A compact flat solar still with high performance

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Abstract

Solar still is a convenient device for desalination, which can provide fresh water for families, ships, islands and so on. The conventional inclined solar still (ISS) is suffer from low efficiency. To overcome disadvantages of ISS, a compact flat solar still (FSS) is proposed, which designed with ultra-hydrophilic glass cover and attached threads. FSS is much more compact and less heat loss than ISS. The results indicate that the energy efficiency of FSS reaches to more than 60% in September and October at Wuhan, China, which is higher than that of ISS by 36%. More interestingly, FSS can also be easily extended to multi-stage system with recovering latent heat. The results show that the efficiency of a double-stage FSS reaches up to 99%. FSS paves a brand new way in designing and optimizing of solar desalination.

Keywords: flat solar still; solar desalination; latent heat recovery; ultra-hydrophilic glass
1. Introduction

The fresh water is of major importance to human beings’ survival as well as our economic activities such as agriculture and industry. Nowadays billions of people are suffering freshwater scarcity 1. Thereby, it is highly desirable to find out effective ways to get fresh water from alternative resources such as wastewater, brackish, ground, sea water and so on 2. Desalination is a promising technology to meet the global fresh water demand, due to saline water account for 97% of the water on earth’s surface. Furthermore, solar desalination is considered as one type of desalination technology, which has many benefits such as no fuel cost and eco-friendly 3, 4.

The solar still, a typical small scale solar desalination system, provide a solution for the water shortage problem in remote regions, arid areas, and emergency situation etc. 5. Solar still has many special features such as low fabrication cost, easy to maintain and portable 6. The great majority of the investigated solar stills are inclined solar still (ISS), which mainly consists of wedge-shape basin and glass cover 7, 8. However, solar still is not universally utilized due to the relatively low productivity as well as the low energy efficiency 9-11. Therefore, many studies have been carried out to improve the productivity as well as the thermal performance of the solar still by different methods, such as improving the structure by designing stepped solar still 12, wick type solar still 13, 14, double slope solar still 15 and so on. Or using special materials, such as sponge 16, charcoal 17 and so forth. Nowadays, the productivity of ISS are usually 2-5 kg/m² per day and the corresponding energy efficiency is around 30-50% 7, 8, 18, 19. Therefore, there is still ample room for further improvements.

Recently, many efforts have been done to improve the performance of solar still by micro/nanotechnologies 4, 20, 21. Most of these works focus on enhancing the solar evaporation process of solar still by using micro/nano structure porous materials, such as plasmonic metals 22, carbon-based materials 23, polymers 24 and semiconductors 25. The energy efficiency of the evaporation process can reach up to more than 90% with
the help of new materials \textsuperscript{26, 27}, which shows the great potential of using micro/nano materials for improving solar still.

Nevertheless, the productivity and efficiency of solar still with micro/nano technologies are still relatively low, due to missing of thermal design optimization. The daily productivity of solar stills with micro/nano materials are usually about 1-4 kg/day and the corresponding efficiency is below 40\% under natural sun, which is similar to the solar still without micro/nano materials \textsuperscript{19, 28-30}. It is found that the inefficient is resulted from the inherent disadvantages of conventional ISS, such as the inefficient condensation, solar reflection on condensation cover, large heat loss of system, and so on \textsuperscript{21,29}. Therefore, there is a demand to design a new type of solar still for solving these problems and effectively improving the system performance\textsuperscript{31}.

In this paper, by imitating the working principle of solar cell, we firstly propose a flat solar still (FSS) which breaks the stereotype and make an innovation in solar still. Similar to that electrons are collected by metallic grid in solar cell, water molecules are produced by solar energy and collected by the capillary grid in the flat solar still. FSS is much more efficient and compact than the conventional ISS. To illustrate the advantages of FSS, firstly, indoor experiments by using solar simulator are carried out to explore the effect of different factors on FSS. Then, the performance of new FSS and conventional ISS is compared by experiment under natural solar irradiation. Meanwhile, thermal analysis is made to understand the difference between FSS and ISS. Lastly, the potential of constructing high efficiency multi-stage FSS is verified and discussed. This work opens a new avenue for the research and application of solar still system.

2. Experimental setup and materials

To show the difference between ISS and FSS, the schematic diagram of ISS and FSS are illustrated in Fig. 1a and 1b. In conventional ISS, the basin is wedge-shape where brackish/saline water is collected at its base. The wall of the basin in ISS is relatively high to ensure the inclined structure for water collecting. When the system
works during the day time, solar irradiation entering the still through the glass and absorbed by solar absorbing materials or water. The water is heated up by solar irradiation and evaporates. The upper surface of the basin is covered by a sealed glass cover, the hot vapor flows up and condenses on the glass cover. The condensate water slides down due to gravity and accumulates outside the still as freshwater.

In FSS, the inclined structure is avoided, due to the condensate water on glass cover is collected by the capillary action of wick instead of the gravity. Thereby, the four walls of the basin in FSS have the same height and can be much lower than that in ISS (Fig. 1b). Therefore, both the areas of walls and glass cover are significantly decreased. The decreased heat dissipating area of the system results in much less heat loss than ISS. Meanwhile, latent heat recovery is of significant importance for enhancing the daily productivity of solar still. FSS can be easily extended to a multi-stage system for latent heat recovery, due to the flat and compact structure. On the contrary, most of the conventional ISS has either complex system configuration or unsatisfying performance for latent heat recovery. Therefore, compared with ISS system, FSS has two very important advantages due to the improved system design: less heat loss and great latent heat recovery performance.

The detailed schematic diagram of FSS is shown in Fig. 1c. The basin of FSS is made of foam and galvanized iron sheet, which contains saline water and prevents heat loss (Fig. S7). Several foam strips float on the saline water and support the wick material on it. Saline water is transported from the basin to the black wick material (linen in this work) by capillary action, then heated by solar energy and evaporates. The floating foam and wick material enable heat localization and high efficiency evaporation at the air-water interface. Meanwhile, carbon black (CB) nanoparticles are dispersed on the surface of wick material to enhance solar absorption and vapor generation. The top basin is sealed by a glass cover and several cotton threads are attached to the glass cover parallelly and uniformly. When condensate water accumulates on the glass cover, it will be absorbed by the cotton threads. Later, the water absorbed by the threads will be transported out of FSS.
through capillary action and drop down by gravity along the vertical threads as fresh water. More details of the materials and setup can be found in Supplementary Information.

![Fig.1 Setup and materials for inclined solar still (ISS) and flat solar still (FSS). The schematic diagram of (a) a conventional ISS and (b) the proposed FSS. (c) Details of the configuration of FSS. The distance between the black wick material and glass cover is fixed at 5 mm unless otherwise mentioned. The picture of (d) conventional soda-lime glass and (e) the ultra-hydrophilic glass, the insert shows the contact angle of glass. (f) SG and UG above hot water.]

To make FSS more efficient, the glass cover is treated to be ultra-hydrophilic. In this work, the conventional glass cover is soda-lime glass (SG) which has high transparency as shown in Fig. 1d. To make the glass ultra-hydrophilic, commercial anti-fog spray is applied to the glass surface. The contact angle before and after treatment is shown in the insert figure of Fig. 1d and 1e, which shows that the contact angle decreases significantly after treatment. The method used in this work for ultra-hydrophilic treatment is only an example. Other materials or methods might also be applied, such as using commercial anti-fog film, coating SiO$_2$ nanoparticles $^{37}$, TiO$_2$ nanoparticles $^{38}$ and TiO$_2$ nanofibers$^{39}$ et al.

The low contact angle of glass allows vapor to condense into a continuous thin
film, which has two benefits. Firstly, the glass will remain clear during the condensation process, hence more solar irradiation will enter the solar still. As shown in Fig. 1f, the patterns under SG are vague and dark due to the light diffusion and reflection by the small condensate droplets. On the contrary, the patterns under ultra-hydrophilic glass (UG) are clear and bright. Secondly, the continuous water film accelerates water transportation from glass to threads. The water film combines all the condensate water as a whole and connects with the cotton threads. Therefore, the condensate water can be absorbed by cotton threads immediately, instead of hanging under the glass as isolated droplets and away from the cotton threads as happened in SG.

3. Results and discussions

Firstly, mini-prototypes of both FSS and ISS were made and investigated indoor by using a solar simulator. The inner volume of the small FSS is 5 cm (length) × 5 cm (width) × 3 cm (height). The intensity of solar irradiation from the solar simulator is fixed at 1kW/m² unless otherwise mentioned. The FSS with ultra-hydrophilic glass and soda-lime glass were compared by the small scale system. The hourly water productivity of the small FSS with UG is 0.75 kg/(m²·h) which is 70% higher than that of using SG (Fig. 2a). This indicates that the ultra-hydrophilic treatment of glass is very important for improving the system performance of FSS. The productivity of a small conventional ISS was also measured. It shows that there is barely fresh water collected after two hours of experiment (Fig. 2a). The poor performance of small ISS might be due to that a lot of water condensed on the wall instead of on the glass.

Besides the effect of glass cover, the effect of cotton threads is also studied on the number of thread (Fig. 2b) and the length of vertical thread (Fig. 2c). The number of thread refers to how many threads are attached to the glass cover parallelly and uniformly. The energy efficiency, η, is calculated based on the following equation 29:
where $\Delta m$ is productivity; $h_{LV}$ is the total enthalpy of phase change, which contains latent heat and sensible heat. $h_{LV}$ can be obtained according to ref. 40; $A$ is the basin area of solar still; $q(t)$ is the instantaneous power density of solar irradiation, which is fixed at 1kW/m$^2$ in the laboratory. The energy efficiency increases very slightly when the number of thread increases (Fig. 2b). The difference between the two threads and six threads is less than 8%. Energy efficiency nearly converged to 54% after 4 threads. It can be concluded that the cotton threads have very excellent water collection ability because the system performance is not greatly affected when only a few threads are used. This conclusion can be further proved by the effect of the length of vertical thread, $L_t$. The water collection is not affected even when $L_t$ is only 2 cm, which means that even very short vertical thread can provide enough driving force for water collection (Fig. 2c).

![Fig. 2](image_url)

Fig. 2 Performance of a small flat solar still (FSS) and inclined solar still (ISS) in laboratory. (a) Water productivity of FSS with ultra-hydrophilic glass (UG) and conventional soda-lime glass
(SG), as well as water productivity of a conventional ISS with soda-lime glass (SG). (b) The efficiency of FSS with different number of cotton threads attached to UG. (c) The productivity of FSS with different lengths of vertical cotton thread, \( L_t \). (d) Temperatures at different positions of FSS. The number of cotton threads and length of vertical threads in laboratory experiments are 1 cm\(^{-1}\) and 6 cm, respectively, unless otherwise mentioned.

The temperatures of FSS in laboratory conditions are also measured for further investigation (Fig. 2d). The temperature of water at the center of the evaporation surface (\( T_{w1} \)) reach up to 70 °C after two hours of the experiment. The glass temperature at the center (\( T_{g1} \)) reaches up to 65 °C. The temperature difference between glass and water enables condensation to occur. However, there is also a large temperature difference between the center and edge for both water and glass. The temperature of water at the center (\( T_{w1} \)) is around 11 °C higher than that at the edge (\( T_{w2} \)). Therefore, some vapor from the center might condense on the water surface near the edge and the surrounding wall instead of on the glass, hence the productivity of the system will be decreased. Nevertheless, this problem can be avoided at a large scale outdoor system, in which the center is away from the edge and the temperature is more uniform.

Besides the results of laboratory experiments, outdoor experiments were also carried out by homemade prototypes of FSS and ISS. Fig. 3a shows the photos of ISS and FSS for an outdoor experiment. The basin area for both ISS and FSS is 25 cm \( \times \) 25 cm. Water with 3.5 wt% NaCl was premixed and placed in the basin. The glass covers in ISS and FSS are treated to be ultra-hydrophilic and attached with cotton threads for water collection. Bottles are used to contain the collected fresh water. The solar stills and all components of the system were manufactured and tested in Huazhong university of science and technology, Wuhan, China (Latitude 30.51° N and longitude 114.41°E), during September and October. For more details about the structure and materials of outdoor ISS and FSS please refer to Supplementary Information.

The results of ISS and FSS are shown in Fig. 3 in a typical experimental day
(29th, October). The ambient temperature is around 20 °C and the maximum solar flux is 577 W/m² at noon (Fig. 3b). The total daily solar insolation is around $1.06 \times 10^7$ J/m² (2.94 kWh/m²) during this period. It should be noted that although the basin area is the same, the low solar elevation during autumn leads to more solar projection area in ISS. Therefore, the solar energy absorbed by ISS is more than FSS. The difference of solar projection area between ISS and FSS will be insignificant during the summer. Details about the analysis of solar projection area can be found in Supplementary Information.

Fig. 3 Outdoor experiments and analysis for comparison between ISS and FSS. (a) The photo of ISS and FSS during outdoor experiments. (b) Solar intensity and productivity of ISS and FSS on 29th, October. (c) The simulated temperature distribution of ISS with 500 W/m² of inlet heat flux on the evaporation surface. (d) The simulated temperature distribution of a FSS with 500 W/m² of heat flux on the evaporation surface. The phase change process is not included in all simulation. The ambient temperature is 20 °C and the convective heat transfer coefficient is 10 W/(m²·K) in simulation.
Fig. 3b shows the hourly productivity of ISS and FSS normalized to the solar projection area. The maximum hourly productivity of FSS and ISS are 0.55 kg/(m²·h) and 0.42 kg/(m²·h), respectively. The accumulated daily productivity of FSS is 2.54 kg/m², which is 36% higher than that of the ISS 1.87 kg/m². Therefore, the daily efficiency of FSS and ISS are 61% and 45%, respectively. The daily productivity of FSS may be further increased by adding mirrors to imitate the wedge-shape structure of ISS, which create more solar projection area.

The thermal performance of ISS and FSS is also analyzed by finite element analysis. The results show that there is a better heat localization on wick material in FSS. Fig. 3c and Fig. 3d shows the simulated temperature distribution of ISS and FSS. The inlet heat flux on solar absorbing surface is 500 W/m² and the phase change process is not included in the simulation. Results shows that the maximum temperature (T_max) of wick material in ISS and FSS are 83 °C and 94 °C, respectively. The temperature in ISS is lower due to more heat dissipation from wick material to other components by radiation and convection. The results indicate that FSS could localize more energy on the evaporation surface during the working time, hence higher productivity.

Besides higher productivity and less energy dissipation, FSS is very easily extended to multi-stage system with latent heat recovery. Fig. 4a shows the schematic diagram a double-stage FSS. A thin saline water layer is added on the glass cover of the first stage to absorb the latent heat released by vapor condensation. The vapor generated at the second stage condenses on the glass cover above it and collected by cotton threads as in the first stage. More stages can be added by repeating the second stage on FSS if necessary. The climate conditions of a typical experimental day (28th, September) is shown in Fig. 4b. The ambient temperature is around 20 °C to 30 °C and the maximum solar flux is 674 W/m² at noon. The total daily solar insolation is around 1.54 × 10⁷ J/m² (4.29 kWh/m²).

The productivity is significantly increased by using double-stage FSS. The daily productivity of double-stage and single-stage FSS are 6.0 kg/m² and 4.1 kg/m²,
respectively (Fig. 4c). Based on the accumulated productivity, the accumulated efficiency is also obtained by using Eq. (1). Both of double-stage and single-stage FSS have low efficiency during the morning, which might be due to that the some part of the energy is used to heat up the system. Eventually, the daily efficiency of double-stage and single-stage FSS are as high as 99% and 68%, respectively. The high efficiency of double-stage FSS shows its great performance at latent heat recovery. Meanwhile, the maximum hourly productivity of double-stage FSS reaches up to 1.1 kg/(m²·h) during 12-13 o’clock, which shows a 62% of enhancement compared to single-stage FSS. The enhancement at noon is greater than both morning and afternoon, which indicates that the performance of double-stage FSS might be even better during the summer due to higher solar insolation. Overall, the FSS proposed in this work shows great performance compared to other state-of-the-art solar stills (Fig. 4d).
double-stage FSS. (b) Solar intensity and ambient temperature on 28th, September, Huazhong university of science and technology, Wuhan, China. (c) Accumulated productivity and efficiency of double-stage and single-stage FSS. (d) Energy efficiency of solar still in this work and ref. 29-41.

4. Conclusion

In conclusion, based on ultra-hydrophilic glass, wick material and carbon black nanoparticles, a high efficient and compact flat solar still is proposed. The indoor results show that the wettability of glass is very important factor in FSS. The hourly productivity of FSS using ultra-hydrophilic glass is 70% higher than that of using ordinary glass. Meanwhile, the number of threads attached to the glass for fresh water collection also affect the productivity. The productivity increases a little when the number of threads increases from 0.4 to 1.2 cm⁻¹. Moreover, the length of thread at vertical direction doesn’t affect the productivity for the range from 2 cm to 10 cm.

Furthermore, the performance of FSS is studied outdoor under natural solar irradiation. Results show that the productivity of single-stage FSS reaches to more than 60% and is 36% higher than that of the conventional ISS under the same conditions, which shows the superiority of FSS. Thermal analysis shows that ISS could localize more heat on the evaporation surface, hence a better productivity and energy efficiency. Besides, with latent heat recovery, the energy efficiency of double-stage FSS reaches up to 99% under only 4.29 kWh/m² of daily solar insolation. The significant enhancement in efficiency and productivity shows the great potential of multi-stage FSS in practical application.

5. Conflicts of interest

There are no conflicts of interest to declare.
6. Acknowledgement

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Supplementary Information

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I. Measurement setup of laboratory experiments

The setup is shown in Fig S1. A solar simulator (CEL-S500 + AM1.5 filter) was used to generate the solar beam, the solar intensity was measured by a power meter (PM-150-50C) and adjusted to 1kW/m². FSS was insulated by foam with 3 cm of thickness. 5 mm of saline (3.5% NaCl) water layer was put inside of the FSS for desalination. The fresh water from cotton thread was collected by a small beaker. The mass of collected water was measured every half an hour by an electric balance (Sartorius Practum 224), the data were recorded by a laptop via a USB cable. The room temperature and humidity during the experiment were controlled at 25 °C and 50% respectively. The temperature was measured by T type thermal couple (Omega, TT-T-40-SLE), and a data acquisition device (Keithley 2700) were used to record the temperature.

Fig. S1. The schematic diagram of measurement setup in laboratory.
**Table S1 Specification of main devices.**

| Name                | Type                | Range             | Error  |
|---------------------|---------------------|-------------------|--------|
| Electronic balance  | Sartorius QUINTIX224-1CN | 0-220 g          | ±0.0002g |
| Power meter         | Coherent PM150-50C  | 300 mW-150 W      | ±3%    |
| Thermal couple      | Omega TT-T40-SLE    | -200-260 °C       | ±0.5°C |
| Data collector      | Keithley 2700       | 1-80 Channel      | -      |
| Solar simulator     | Aulight CEL-S500    | 800-3000 W/m²     | ±1%    |

**II. Characteristics of materials**

In this work, the black linen cloth and cotton thread were chosen as the wick material, (shown in Fig. S2 and Fig. S3). However, some other daily materials can also be chosen as the wick material, such as tissue, paper and so on, as long as the capillary action is strong enough. The capillary action ability of the wick material can be described by the rate of moisture regain, which is 12.5% for linen and 8.5% for cotton. A double layer structure of linen cloth is used in FSS for water evaporation, which enables great water absorption ability, hence preventing salt accumulation on evaporation surface. The mass density of carbon black (CB) nanoparticles on the surface of wick material is 10 g/m². For laboratory experiment, each thread on the glass only contains a single cotton thread as shown in Fig S3. However, 5 single cotton threads are twisted to be a bundle of large thread and attached to the glass cover in outdoor FSS, due to the side length of glass in outdoor FSS is 5 times the side length of the small FSS in laboratory, hence needs stronger water transporting ability.
**Fig. S2** (a) The picture of linen cloth. (b) The scanning electron microscope (SEM) image of linen cloth. (c) The transmission electron microscope (TEM) of carbon black (CB) nanoparticles. The size of CB is around 30-40 nm. (d) The SEM image of CB on linen cloth.

**Fig. S3** (a) A dry cotton thread. (b) A wetted cotton thread. The diameter of a single cotton thread is around 0.4 mm.
Table S2 The characteristics of the wick material and carbon black.

| material       | characteristic         | value |
|----------------|------------------------|-------|
| linen          | Rate of moisture regain [%] | 12.5  |
|                | Mass density [g/m^2]    | 250   |
|                | Thickness [mm]          | 0.5   |
| Cotton         | Rate of moisture regain [%] | 8     |
|                | Diameter [mm]           | 0.4   |
| Carbon black   | Diameter [nm]           | 30-40 |

III. Solar absorption and evaporation performance

The solar absorptivity of black wick material (linen) and wick material with carbon black is shown in Fig. S4 (a). Black wick material has very high absorptivity (around 99%) in the visible light region. However, the absorptivity decrease to 80% in the near-infrared region. With the help of carbon black, the absorptivity keeps at 97% in almost the entire solar spectrum.

![Fig. S4](image)

**Fig. S4** (a) The solar absorptivity of black wick material (linen) and wick material with carbon black. (b) The evaporation rate of the small scale FSS.

The evaporation performance of the small scale FSS (5 cm × 5 cm × 3 cm) is measured as shown in Fig. S4(b). During the measurement process, the glass cover and cotton threads of FSS are removed. Water evaporates from the surface of linen,
and the generated vapor diffuses freely to the environment, which is the same as the works for solar evaporation study \(^5, 6\). The evaporation rate is around 1.25 kg/(m\(^2\)·h) under 1 kW/m\(^2\) of solar intensity. The evaporation rate from references can reach up to 1.5~3.6 kg/(m\(^2\)·h) by using advanced nano/micro materials \(^7-9\). Therefore, the productivity of FSS can be further increased by integrating with these advanced evaporation technologies.

IV. Effect of water - glass distance

The water-glass distance means the distance between glass cover and the water evaporation surface. The distance in the main text is fixed at 5 mm for both laboratory and outdoor experiments. Herein, the system performance of FSS with 10 mm of water - glass distance are shown in Fig. S5 (a). The productivity decreases 6% compared to 5 mm of water - glass distance. This result proved the importance of the compact structure in FSS. The temperature also decreases compared to 5 mm of water - glass distance. The temperature at the center of evaporation surface (\(T_{w1}\)) is 67.5 °C which is 2.5 °C less than 5 mm of water - glass distance. The glass temperature at the center (\(T_{g1}\)) decreases 6 °C compared to that of 5 mm. The temperature at the edge (\(T_{w2}\) and \(T_{g2}\)) is very similar to that of 5 mm. Although the temperature of system decreased, the water – glass temperature difference is increased. Theoretically, the increased water – glass temperature difference should increase the condensation and productivity\(^10\). However, the productivity decreases although the temperature difference increases. This might be due to that the increased water-glass distance provides more area of cold wall for vapor condensation. Thereby, water condensation on the glass cover decreases. For larger scale FSS, the effect of water - glass distance will be more complicated and requires more studies.
Fig. S5 (a) The productivity of FSS with 5 mm and 10 mm of water - glass distance. (b) The temperature of FSS with 10 mm of water - glass distance.

V. Effect of solar intensity

The productivity of FSS under 650 W/m² of solar intensity was also measured to show the effect of solar intensity Fig. S6 (a). The productivity is 0.44 (kg/m²·h), hence the efficiency is around 47%, which is 6% lower than that of 1000 W/m². Therefore, the performance of FSS during the summer might be a little better than during the autumn. This result agree with the outdoor experiments which shows that the efficiency on 28th September (Daily solar insolation 4.29 kWh/m²) is 7% higher than that on 29th October ((Daily solar insolation 2.94 kWh/m²).

Fig. S6 (a) The productivity of FSS under 650 W/m² of solar intensity. (b) The temperature of FSS under 650 W/m² of solar intensity.
Fig. S6 (b) shows the temperature of FSS under 650 W/m² of solar intensity. The water temperature at the center of evaporation surface (T_{w1}) keeps increasing during the measurement. T_{w1} reach up to 56.5 °C after 2.5 hours, which is 13.5 °C lower than that of 1000 W/m². Nevertheless, the temperature difference between the center and edge (T_{w1} - T_{w2}) remains very high and reach up to 8 °C. This indicates that the condensation on the water surface and wall at the edge might be still very severe in this small FSS.

VI. Solar projecting area

The yellow region in Fig. S7 shows the actual solar projection area, A, of a solar still, which depends on the solar elevation, α, and the solar azimuth, β:

\[ A(t) = L(L + Hcos(\beta(t)))/\tan(\alpha(t)) \]  

(S1)

L is the side length of the basin, H is the height of the back wall, which is zero for FSS. All values vary with time t and location. α and β can be obtained according to ref. 11. The solar projection area of ISS will be close to that of FSS during the summer. Due to more solar projecting area, the temperature in ISS is higher than that of FSS as shown in Fig. S8.
Fig. S7 Schematic diagram for calculating solar projection area.

Table S3 The solar elevation and the solar azimuth for calculation

| Time   | 2019/09/28 | 2019/10/29 |
|--------|------------|------------|
|        | Azimuth angle | Elevation | Azimuth angle | Elevation |
| 8:00:00| -74.0568    | 21.7834    | -63.144       | 16.4944    |
| 9:00:00| -63.9463    | 33.8271    | -52.7158      | 27.4234    |
| 10:00:00| -50.548     | 44.6997    | -39.4221      | 36.7353    |
| 11:00:00| -31.6405    | 53.2344    | -22.4047      | 43.3966    |
| 12:00:00| -6.1618     | 57.4686    | 18.4441       | 44.2955    |
| 13:00:00| 21.0828     | 55.7436    | 36.2137       | 38.314     |
| 14:00:00| 42.9662     | 48.8078    | 50.1939       | 29.4356    |
| 15:00:00| 58.4721     | 38.762     | 61.0976       | 18.763     |
| 16:00:00| 69.7708     | 27.1248    | 69.9557       | 7.0648     |
| 17:00:00| 78.7455     | 14.7065    | 77.6362       | -5.4102    |
| 18:00:00| 86.6179     | 2.1154     |              |            |

Fig. S8 Temperature of water and glass cover of ISS and FSS.
VII. Inner structure of outdoor solar stills

Fig. S9 and Fig.S10 shows the inner structure of outdoor solar still. To effectively supply water for evaporation and rejecting the salt from the evaporation surface, the insulation foam under evaporation surface is designed as cuboid, 25 cm x 3 cm x 2 cm.

Fig. S9 (a) Inner structure of FSS. (b) Inner structure of ISS.

Fig. S10 Schematic diagram of the side view of evaporation setup in FSS and ISS.

VIII. Salt rejecting ability

The salt rejecting ability of solar still is very important for preventing salt crystallization. The traditional solar still directly heats up the bulk water to evaporate
without the problem of salt crystallization. However, the evaporation setup in this works contains very thin layer of water. Therefore, if the evaporation is too fast, the salt concentration will be too high on the evaporation surface, and finally lead to salt crystallization. In order to guide the design of evaporation setup, the effect of the structure parameters of the evaporation setup should be discussed.

Fig. S11 shows the schematic diagram of the cross section of a evaporation unit. Given that the evaporation unit does not change along the Y direction (perpendicular to paper), only x-z section is taken as the analysis object. There are three main structural parameters that affect the salt rejecting, including the half width of evaporation surface \( L_1 \), the height of evaporation surface \( L_2 \) and the thickness of wick material \( \delta \). During the evaporation process, a salt concentration gradient is formed along the direction of salt diffusion (Direction X). The concentration of salt at three positions are important in analysis, including the concentration of salt in the center of the evaporation surface \( C_1 \), the concentration of salt at the edge of the evaporation surface \( C_2 \) and the initial concentration of salt water \( C_3 \). In analysis, the salt concentration gradient in the direction of thickness of wick material is ignored.

![Fig. S11 Schematic diagram of the cross section of a evaporation unit](image)

The salt rejecting process in the wick material can be described as:

\[
J = D_{NaCl} \delta \rho \frac{\Delta C}{L}
\]  

(S2)
Where \( J \) is the mass flux of salt, \( D_{NaCl} \) is the diffusion coefficient of NaCl in water. When there is no advection, \( D_{NaCl} = 1.99 \times 10^{-9} \text{ m}^2/\text{s} \). \( \rho \) is the density of brine water (~1.3 g/cm\(^3\)). \( \Delta C \) is the difference of salt concentration, \( L \) is the diffusion length.

In the evaporation process, the mass of salt accumulated on the evaporation surface is:

\[
M_{NaCl}^E = \frac{C_3}{1 - C_3} \left( L_1 + \frac{\delta_F}{2} \right) \tilde{m}
\]  

(Equation S3)

Where \( \tilde{m} \) is the evaporation rate of water per unit area.

When the evaporation is stable, the salt rejected by the wick material is equal to the salt contained in the evaporated water. In the vertical direction of the wick material, evaporation does not occur. Therefore, all salt absorbed by the wick material reaches the horizontal evaporation region through vertical non-evaporation region, and the accumulated salt in evaporation region is also rejected into the bulk water through non-evaporation region. Thereby:

\[
\frac{C_3}{1 - C_3} \left( L_1 + \frac{\delta_F}{2} \right) \tilde{m} - D_{NaCl} \delta_F \rho \frac{C_2 - C_3}{L_2} = 0
\]  

(Equation S4)

In evaporation region, the water transportation and salt diffusion are shown in Fig. S12. The mass of salt produced \( (M_{NaCl}^E (x)) \) and rejected \( (J(x)) \) at each \( dx \) are:

\[
M_{NaCl}^E (x) = \tilde{m} \frac{C_x}{1 - C_x} dx
\]  

(Equation S5)

\[
J(x) = D_{NaCl} \delta_F \rho \frac{dC_x}{dx}
\]  

(Equation S6)

![Fig. S12 Mass conservation of water and salt.](image)

Based on the mass conservation of water and salt, we can obtain that:
\[- D_{\text{NaCl}} \delta_F \rho \frac{dC_x}{dx} - \int_0^x \dot{m} \frac{C_x}{1 - C_x} dx = 0 \]  \hspace{1cm} (S7)

\[\int_0^{L_1 + \delta_F/2} \dot{m} dx = \left( L_1 + \frac{\delta_F}{2} \right) \dot{m} \]  \hspace{1cm} (S8)

\[\int_0^{L_1 + \delta_F/2} \dot{m} \frac{C_x}{1 - C_x} dx = \frac{C_3}{1 - C_3} \left( L_1 + \frac{\delta_F}{2} \right) \dot{m} \]  \hspace{1cm} (S9)

Therefore:

\[- D_{\text{NaCl}} \delta_F \rho \frac{dC_x}{dx} - \int_0^x \dot{m} \frac{C_x}{1 - C_x} dx = 0 \]  \hspace{1cm} (S10)

\[- D_{\text{NaCl}} \delta_F \rho \frac{d^2C_x}{dx^2} - \dot{m} \frac{C_x}{1 - C_x} = 0 \]  \hspace{1cm} (S11)

The boundary conditions is:

\[x + dx = L_1 + \frac{\delta_F}{2} \quad C_x = \frac{C_3}{1 - C_3} \frac{\left( L_1 + \frac{\delta_F}{2} \right) \dot{m} L_2}{D_{\text{NaCl}} \delta_F \rho} + C_3 \]  \hspace{1cm} (S12)

When salt crystallizes at the center, \( C_1 = 26 \text{ wt\%} \), therefore:

\[x = 0 \quad C_{x=0} = 0.26 \]  \hspace{1cm} (S13)

\[\dot{C}_{x=0} = 0 \]  \hspace{1cm} (S14)

Combining Eq. S11-S14, S11 can be solved by the fourth-order Runge Kutta method.

In order to obtain the actual salt diffusion coefficient in the experiment, we measured the salt crystallization conditions. The experimental results show that when the evaporation rate \( \dot{m} \) is 1.2 kg/(m\(^2\)·h), the half width of the evaporation surface \( L_1 = 1.5 \) cm, the height of the evaporation surface \( L_2 = 2 \) cm, and the initial concentration of salt water \( C_3 = 3.5 \text{ wt\%} \), salt will crystallize at the center if \( \delta_f = 0.5 \) mm (single-layer linen). However, if \( \delta_f = 1 \) mm (double-layer linen), there is no salt crystal at the center of the evaporation surface. Therefore, assuming that \( \delta_f = 0.75 \text{mm} \) is the critical point of salt crystallization, the actual salt diffusion coefficient \( D_{\text{NaCl}} \approx 6.1 \times 10^{-8} \text{ m}^2/\text{s} \). In fact, \( D_{\text{NaCl}} \approx 6.1 \times 10^{-8} \text{ m}^2/\text{s} \). The actual diffusion coefficient is much larger than that of salt when the water is still, which shows that salt can be rejected to the bulk water through advection under the effect of temperature gradient,
concentration gradient, gravity and capillary flow.

IX. Data of energy efficiency in references

Table S4 The energy efficiency of solar still in references plotted in Fig. 4d of main text.

| Average solar density (W/m²) | Energy efficiency | Number of stage | Ref. |
|-------------------------------|-------------------|-----------------|------|
| 440                           | 99%               | 2               | This work |
| 440                           | 68%               | 1               | This work |
| 387                           | 61%               | 1               | This work |
| 650                           | 41.80%            | 1               | 12   |
| 580                           | 24.50%            | 1               | 4    |
| 830                           | 45.50%            | 1               | 13   |
| 522                           | 41%               | 1               | 14   |
| 593                           | 67%               | 3               | 15   |
| 436                           | 24.50%            | 1               | 16   |
| 622                           | 43%               | 1               | 17   |
| 850                           | 56%               | 1               | 18   |
| 643                           | 53%               | 1               | 19   |
| 500                           | 72%               | 2               | 20   |
| 560                           | 36%               | 1               | 21   |
| 560                           | 57%               | 2               | 21   |
| 625                           | 32%               | 1               | 22   |
| 625                           | 44%               | 2               | 22   |

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