view of Fig. 6 is exhibited in Fig. 7.

The sun light is a beam of parallel light, and the solar still's inclined glass always faces the solar beams with the highest energy. That is to say, the solar beams introduced to the side walls belong to the direct beams. If the support frames are parallel to the plane "afgj", there will be no direct beams transmission through side lenses, and the graphic demonstration is presented in Fig. 8. Then, it is a front view in Fig. 9, and we use the cross "×" to indicate that the direct beams are perpendicular to the paper, and they are inward. It is clear that the direct beams cannot be refracted due to $\alpha = 0$. To sum, the angle α must be bigger than zero, and it should be large enough so that the direct beams can be refracted and concentrated on the surface of "afgj". In order to ensure that the energy on the focal plane can be absorbed easily, we still

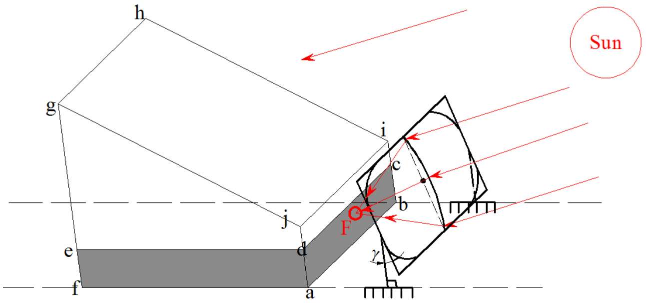

Fig. 3. Simple 3D view of the lens in the front of LTSS.

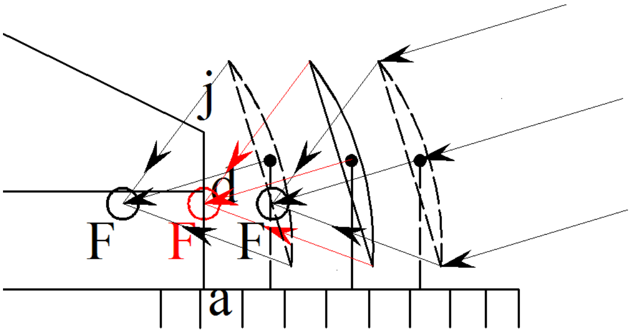

Fig. 4. Left view of the front lens.

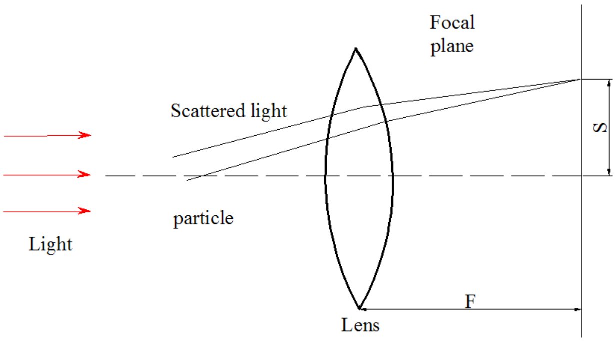

Fig. 5. Simple exhibition of Fraunhofer diffraction.

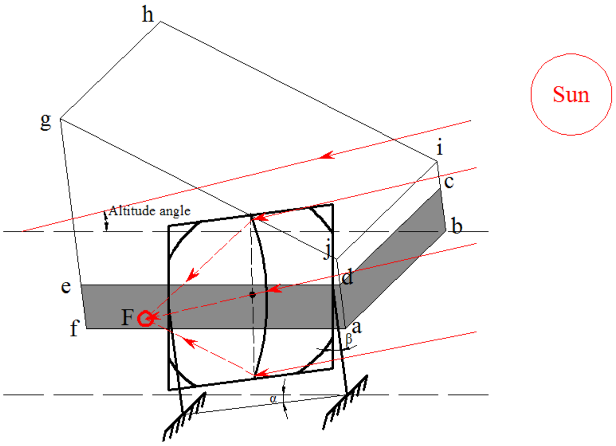

Fig. 6. Simple 3D view of the lens on the left side of LTSS.

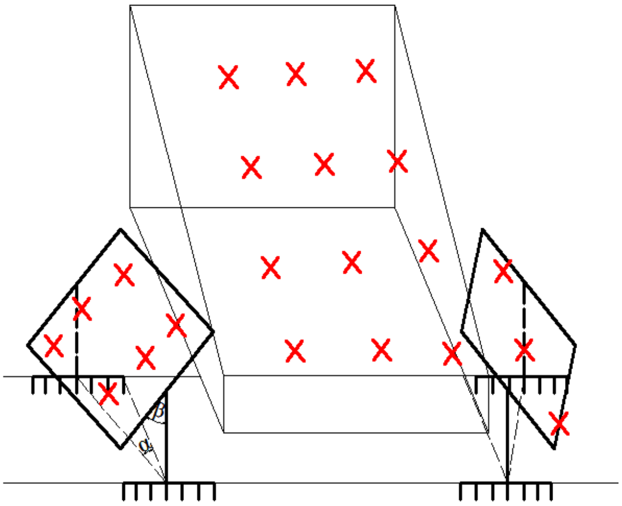

Fig. 7. Front view of the lenses on both sides of LTSS.

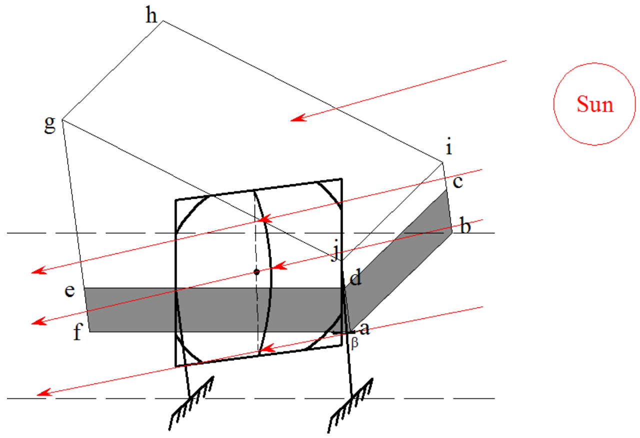

Fig. 8. Support frames are parallel to the side walls.

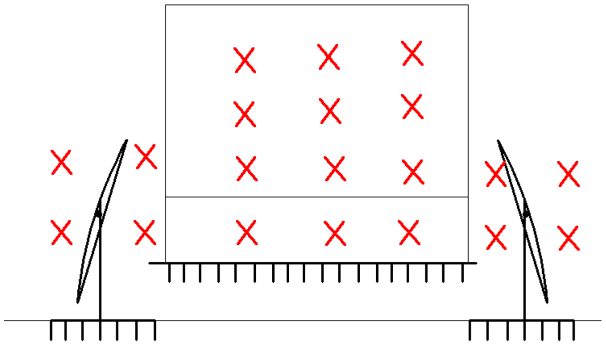

Fig. 9. Front view to exhibit the support frames are parallel to the side walls.

propose to blacken the side glass walls. And the angle β can be adjusted to achieve the optimum focal plane on side walls. In Figs. 3, 6, and 8, we use plane "adef" to represent the blackened area, and the height of blackened area is determined by the highest focal plane position.

2.2. The external reflector' working mechanism to introduce more sunrays into the solar still

We present a geometrical model to evaluate the effect of an external flat plate reflector mounted on the back wall of the still. We have theoretically analyzed the solar radiation reflected by external reflectors and then absorbed by the basin liner. In winter, the altitude angle of the sun decreases so a considerable amount of the reflected radiation from the external reflector would escape to the ground without hitting the basin liner [36]. Therefore, the reflector should be inclined slightly forward to reflect the sunrays to the basin liner effectively, as shown in Fig. 10. On the other hand, the altitude angle of the sun increases in summer, so the external reflector should be inclined slightly toward the back as shown in Fig. 11. As such, we propose to add an adjustable frame to the external reflector, which can be forward in winter and backward in summer. The amount of solar radiation can be reflected by the inclined external reflector (forward in winter and backward in summer) and then absorbed by the basin liner.

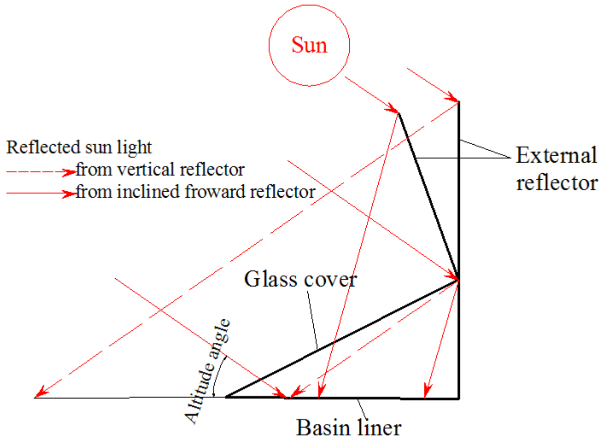

Fig. 10. Reflected sunrays from inclined external reflectors to the basin liner in winter.

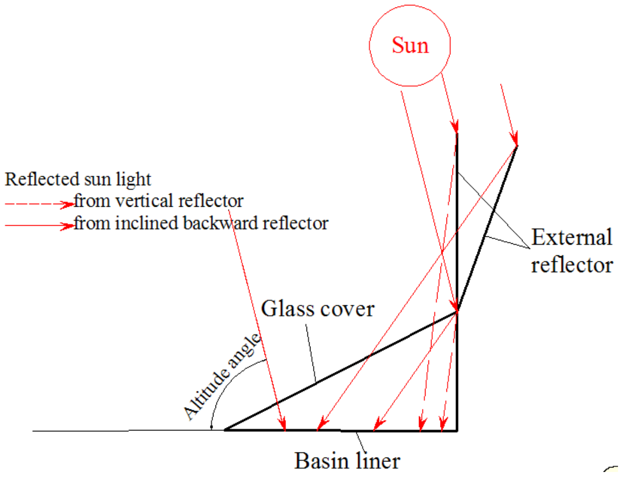

Fig. 11. Reflected sunrays from inclined external reflectors to the basin liner in summer.

2.3. Innovations of the design of the lens type solar still

The sun light passing through the inclined glass of the solar still is taken as the direct beams in this research, and we utilize the lenses to change the incident direction of the direct beams around the still, so that the direct solar radiation not only through the inclined glass enters into the still's inside, but also be absorbed by the glass side walls of the still. Besides, a part of sunlight can be reflected by a back mirror onto the blackened liner. Finally, the sawtooth type heat collecting plate at the bottom of the evaporator cavity can absorb the sunlight from five ways (the inclined glass, the front wall, both side walls, the mirror). As such, the heating effect of the solar still is expected to grow exponentially, resulting in the increase of the yield of freshwater, further, this new style still has the advantages of simple manufacture, low cost, safety and reliability, easy operation, and wide market prospect.

3. Experimental apparatus and procedure

A series of experiments on the performance analysis of the lens style solar still has been conducted under actual weather conditions in Hangzhou, Zhejiang Province of China. Before the experiments, the accuracy of all the thermocouples used in the test and the electronic weighing apparatus was checked. Solar irradiance was acquired by a thermoremanent magnetization (TRM-2) type solar energy testing system, and the acquisition time interval was 3 min. The temperature data was collected by a multi-channel temperature recorder with 3 min time interval of sampling. In order to obtain the accurate change of the water temperature in the solar still, four thermocouples were scattered evenly in the brackish water body, and the average value of these four thermocouples was taken as the measured water temperature. In addition, the steam quantity was estimated according to freshwater production in freshwater collector.

This paper used a disc condenser system with single slope and single basin as the basic installation to verify the thermal performance under the condition of high concentration ratio of sunlight on the brackish water. In the practice, the experimental apparatus was composed of a disc evaporator, a sunlight concentration system and a data acquisition system, and a snap shot of an outdoor experimental apparatus is shown in Fig. 12. The experimental site was in the city of Hangzhou of China (30.3°N latitude and 120.2°E longitude).

The operation process of the experimental device in the test can be concluded in the following. The incident sunrays were transmitted through the inclined glass, and refracted by convex lenses or reflected by the mirror onto the blackened liner of the solar still, and further, the sawtooth type heat collecting plate absorbed these sunrays to heat the brackish water generating high temperature steam. Then, the steam pressure and temperature in the evaporator cavity were greater than the outside, hence the steam was condensed or squeezed into a collecting bottle to generate freshwater. The water outlet is provided with a metal valve, and a steam output pipeline was linked with metal valve. In order to eliminate other effects of miscellaneous lights on the test results, the outer surfaces of the evaporator were painted black to prevent escaping lights, and moreover, the painted walls can absorb the refracted lights and diffuse lights. A simple exhibition of the experimental apparatus is shown in Fig. 13, and the optical path configuration of the experimental apparatus is displayed in Fig. 14.

The body of the solar still was made up of fiber reinforced plastic with 5 mm thickness. The basin body was enclosed by an insulating film just to reduce the side and base heat loss. The base dimensions of the basin were 1.0 × 1.0 m^2, and the inclination of the glass cover (1 × 1.06 m^2) was 30° from the horizontal which is approximately equal to the latitude of Hangzhou (30.3°) as suggested by Khalifa [37] and Singh and Tiwari [38].

To increase the absorption of the solar radiation, the bottom and the side walls' inner surfaces of the solar still were painted black, and the painting height of the side walls was 15 cm because we control the focal plane in this area (10–15 cm height of side walls). The solar still was mounted on an iron stand of 0.2 m height. Distilled water from the glass cover of the solar still was collected and taken out through flexible pipes into measuring jars. A conventional simple single slope solar still of identical dimensions and material was kept in operation parallel to the lens type still, just to compare their performances.

Fig. 12. The device structure in the experimental site layout.

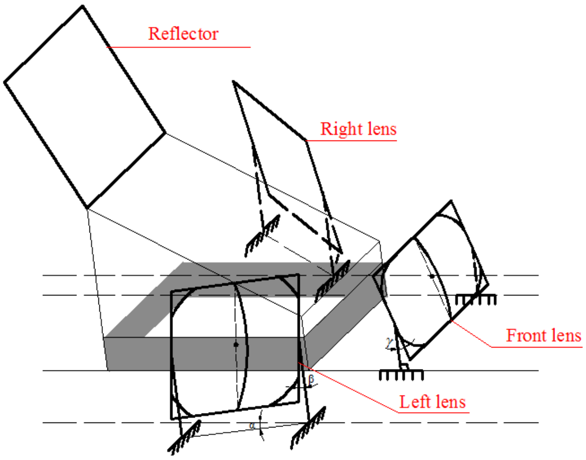

Fig. 13. Simple exhibition of the experimental apparatus.

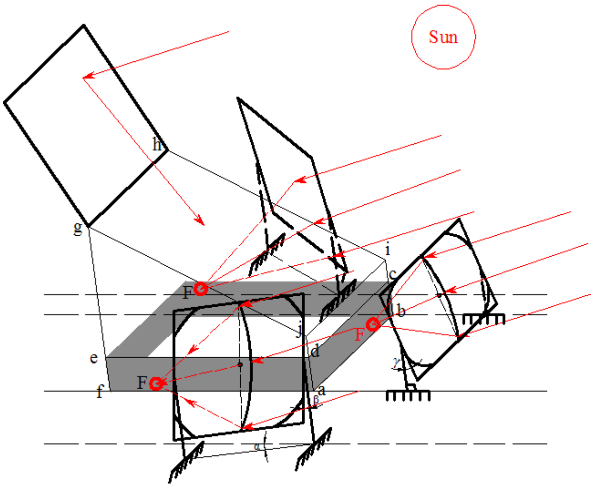

Fig. 14. Optical path configuration of the experimental apparatus.

3.1. Experimental models according to design concept

There are four experimental models based on the proposed design concept:

- Model-1: modified solar still with one lens.
- Model-2: modified solar still with two lenses.
- Model-3: modified solar still with three lenses.
- Model-4: modified solar still with three lenses and one mirror.

A sketch of different design modifications is shown in Fig. 15.

3.2. Instruments used in the experiments

Following measuring instruments were used during the experimental work.

- TRM-2 thermal performance testing system: TRM is made by Jinzhou Sunshine Science and Technology Company in China. It can measure solar radiation, ambient temperature, and ambient wind velocity. The solar radiation measurement range is 0–1,000 W/m^2, and its accuracy is ±20 W/m^2.
- Thermocouples: copper–constantan thermocouples were used to probe the temperatures of the basin water, vapor, and condensing covers' inner and outer surfaces. The thermocouples were calibrated with the zeal thermometer. A multi-channel digital temperature indicator was used to indicate the temperature. The thermocouple measurement range is 0°C–200°C, and its accuracy is ±0.1°C.
- Measuring jars: measuring jars were used to measure the distillate output. The reading range of measuring jars is 0–1,000 mL, and its accuracy is ±5 mL.

Contrast experiments were carried out between a conventional still and models (Model-1, Model-2, Model-3, and Model-4) on four alternate days: 20/7/2017, 21/7/2017, 22/7/2017, and 23/7/2017, respectively. Testing data of solar intensity, different temperatures, and distillate output were recorded between 6:00 a.m. and 24:00 p.m. daily at intervals of 0.5 h.

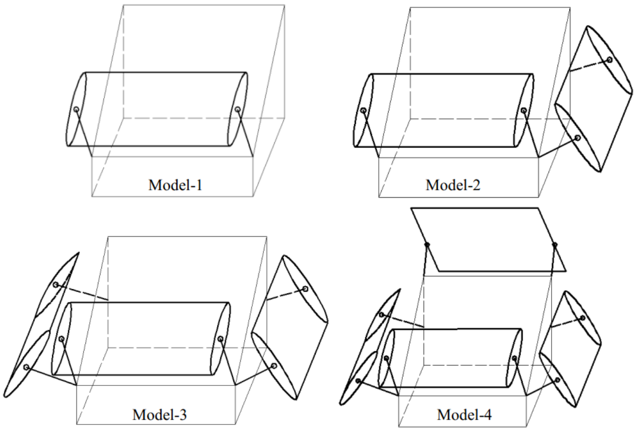

Fig. 15. Experimental setup with different design modifications.

4. Results

4.1. Different modifications on the traditional disc type solar still

Solar energy utilization efficiency of the brackish water in the lens style solar still was tested compared with the traditional disc type solar still at the same time interval, so we got the change rule of the temperature rise and the heat energy utilization efficiency of each test model under the similar test conditions.

Model-1 was made to run on 20/7/2017, other different modifications (Model-2, Model-3, and Model-4) were implemented on the next three consecutive days of 21/7/2017, 22/7/2017, and 23/7/2017. All the modifications were compared with the traditional disc type stills with 0.15 m water depth. The climate conditions are very stable in these days.

4.1.1. Effect of adding one lens (Model-1 vs. traditional still)

Variation of the solar radiation and the ambient temperature was stable on 20/7/2017, 21/7/2017, 22/7 2017, and 23/7/2017, and the trend of solar intensity of these 4 d are similar. The curves of the solar radiation and the ambient temperature of the experiments are exhibited in Fig. 16, and the water temperature with heating time curve is shown in Fig. 17.

With the sustained increase of the solar radiation intensity before 16:00 o'clock (p.m.), it is seen from Fig. 17 that brackish water temperatures in both of the traditional solar still and the lens style solar still (Model-1) rose gradually. Under the condition of the high concentration of sunrays, the maximum temperature of the brackish water could reach 54.3°C, which is 2.1°C higher than that of the traditional solar still. In the range of the testing time, the water temperature in the lens style solar still was 4°C higher than that of the traditional solar still on average. Both of them could reach the evaporation temperature, but the time needed to reach the evaporation temperature of the lens style solar still was shorter than that of the traditional solar still. In the traditional solar still, the brackish water needed 360 min to heat up from the initial temperature to the temperature of 50°C, while in the new style solar still with the concentrating solar collector, the time for reaching the same situation of brackish water was 180 min. It was obvious that the adding of the lens gave the still a strong sunlight concentration function, which reduced the heating time by half. It also can be seen from Fig. 17 that the brackish water in the traditional solar still and

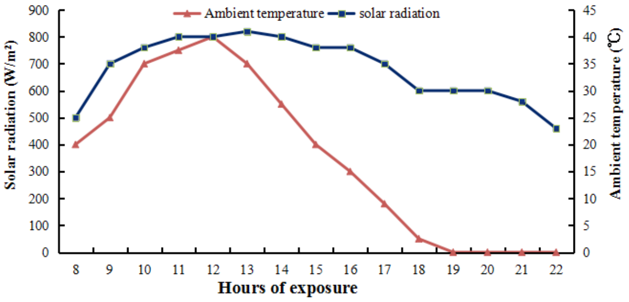

Fig. 16. Curves of solar radiation and ambient temperature during the experimental process.

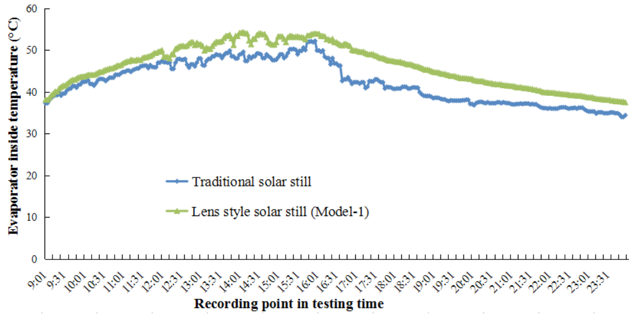

Fig. 17. Comparison of water temperature between Model-1 and traditional still (20/7/2017).

the lens style solar still had the same temperature rise rate (slope), but the traditional solar still's cooling rate (slope) was bigger than the lens style solar still. The result shows that the higher the peak temperature in the still, the poorer the natural cooling effect.

According to the experimental measurement of steam volumes of the traditional solar still and the lens style solar still in the unit time, we had figured out the freshwater production per hour, and the result is shown in Fig. 18.

Fig. 18 shows that there were more freshwater production after 14:00 o'clock, and the production reached the peak in the evening at about 16:00 o'clock for both solar stills. The freshwater output per hour in the traditional solar still is close to the freshwater production in the lens style solar still, however, in terms of heat energy utilization efficiency, the efficiency of lens style solar still was slightly higher.

4.1.2. Effect of adding two lenses (Model-2 vs. traditional still)

The next modification was adding two lenses, and it is named as Model-2. There was 17.46% increment in yield through Model-2 at 0.15 m water depth (Fig. 19), compared with the traditional still. This is due to the sunrays refracted by two convex lenses to the solar still were more than that of Model-1. Therefore, the blackened liner absorbed an extra solar energy to heat the brackish water generating high temperature steam. Higher temperature difference between the water in the still and the cover enhances internal heat transfer rate and produces more evaporation.

4.1.3. Effect of adding three lenses (Model-3 vs. traditional still)

The freshwater production of Model-3 was higher by 20.32% than that of the traditional solar still at 0.15 m water depth, and the yield comparison is shown in Fig. 20. This modification was adding three lenses, and the promoting effect of extra one lens is not significant. We could explain that the internal heat absorption effect is obvious, but the glass cover releases heat to the surrounding environment is not quick enough, and thus produces less condensation water. That is to say, we need to select a suitable cover to accelerate external heat transfer rate from the still to the atmosphere resulting in faster condensation.

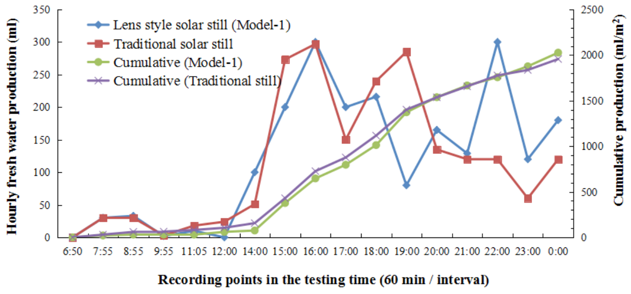

Fig. 18. Comparison between yields of Model-1 and the traditional still at 0.15 m water depth (20/7/2017).

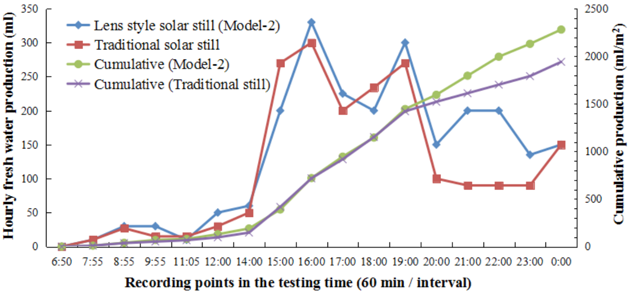

Fig. 19. Comparison between yields of Model-2 and traditional still at 0.15 m water depth (21/7/2017).

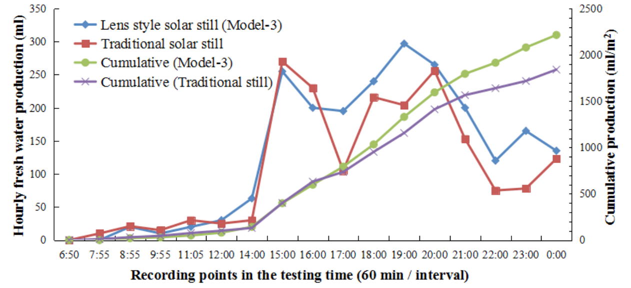

Fig. 20. Comparison between yields of Model-3 and traditional still at 0.15 m water depth (22/7/2017).

4.1.4. Effect of adding three lenses and one mirror (Model-4 vs. traditional still)

The last modification (termed Model-4) was adding three lenses and one mirror. Fig. 21 shows that the maximum promotion of water production occurs through the Model-4. Compared with the traditional still, there was 32.0% increment in yield through Model-4 at 0.15 m water depth, and the production reached the peak at about 19:00 o'clock.

4.2. Comparison of water temperature in basin between models

According to Fig. 22, there was a common phenomenon that the brackish water temperatures in lens style solar still models rose gradually before 16:00 o'clock (p.m.). Under the condition of high concentration of sunrays, the maximum temperature of the brackish water in Model-2 could reach 65.16°C, which is higher by 10.86°C in comparison with

Model-1. Then, the maximum temperature of the brackish water in Model-3 could reach 65.56°C, which is close to that of Model-2. Also, the heating process of Model-3 is similar to that of Model-2. For the Model-4, the temperature of the brackish water could reach the peak of 80.25°C, which is higher by 25.95°C in comparison with Model-1. In the range of the testing time, the water temperature in the lens style solar still of Model-4 was 10°C higher than that of the traditional solar still on average. In the traditional solar still, the brackish water needed 360 min to heat up from the initial temperature to the temperature of 50°C, while in the new style solar still with the concentrating solar collector (Model-4), the time for reaching the same situation of brackish water was 60 min. It is obvious that the adding of the lens and the mirror gave the still a strong sunlight concentration function, which reduced the heating time by 5/6. In order to clearly show the improving effect of adding lenses and reflectors, Table 3 is figured out in this paper.

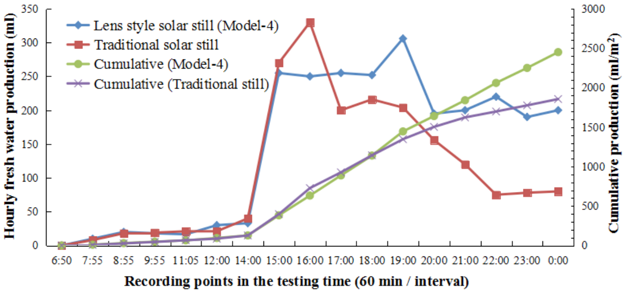

Fig. 21. Comparison between yields of Model-4 and traditional still at 0.15 m water depth (23/7/2017).

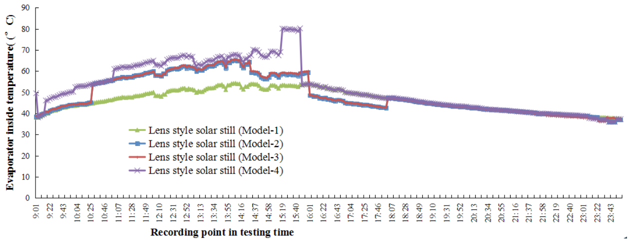

Fig. 22. Comparison of water temperature between models at 0.15 m water depth.

5. Discussion

5.1. Optimization of the orientation and slope of the still

The experimental site is in Hangzhou, China (30.3°N latitude and 120.2°E longitude), so the best orientation of the still is southward. And the inclination of the loci of the sun differs with the latitude angle, therefore, the reflected radiation from the still cover varies with the latitude angle of the test area and hence the still productivity is affected. Some authors report an optimum cover tilt angle that is close [39–41] or almost equal [42–46] to the latitude angle. Furthermore, we suggest an optimum cover tilt angle that is close to the latitude angle of the test location, so the slope of the inclined glass is 30°.

The altitude angle of the sun increases in summer, so the height of the focal plane of the side lenses decreases according to Fig. 23. As such, we propose to make the support legs adjustable for modifying the height, which is shown in Fig. 24. The amount of solar radiation can be refracted by the lenses (lower in winter and higher in summer) and then absorbed by the blackened liner.

5.2. Seasonal production of Model-4

Model-4 was further tested for a period of 1 year at 0.15 m water depth. And we only considered the sunny days. Fig. 25 exhibits seasonal production of Model-4. Productivity of the still with three lenses and one external reflector is higher in summer (May–July) and lower in winter (November–February). Location of solar still has maximum temperature of 43°C in summer and minimum –3°C in winter. Average lower ambient temperature in winter causes higher external heat transfer and higher condensation in comparison with summer. But on the other hand, it is shown that sunshine hours are less in winter (average 10.6 h) and more in summer (average 13.8 h). So the energy entering the still is higher in summer and lower in winter that causes variation in still output.

5.3. Economic analysis of the system with a different number of lenses and reflectors

Economic analysis of water desalination unit has been given by Fath et al. [47], Kumar and Tiwari [5], and Govind and Tiwari [48]. The capital recovery factor (CRF), the fixed annual cost (FAC), the sinking fund factor (SFF), the annual

Table 3
Parameters comparison between different models

Models	Modifications	Maximum temperature (°C)	Average temperature (°C)	Heating time up to 50°C (min)	Enhancement (compared with traditional design) (%)
Model-1	Adding one lens	54.30	46.276	180	5.50
Model-2	Adding two lenses	65.16	48.837	90	17.46
Model-3	Adding three lenses	65.56	48.90	90	20.32
Model-4	Adding three lenses and one mirror	80.25	52.20	60	32.00

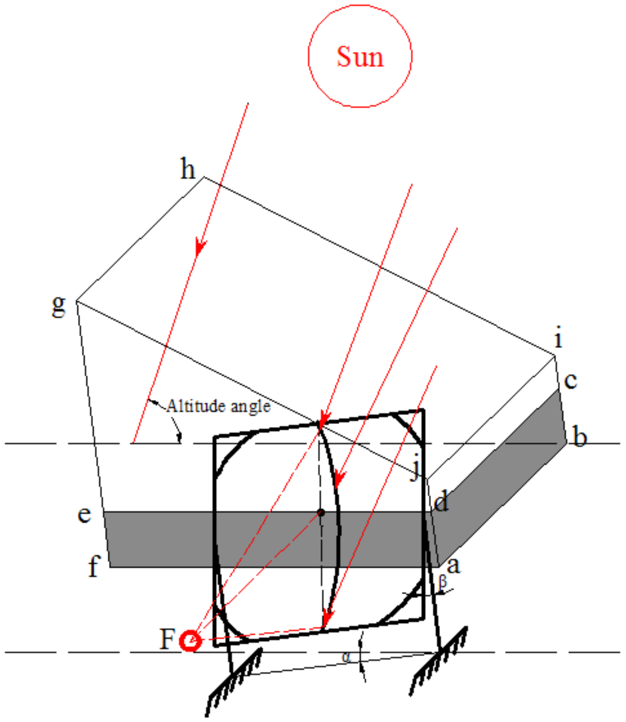

Fig. 23. Refracted sunrays from side lenses onto the ground in summer.

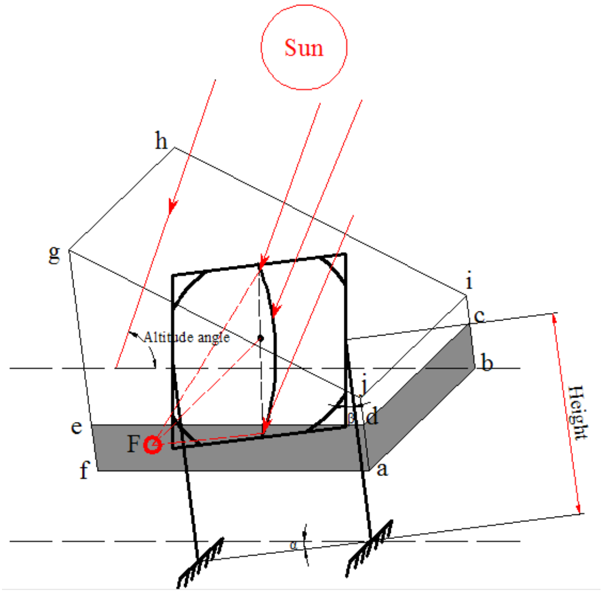

Fig. 24. Refracted sunrays from side lenses onto the blackened liner in summer.

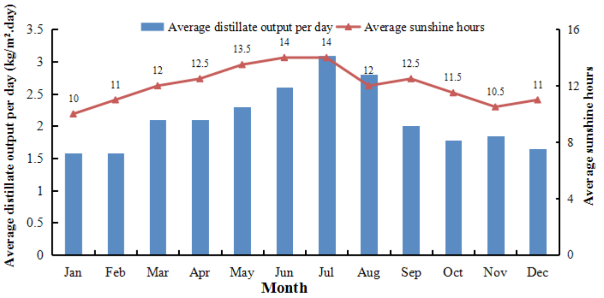

Fig. 25. Exhibition of the seasonal production of Model-4.

salvage value (ASV), average annual productivity (M), and annual cost (AC) are the main calculation parameters used in the cost analysis of the desalination unit. The annual maintenance operational cost (AMC) of the solar still is required for regular filling of brackish water, collecting the distilled water, cleaning of the glass cover, removal of salt deposited, and maintenance of the DC pump (active solar stills). The higher the depth of water, the less frequent will be the filling of water in the basin. As the system life passes on, the maintenance on it also increases. Therefore, 10% of net present cost has been considered as maintenance cost. Finally, the cost of distilled water per liter (CPL) can be calculated by dividing the annual cost of the system AC by annual yield of solar still (M). The abovementioned calculation parameters can be expressed as [47]:

$$\text{SFF} = \frac{i}{(1+i)^n - 1} \tag{1}$$

$$\text{CRF} = (\text{SFF}) \times (1+i)^n \tag{2}$$

$$\text{FAC} = \text{P} \times (\text{CRF}) \tag{3}$$

$$\text{S} = 0.2 \times \text{P} \tag{4}$$

$$\text{ASV} = (\text{SFF}) \times \text{S} \tag{5}$$

$$\text{AMC} = 0.15 \times \text{FAC} \tag{6}$$

$$\text{AC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{7}$$

$$\text{CPL} = \frac{\text{AC}}{\text{M}} \tag{8}$$

where P is the present capital cost of solar still or modified solar still; i is the interest per year, which is always assumed as 12%; n is the number of life years, which is assumed as 10 years in this paper. The prices of raw materials are all according to the Hangzhou materials market in this study. Table 4 shows the cost comparison of different solar stills. The economic indicators of present capital cost of solar still (p), the CRF, the FAC, the SFF, the ASV, the AMC, AC, average annual productivity (M), and CPL are presented in Table 4.

The average costs of distilled water for different types of solar stills are presented in Table 4. The results show that the best water production cost for LTSS is around 0.483 Ren Min Bi (RMB)/L using Model-2 with two lenses, and Model-4 with

Table 4
Cost (in RMB) comparison of different solar stills (RMB = US $0.145)

Solar still	P	SFF	CRF	FAC	S	ASV	AMC	AC	M	CPL
Traditional basin type solar still	1,335	0.057	0.177	236.295	267	15.219	35.444	256.520	586.87	0.437
Model-1 with one lens	1,535	0.057	0.177	271.695	307	17.499	40.754	294.950	607.9	0.485
Model-2 with two lenses	1,735	0.057	0.177	307.095	347	19.779	46.064	333.380	689.85	0.483
Model-3 with three lenses	1,935	0.057	0.177	342.495	387	22.059	51.374	371.810	705.67	0.527
Model-4 with three lenses and one reflector	2,000	0.057	0.177	354.000	400	22.800	53.100	384.300	758.16	0.507

three lenses and one external reflector has the highest production with cost of 0.507 RMB/L.

6. Conclusions

In our research, an LTSS was proposed which could improve the freshwater output. According to the traditional design of solar still, there is only one way available for the entrance of sunlight and that is the reason why its working efficiency is very low. Hence, this study used three lenses to refract and aggregate the surrounding sunrays from three side walls, and one mirror was set on the back of the still to avoid the sunlight loss.

- Under the same climatic conditions, the proposed Model-1 (adding one lens) had only a minor effect by 5.5% growth of freshwater output, and Model-2 (adding two lenses) produces about 17.46% higher yield in comparison with the traditional solar still. Model-3 (adding three lenses) produced about 20.32% yield growth, and there was a small gap between the performances of Model-2 and Model-3.
- In the traditional solar still, the brackish water needed 360 min to heat up from the initial temperature to the temperature of 50°C. The added lenses can enhance the internal heating exchange. Compared with traditional design, one lens reduces the heating time from about 38°C to 50°C by 50%, and two lenses reduce the heating time by 75%, and three lenses reduce the heating time by 75%.
- Extra one mirror improves the freshwater yield. The mirror is used as a reflector to reflect the sunrays from the back of the still onto the blackened liner. The yield of Model-4 (adding two lenses and one mirror) was 32.0% higher than that of the traditional solar still.
- Model-4 has the optimal heating effect, three lenses and one mirror can reduce the heating time from about 38°C to 50°C by 83.33%, compared with traditional design. In the range of the testing time, the water temperature in the lens style solar still of Model-4 was 10°C higher than that of the traditional solar still on average.

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