Sunlight concentration effect analysis of lenses on single-slope solar still

Shibiao Fang, Wenrong Tu, Lili Zhu and Zhilin Sun

ABSTRACT

In this paper, an experimental study has been conducted to monitor the productivity of a single-slope active solar still with three lenses and one mirror. The lenses and the mirror were proposed to be attached to a basin-type single-slope active solar still because of their concentration effect for sunlight. After 24-hour performance monitoring, a higher yield was observed in the new style of solar still as compared with the conventional single-slope still. The lenses refract and aggregate the sunlight from three side walls, and one mirror set on the back of the evaporator can avoid sunlight loss. Model-3 with three lenses produced about a 21.03% yield increment, and an extra 8.77% yield was observed by adding one mirror in Model-4. The yield of the proposed solar still could reach the maximum freshwater production through Model-4 (adding three lenses and one mirror) of 0.8 kg/m^2.d on 1/8/2016. Compared with the traditional still, there was a 29.8% increment in yield through Model-4 at 0.15 m water depth, and the production reached its peak at about 16:00.

Key words | experimental study, lenses, production improvement, reflector mirror, solar still, sunlight concentration

Shibiao Fang
Zhilin Sun (corresponding author)
Ocean College,
Zhejiang University,
Hangzhou 310058,
China
E-mail: *oceansun@zju.edu.cn*

Wenrong Tu
College of Civil Engineering and Architecture,
Zhejiang University,
Hangzhou 310058,
China

Lili Zhu
Department of Hydraulic Engineering, College of Civil Engineering and Architecture,
Zhejiang University,
Hangzhou 310058,
China

INTRODUCTION

A traditional solar still is very simple and inexpensive, and it can produce freshwater even if there is no high-grade solar energy. It is made up of a blackened basin, an inclined glass, several heat insulation walls, a distilled water collector and a brine collector. Sunlight will transmit through the inclined glass and be absorbed by the blackened liner, then the water heated up by the blackened liner will evaporate, and because of partial pressure difference and temperature difference, the pure water vapor condenses on the cool inside-surface and drips down (Omara *et al.* 2017).

The single-slope solar still is a common form because it is beneficial for keeping the solar still facing the sun, and most researchers focus on parameters such as water color, added dyes and charcoal pieces, and the equipped heat collector. Jamil & Akhtar (2017) also considered floating surfaces of different thickness (3 mm, 6 mm, 10 mm, 15 mm) with different density (24 kg/m^3, 20 kg/m^3, 15 kg/m^3) in their experiment. It is considered that the dark color of water could absorb a greater amount of solar radiation which causes it to heat up quickly, and the maximum yield was obtained with a floating sheet of density 20 kg/m^3 and 3 mm thickness (Jamil & Akhtar 2017).

The inclined slope provides a unique way for collecting condensed water, and in such a way, water mist on glass causes entry deterrence for sunlight. In order to force the steam to condense to water, a type of double-slope solar still has been figured out. One slope of this type of solar still is used for sunlight entrance, and the extra one is applied for condensation. Experimental work was conducted on both active and passive solar distillation systems by Kumar & Tiwari (2009), and the effects of various parameters like interest rate, life of the system and the maintenance cost were taken into account. The average annual solar yield of a conventional double-sloped single-basin

doi: 10.2166/ws.2018.009

pyramid solar still is approximately 4.0 l/m^2 day (Sahota *et al.* 2017).

A single-axis sun-tracking system is accessory equipment for a solar still, and the sun tracking is more effective than a fixed system and it is capable of enhancing the productivity. The production of water by a sun-tracked solar still was increased by around 22% compared with a fixed solar still, due to the increase of overall efficiency by 2% (Skouri *et al.* 2016). A sun-tracking system is expensive, however, increasing the desalination cost.

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. It is not easy to capture the sunlight due to the change of altitude angle of the sun in different seasons (Tanaka 2009).

The sunlight concentration effect of concave lenses has been proved by experiments. Morad *et al.* (2017) set concave mirrors to reflect and concentrate the sun-rays on a solar still (a point-focus elliptical-shape solar still with concave mirrors). The experimental results showed a significant improvement of the productivity of desalinized water, about 303% compared with the other thermal solar stills (Morad *et al.* 2017).

Nowadays, there is an innovative design, creating a vacuum by natural forces in the desalination system (Bilgil & Hırlakoğlu 2017). Because of the vacuum, the evaporation temperature of water is lowered so that vapor can be easily achieved from a flat-plate collector. The latent heat of condensation can be utilized in multi-effect from one stage to evaporate water in the next stage, which will increase production working on the same principle.

After literature research, it is concluded that there is only one way available for the entrance of sunlight in the traditional solar still, and its working efficiency is relatively low. In addition, the traditional solar still is not easy to adjust according to the position of the sun. As such, the modifications of the active solar still are necessary. In this paper, experiments have been conducted to analyze the performance of a modified basin-type solar still, adding three lenses and one mirror. The improved performance was compared with that of the conventional basin-type single-slope solar still, and the same size and material were guaranteed through the perfect synchronous experiment. Effects of adding one lens, adding two lenses, adding three lenses, and adding three lenses and one mirror have also been analyzed.

METHODS

Illustration of experimental set-up

Experiments were conducted under actual weather conditions in Hangzhou, Zhejiang Province of China. Solar irradiance was acquired by a solar energy testing system. The temperature data were collected by a multi-channel temperature recorder. Four thermocouples were scattered in the brackish water body to detect the measured water temperature. The distilled water production was achieved according to the reading of the freshwater collector. The experimental site was in the city of Hangzhou of China (30.3°N latitude and 120.2°E longitude).

This is the design concept of the newly designed solar still in our research: the incident sun-rays were transmitted through the inclined glass, and refracted by convex lenses or reflected by the mirror onto the blackened liner of the solar still so that the blackened liner absorbed more sun-rays than that of a traditional solar still. 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 was provided with a metal valve, and a steam output pipeline was linked with the metal valve. The outer surfaces of the evaporator were painted black to prevent escaping light, and moreover, the painted walls could absorb the refracted light and diffuse light. A simple exhibition of the new design is shown in Figure 1, and the optical path configuration of the experimental apparatus is displayed in Figure 2.

The body of the solar still was made up of fiber-reinforced plastic of 5 mm thickness. The base dimensions of the basin were $1.0 \times 1.0\ m^2$, and the inclination of the glass cover ($1 \times 1.06\ m^2$) was 30° from the horizontal, which is approximately equal to the latitude of Hangzhou (30.3°) as suggested by Singh & Tiwari (2004) and Khalifa (2011).

Experimental models in this research

A sketch of different design modifications is shown in Figure 3.

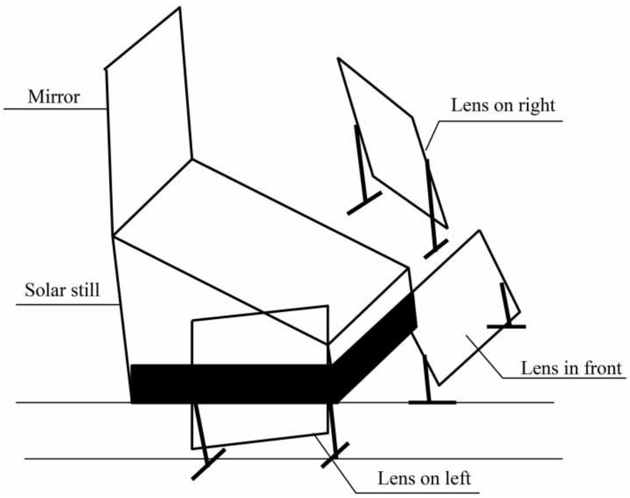

Figure 1 | A simple exhibition of the newly designed solar still.

Instruments used in the experiments

Contrast experiments were carried out between a conventional still and models (Model-1, Model-2, Model-3, Model-4) on four alternate days: 29/7/2016, 30/7/2016, 31/7/2016 and 1/8/2016 respectively. Testing data of solar intensity, different temperatures and distillate output were recorded between 6:00 and 24:00 daily. Instrument parameters in this study are shown in Table 1.

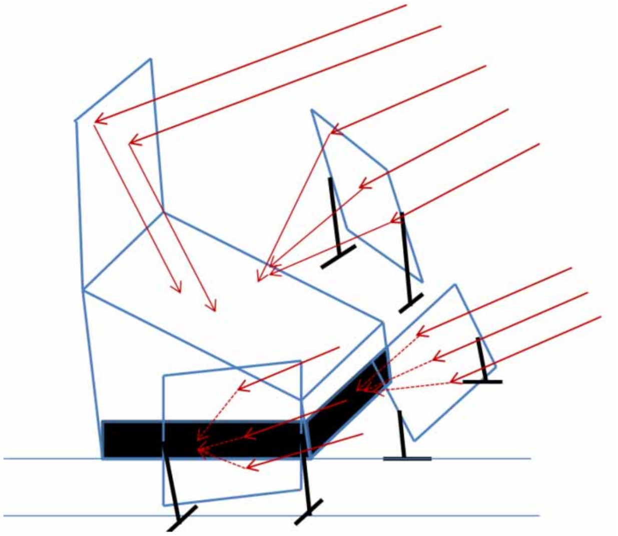

Figure 2 | The optical path configuration of the experimental apparatus.

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. 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 (Baibutaev & Achilov 1968; Baibutaev & Achilov 1970; Akash *et al.* 2000) or almost equal (Abd Elkader 1998; Al-Hinai *et al.* 2002; Omri *et al.* 2005; Aybar & Assefi 2009; Khalifa & Hamood 2009) 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 in Figure 4. As such, we propose to make the support legs adjustable for modifying the height, which is shown in Figure 5. 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.

RESULTS AND DISCUSSION

Different modifications of traditional disc-type solar evaporator

Solar energy utilization efficiency of brackish water in the lens-style solar still was tested compared with a traditional disc-type solar evaporator in the same time interval, so we got the change rule of temperature rise and heat energy utilization efficiency of each test model under similar test conditions. The energy utilization efficiency of the brackish water was calculated and analyzed in the operating temperature range (40–70 °C), Model-1, Model-2, Model-3, and Model-4 on four alternate days: 29/7/2016, 30/7/2016, 31/7/2016 and 1/8/2016 respectively.

Model-1 was made to run on 29/7/2016, and the other different modifications (Model-2, Model-3, Model-4) were implemented on the next three consecutive days of 30/7/2016, 31/7/2016 and 1/8/2016. All the modifications were

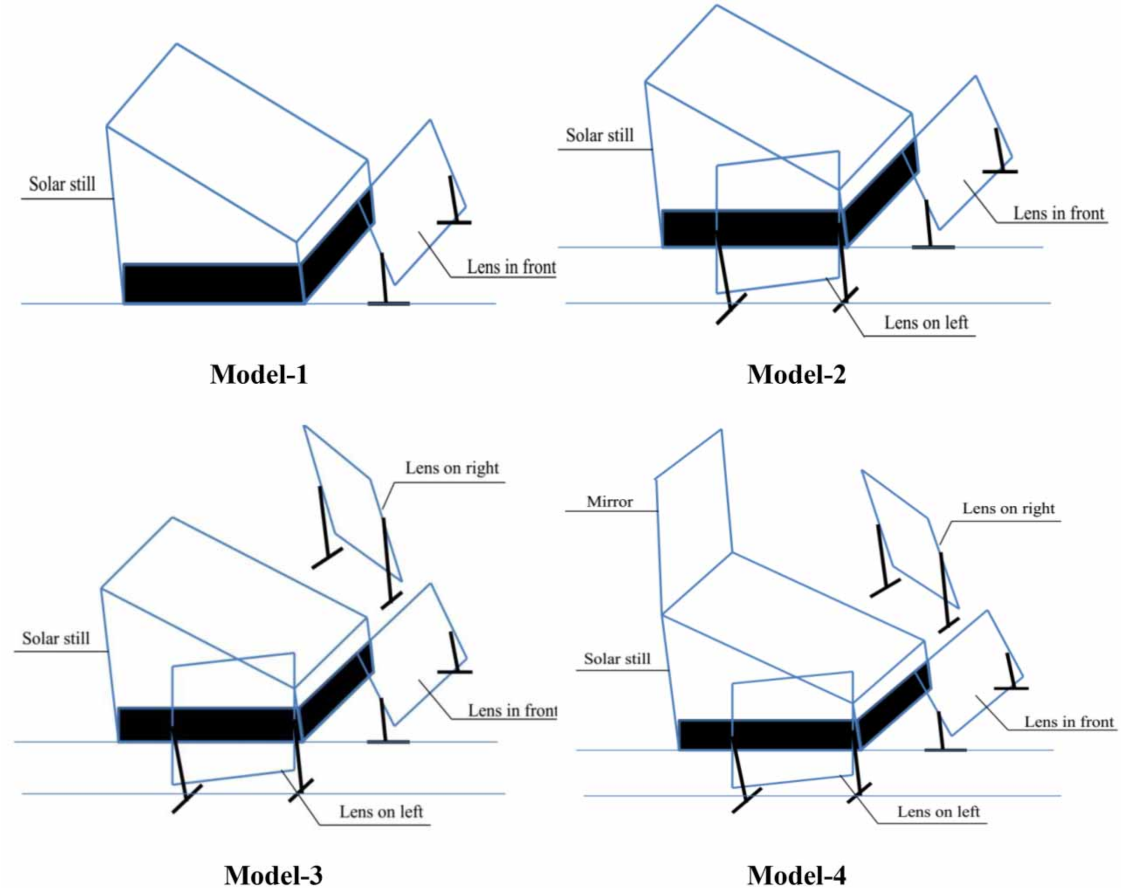

Figure 3 | Experimental set-up with different design modifications. Model-1: solar still with one lens; Model-2: solar still with two lenses; Model-3: solar still with three lenses; Model-4: solar still with three lenses and one mirror.

compared with a traditional disc-type still at 0.15 m water depth. The climate conditions were very stable in these days.

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

One lens was added to the traditional solar still, and this is named Model-1. The variation range of the solar irradiance and ambient temperature is shown in Figure 6, and the water temperature with heating time curve is shown in Figure 7.

In Figure 7, with the sustained increase of solar radiation intensity before 16:00, brackish water temperatures in both the traditional solar still and lens-style solar still (Model-1) rose gradually. Under the condition of high

Table 1 | Instrument parameters in this study

No.	Instruments	Test items	Measurement range	Accuracy
1	Thermal performance testing system	Solar radiation, ambient temperature, ambient wind velocity	0–1,000 W/m^2	±20 W/m^2
2	Thermocouples	The temperatures of the basin water, vapor, and condensing cover's inner and outer surfaces	0–200 °C	±0.1 °C
3	A multi-channel digital temperature indicator	Indicating the temperatures	0–200 °C	±0.1 °C
4	Measuring jars	The distillate output	0–1,000 ml	±5 ml

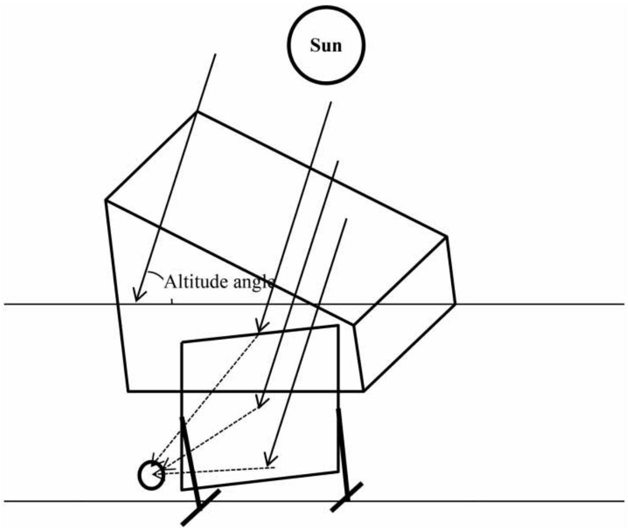

Figure 4 | Refracted sun-rays from side lenses onto the ground in summer.

concentration of sunlight, the maximum temperature of the brackish water could reach 54.3 °C, which was 2.1 °C higher than in 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, and 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 minutes 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 made the evaporator have a strong sunlight concentration function, which reduced the heating time by half.

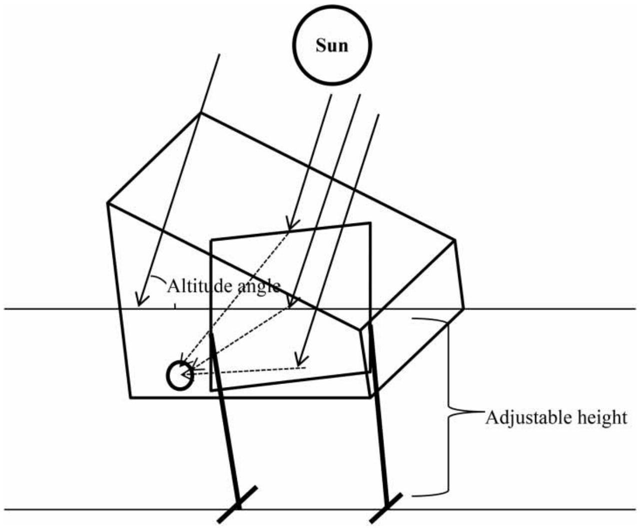

Figure 5 | Refracted sun-rays from side lenses onto the blackened liner in summer.

According to the experimental measurement of the steam volume of the traditional solar still and lens-style solar still in unit time, we figured out the utilization efficiency of thermal energy, expressed by the freshwater production per hour, and the result is shown in Figure 8.

The data in Figure 8 show that there was more freshwater produced after 14:00, and the production reached its peak in the evening at about 19:00 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 the lens-style solar still was slightly higher.

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

The next modification was adding two lenses, and this is named Model-2. There was an 18.287% increment in yield through Model-2 at 0.15 m water depth (Figure 9), compared with the traditional still. This is due to the sunlight refracted by two convex lenses to the inside of the evaporator being more than in Model-1, and the sawtooth-type heat-collecting plate absorbed a large amount of the sunlight to heat the brackish water generating high-temperature steam. A higher temperature difference between water in the still and the cover enhances the internal heat transfer rate and produces more evaporation and then condensation.

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

The freshwater production of Model-3 was higher by 21.03% than that of the traditional solar still at 0.15 m water depth, and the yield comparison is shown in Figure 10. This modification was adding three lenses, and the promoting effect of one extra lens was not significant. We could explain that the internal heat absorption effect is obvious, but the glass cover releasing heat to the surrounding environment is not quick enough, and thus produces less condensation water. That

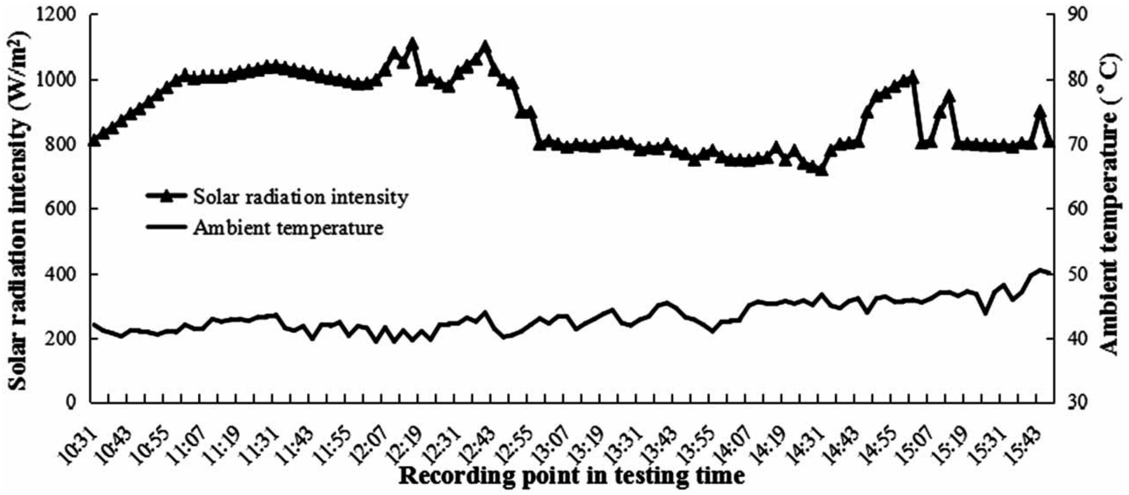

Figure 6 | Curves of solar irradiance and ambient temperature on 29/7/2016.

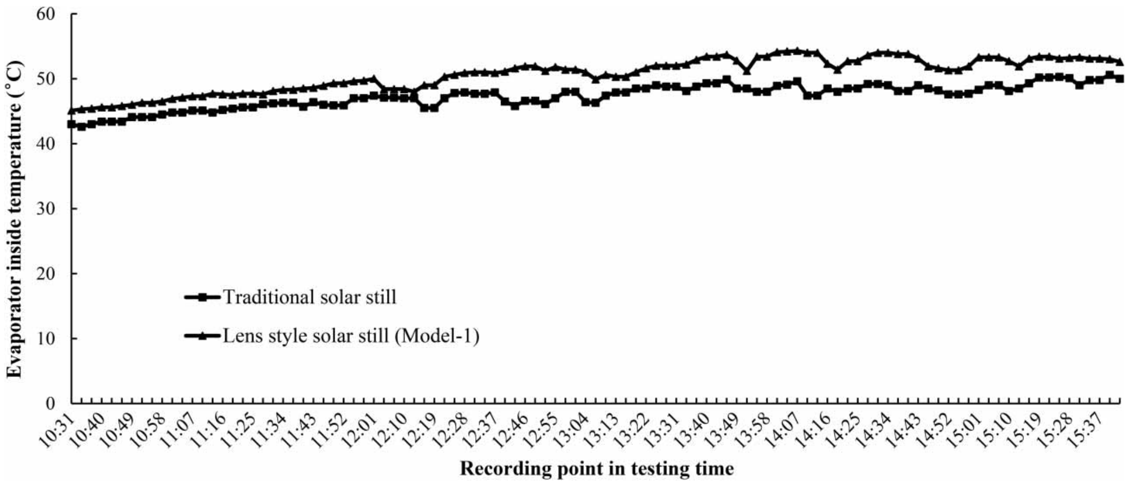

Figure 7 | Comparison of water temperature between Model-1 and traditional still at 0.15 m water depth (29/7/2016).

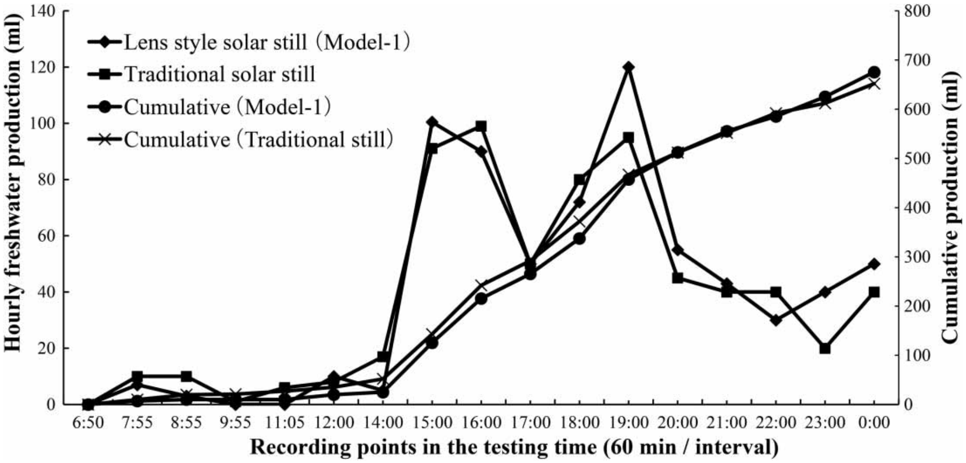

Figure 8 | Comparison between yields of Model-1 and traditional still at 0.15 m water depth (29/7/2016).

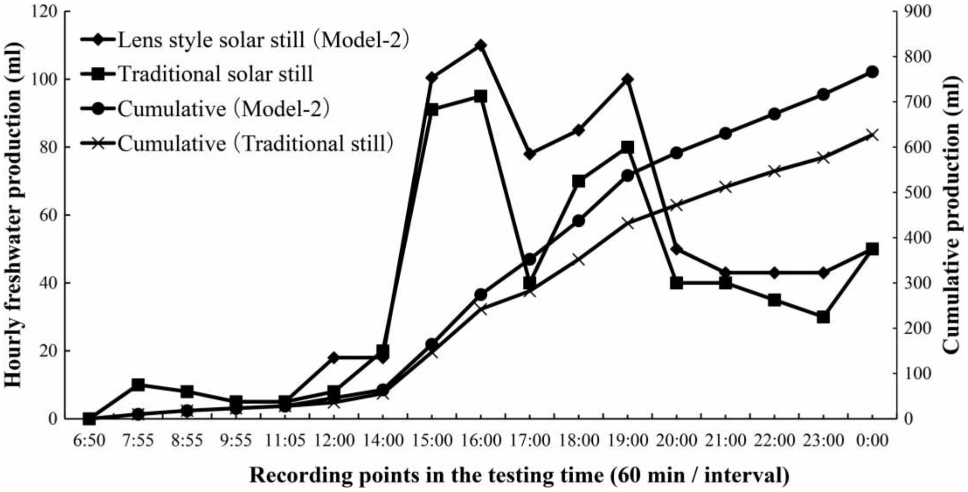

Figure 9 | Comparison between yields of Model-2 and traditional still at 0.15 m water depth (30/7/2016).

is to say, we need to select a suitable cover to accelerate the external heat transfer rate from the still to the atmosphere resulting in faster condensation.

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. Figure 11 shows that the maximum promotion of water production occurs through Model-4. Compared with the traditional still, there was a 29.8% increment in yield through Model-4 at 0.15 m water depth, and the production reached its peak at about 16:00.

Comparison of water temperature in basin between models

According to experimental testing, there was a common phenomenon that brackish water temperatures in lens-style solar still models rose gradually before 16:00. Under the condition of high concentration of sunlight, 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 Model-4, the temperature of the

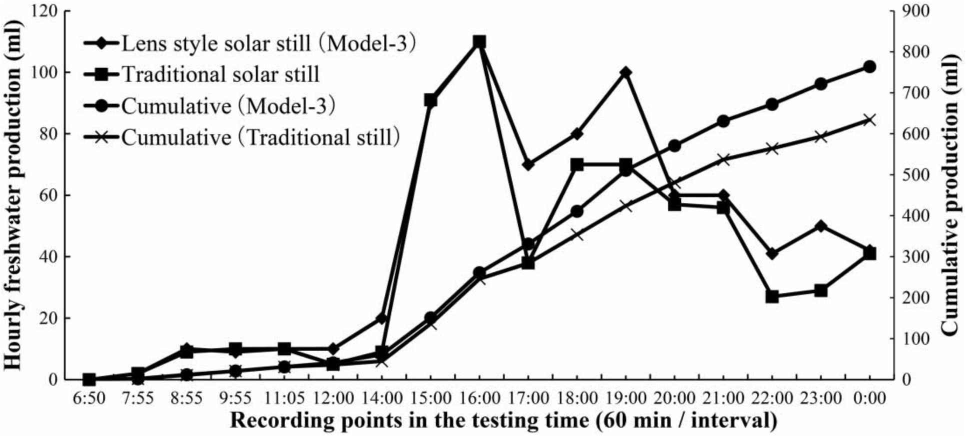

Figure 10 | Comparison between yields of Model-3 and traditional still at 0.15 m water depth (31/7/2016).

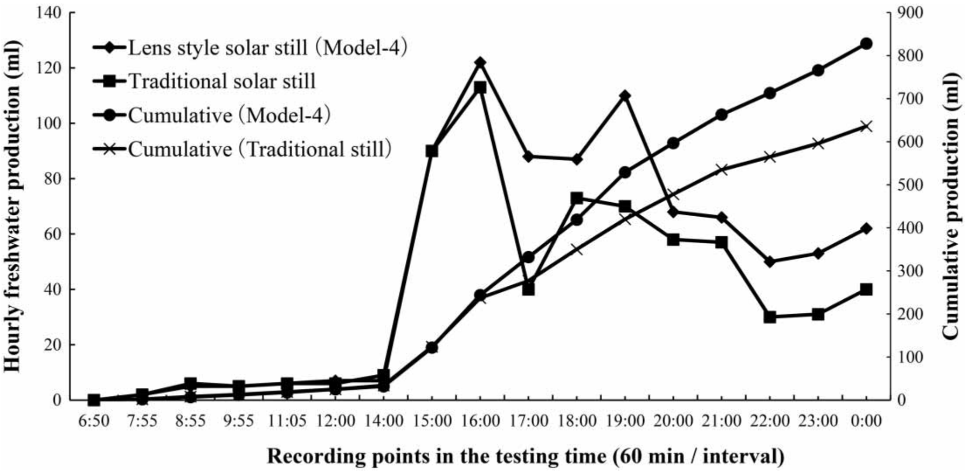

Figure 11 | Comparison between yields of Model-4 and traditional still at 0.15 m water depth (1/8/2016).

Table 2 | Parameter comparison through different models

Models	Modifications	Maximum temperature	Average temperature	Heating time up to 50 °C	Enhancement (compared with traditional design)
Model-1	Adding one lens	54 °C	46 °C	180 min	1.05%
Model-2	Adding two lenses	65 °C	49 °C	90 min	18.287%
Model-3	Adding three lenses	65 °C	49 °C	90 min	21.03%
Model-4	Adding three lenses and one mirror	80 °C	52 °C	60 min	29.8%

brackish water can reach a 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 minutes 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 was obvious that the adding of the lens and mirror made the evaporator have 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 a mirror, Table 2 is presented in this paper.

CONCLUSIONS

In our research, a lens-type solar still was proposed which could improve freshwater output. A higher yield was observed in the new style of solar still as compared with the conventional single-slope still. The lenses refract and aggregate the sunlight from three side walls, and one mirror set on the back of the evaporator can avoid sunlight loss. The following conclusions are deducted:

1. After 24-hour performance monitoring, we could find that the proposed Model-1 (adding one lens) has only minor effects by 1.05% growth of freshwater output, and Model-2 (adding two lenses) produces about 18.29% higher yield in comparison with the traditional solar still. Model-3 (adding three lenses) produces about 21.03% yield increment, and the performance difference between Model-2 and Model-3 is small.
2. The added lenses can enhance internal heating performance. Compared with the traditional design, one lens reduces the heating time from about 38 °C to 50 °C by 50%, two lenses reduce the heating time by 75%, and three lenses reduce the heating time by 75%. Model-4 (three lenses and one mirror) can reduce the heating time by 80%, compared with the traditional design.

3. We have proved that the reflector can effectively prevent sun-ray-loss, and the added mirror improves the fresh-water yield according to our research. An extra 8.77% yield is observed in Model-4, which is caused by the mirror being applied as a reflector to collect the sunlight on the back of the solar still.
4. Because there is no heat insulation device, the production of pure water in our research is not stable. As such, we plan to modify the solar still in the future, and the solar still's basin body will be enclosed by an insulating film just to reduce the side and base heat loss. In addition, the solar still is installed with a double wall surface, and the vacuum treatment of the double wall surface will be conducted.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from Major Science and Technology Project of Xinjiang Uygur autonomous region (2016A03008-02), Fundamental Research Funds for the Central Universities (Grant No. 2015XZZX002-06), Project Supported by the Major Research plan of the National Natural Science Foundation of China (Grant No. 91647209) and National Key Research and Development Plan of China (Grant No. 2016YFC0402305-02).

REFERENCES

Abd Elkader, M. 1998 An investigation of the parameters involved in simple solar still with inclined yute. *Renew. Energy* **14**, 333–338.

Akash, B. A., Mohsen, M. S. & Nayfeh, W. 2000 Experimental study of the basin type solar still under local climate conditions. *Energy Convers. Manage.* **41**, 883–890.

Al-Hinai, H., Al-Nassri, M. S. & Jubran, B. A. 2002 Effect of climatic, design and operational parameters on the yield of a simple solar still. *Energy Convers. Manage.* **43**, 1639–1650.

Aybar, H. Ş. & Assefi, H. 2009 Simulation of a solar still to investigate water depth and glass angle. *Desalination Water Treat.* **7**, 35–40.

Baibutaev, K. B. & Achilov, B. M. 1968 Comparative testing of a solar distiller. *Appl. Sol. Energy* **4**, 69–72.

Baibutaev, K. B. & Achilov, B. M. 1970 Effect of the inclination of the transparent solar still surface on the condensation and collection processes. *Appl. Sol. Energy* **6**, 34–38.

Bilgil, A. & Hırlakoğlu, B. 2017 An experimental study on desalination at vacuum environment under low pressure and low condensation temperatures. *Desalination* **411**, 9–18.

Jamil, B. & Akhtar, N. 2017 Effect of specific height on the performance of a single slope solar still: an experimental study. *Desalination* **414**, 73–88.

Khalifa, A. J. N. 2011 On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes. *Energy Convers. Manag.* **52** (1), 431–436.

Khalifa, A. J. N. & Hamood, A. M. 2009 Experimental validation and enhancement of some solar still performance correlations. *Desalination Water Treat.* **4**, 311–315.

Kumar, S. & Tiwari, G. N. 2009 Life cycle cost analysis of single slope hybrid (PV/T) active solar still. *Appl. Energy* **86** (10), 1995–2004.

Morad, M. M., El-Maghawry, H. A. M. & Wasfy, K. I. 2017 A developed solar-powered desalination system for enhancing fresh water productivity. *Solar Energy* **146** (4), 20–29.

Omara, Z. M., Abdullah, A. S., Kabeel, A. E. & Essa, F. A. 2017 The cooling techniques of the solar stills' glass covers – a review. *Renewable and Sustainable Energy Reviews* **78**, 176–193.

Omri, A., Orfi, J. & Ben Nasrallah, S. 2005 Natural convection effects in solar stills. *Desalination* **183**, 173–178.

Sahota, L., Shyam & Tiwari, G. N. 2017 Energy matrices, enviroeconomic and exergoeconomic analysis of passive double slope solar still with water based nanofluids. *Desalination* **409**, 66–79.

Singh, H. N. & Tiwari, G. N. 2004 Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination* **168**, 145–150.

Skouri, S., Ali, A. B. H., Bouadila, S., Salah, M. B. & Nasrallah, S. B. 2016 Design and construction of sun tracking systems for solar parabolic concentrator displacement. *Renewable and Sustainable Energy Reviews* **60**, 1419–1429.

Tanaka, H. 2009 Tilted wick solar still with external flat plate reflector: optimum inclination of still and reflector. *Desalination* **249**, 411–415.

First received 16 May 2017; accepted in revised form 22 December 2017. Available online 16 January 2018