# 1 Experimental Research on the Operation Characteristics of Solar

2

3 **Chimney Power Plant Combined with Distillation (SCPPCD)**  4 [[1]](#footnote-1), a, Ziyang Yan a, Pengzhan Dai a, Tian Zhou a, Bo Qu a, Yue Yuan a, Yunting Ge b

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11 **ABSTRACT**: In this paper, a comprehensive test platform for solar chimney power 12

13 plant combined with distillation (SCPPCD) that can realize water-electricity 14

15 cogeneration was designed and built. Experimental research on SCPPCD was carried

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18 out under actual meteorological conditions to explore the system operation performance

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20 and the laws of freshwater production and power generation. The interaction 21

22 mechanism between parameters such as seawater temperature, airflow temperature, 23

24 temperature difference between seawater and solar still cover, freshwater yield and 25

26 generated power was revealed. The results show that the daily water yield of solar stills

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28 decreases from the heat collector inlet to the chimney. Solar stills are recommended to

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31 be arranged in the area from collector inlet to the one-third radius of the collector. The

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33 high-water yield period occurs between sunset and 1-3 a.m., and it contributes most of

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35 the freshwater produced. Temperature difference is the main factor affecting water 36

37 production during the rising period of freshwater production, and seawater temperature38

39 is the main factor affecting freshwater production during the decline period. The 40

41 maximum temperature rise of airflow in the chimney is 17 , and the temperature rise

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44 is maintained above 5 at night. The variation of generator power is similar to that of

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46 airflow temperature rise, and the maximum power reaches 0.71 mW. This study

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48 provides detailed experimental data and theoretical reference for future mathematical

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50 simulation research and commercial application of SCPPCD.

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52 **Keywords:** Solar chimney; Solar desalination; Water-electricity cogeneration; Freshwater yield; 53 54 Turbine

# 1. Introduction

The rapid growth of the world's population places a serious burden on the environment. The growing demand for energy and freshwater in developing countries results in even greater environmental damage. As a renewable energy generation 8

9 technology with simple structure and low operating cost, solar chimney power plant 10

11 (SCPP) technology [1-3] is particularly suitable for developing countries and regions. 12

13 It can make effective use of the abundant local solar energy resources and cheap land

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15 to provide electricity to local residents in a clean way.

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18 Many experimental studies on SCPP have been reported around the world, such as

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20 in Florida, USA [4], Wuhan, China [5], University of Zanjan, Iran [6], Damascus 21

22 University, Syria [7], Aswan, Egypt [8], Warangal, India [9] and other regions. These 23

24 studies have proved the theoretical feasibility of SCPP technology and made some 25

26 optimizations on the influencing parameters of SCPP. But the studies also pointed out 27

28 that SCPP is too inefficient. Raising the chimney height is the key to improving the

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31 efficiency of SCPP [10], but it brings construction difficulties and raise the investment

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33 cost. Under the dual background of the difficulty in improving the efficiency of SCPP

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35 and the global shortage of freshwater resources, the concept of SCPP technology for

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37 seawater desalination has been put forward one after another, so that the system can 38

39 produce freshwater while generating electricity, and improve the utilization rate of solar 40

41 energy.

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44 The concept of humidification-dehumidification is widely used in the desalination

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46 process of integrated SCPP systems. Seawater desalination can be effectively achieved

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48 by humidifying the hot air in the system and condensing the hot and humid air in the 49

50 chimney area. It is a common practice to arrange open seawater pools under the heat 51

52 collector of the SCPP. Wang et al. [11] designed to transform the ground below the heat 53

54 collector of SCPP into a large open seawater storage tank, and arranged a high-

efficiency condensing device on the chimney top to condense hot and humid air to produce freshwater by the way of indirect condensation. The feasibility of the water production principle was verified by simulation experiments of the condensing device. Zhou et al. [12] developed a mathematical model based on energy balance to evaluate the performance and economy of the system proposed by Wang et al. [11] and the conventional SCPP, and made a comparison. Azad et al. [13] also conducted a 8

9 numerical simulation research on such hybrid solar chimney systems. The genetic 10

11 algorithm optimization was used to determine the optimal geometric design variables. 12

13 Kiwan et al. [14] proposed to transform part of the ground thermal storage layer into an 14

15 open annular pool, so that the airflow carried water vapor after passing over the pool,

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17

18 and then condensed on the inner wall of the chimney. A mathematical model was

19

20 established to explore the effect of operating parameters and geometric parameters on 21

22 system performance. Abdelsalam et al. [15] proposed to combine the cooling tower and 23

24 traditional SCPP technology for electricity generation and seawater desalination. A bi25

26 directional turbine was installed in the hybrid system, allowing the system to operate 27

28 as a cooling tower at night and as an SCPP during the day. The theoretical calculation

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31 showed that the total utilization rate of the hybrid system was 0.73%, 1.4 times that of

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33 the traditional SCPP. Abdelsalam et al. [16] explored the performance parameters of

34

35 the hybrid system, such as electricity output, freshwater production, and carbon dioxide 36

37 emissions, based on the environmental conditions in Doha, Qatar. The cash flow 38

39 analysis showed a high return on investment for the system. Abdelsalam et al. [17] also 40

41 analyzed the performance of the hybrid system in 16 cities in the Kingdom of Saudi

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44 Arabia to select the optimal location for installation. Salameh et al. [18] studied the

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46 electrical power and distilled water of the hybrid SCPP system under the geographic

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48 location and metrological data of Sharjah and Alain (in UAE), and explored the effect

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50 of wind speed on system performance.

51

52 In some systems, sprayers were designed to be installed at the entrance of the heat 53

54 collector or at the chimney base to increase the humidity of the hot air. Niroomand et

al. [19] designed to set up seawater sprayers and dehumidification tubes in the inlet section of the SCPP heat collector, so as to obtain freshwater in the humidification and dehumidification process of the airflow within the system. The feasibility of the system was verified by the established mathematical model. Ming et al. [20] proposed a SCPP system without heat collector by replacing the heat collector roof with black spiral pipes filled with hot water. The hot airflow in the system was humidified by a warm water 8

9 shower at the bottom of the chimney. Then the hot and humid air in the chimney reaches 10

11 the dew point and precipitation occurs if the chimney is high enough. The effectiveness 12

13 of freshwater generation of the system was evaluated by the developed flow and heat 14

15 transfer mathematical model. Subsequently, Ming et al. [21] considered adding air

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18 turbine generators and water generators to the system to achieve power output, and

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20 further analyzed the system performance parameters. It was found that the total energy 21

22 efficiency of the system was close to 7% when the chimney height was 3 km. Ming et 23

24 al. [22] designed to spray seawater droplets at the chimney base to humidify the thermal 25

26 airflow, thereby reducing the chimney height. Numerical simulation results showed that 27

28 humidification helped to improve the desalination efficiency.

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31 Multi-stage flash technology and membrane distillation technology also have

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33 certain applications in the desalination process of integrated SCPP systems. Méndez et

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35 al. [23] proposed a multigeneration system with solar chimney and wind turbine 36

37 integration for hybrid desalination and power generation. In the system, multi-stage 38

39 flash technology was used in a cascaded manner to produce freshwater, utilizing the 40

41 heat source of the solar chimney thermal storage. Zuo et al. [24] designed an air gap

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44 membrane distillation module and installed it vertically in the disc distiller of the SCPP

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46 system. Water vapor could pass through the vertical hydrophobic membrane under the

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48 action of pressure difference. It then passed through a narrow air gap to the surface of

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50 the condensation plate and condensed into droplets.

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52 Another commonly used method for seawater desalination of is to arrange closed 53

54 disc solar stills on the ground under the heat collector, and use the principle of disc

distillation to produce freshwater. Zuo et al. [~~14~~25] designed to install closed solar stills under the heat collector roof, and proposed a solar chimney power plant combined with seawater desalination (SCPPCSD). This design realized the water-electricity cogeneration and the improvement of land resource utilization rate. The conventional SCPP and SCPPCSD were evaluated by the mathematical model based on energy balance and the economic analysis model. The results showed that SCPPCSD had a 8

9 higher solar energy daily utilization rate and better economic benefits. Asayesh et al. 10

11 [~~15~~26] utilized the particle swarm optimization to optimize the design of the SCPPCSD, 12

13 and verified the existence of the optimal ratio between the seawater thermal storage 14

15 layer and the rock thermal storage layer in the system. Zuo et al. [~~16~~27, ~~17~~28]

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17

18 introduced a wind supercharger device into the SCPPCSD to provide negative pressure

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20 for the chimney outlet. It was found by numerical simulation that the wind supercharger

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22 device made up for the loss of power generation caused by the coupling of seawater

23

24 desalination technology. For the purpose of reducing atmospheric pollution caused by 25

26 industrial waste heat and realizing energy recovery, Zuo et al. [~~18~~29, ~~19~~30] proposed to 27

28 combine the thermal power plant chimney with the solar chimney. High temperature

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31 flue gas from the thermal power plant was introduced into the SCPPCSD through the

32

33 spiral heat exchange pipe under solar stills to heat the seawater in the solar still.

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35 Theoretical analysis showed that the system power output and water production was 36

37 greatly improved, and the stability of system operation was also improved. Rahdan et 38

39 al. [~~20~~31] utilized the CFD method to optimize the inclination angle of the chimney, 40

41 heat collector and solar still cover in a hybrid system of solar chimney and water

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44 desalination. Rahbar et al. [32] proposed a solar chimney power plant integrated with

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46 transparent photovoltaic cells and desalination (PVDSCP), and established a one-

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48 dimensional mathematical model of the system. In the system, part of the solar radiation 49

50 was absorbed by the heat collector roof composed of transparent photovoltaic cells for 51

52 power generation, and the rest of the radiation energy was used to heat the seawater in 53

54 the solar still for desalination. The calculation results showed the heat collection

efficiency of the heat collector in PVDSCP was 26.13% higher than that in traditional

SCPP. Kiwan et al. [33] designed to install photovoltaic panels in the traditional SCPP

to increase the system power generation, and install solar stills to achieve freshwater production. The calculation results showed that the total utilization rate of the improved system increased from 0.51% to 4.37%, and the cost of producing freshwater was 1.6

US$/m3, 46.3% cheaper than other similar systems.

8

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24 ~~humid air in the chimney reaches the dew point and precipitation occurs if the chimney~~ 25

26 ~~is high enough. The effectiveness of freshwater generation of the system was evaluated~~ 27

28 ~~by the developed flow and heat transfer mathematical model. Subsequently, Ming et al.~~

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34

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48 ~~over the pool, and then condensed on the inner wall of the chimney. A mathematical~~ 49

50 ~~model was established to explore the effect of operating parameters and geometric~~

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52 ~~parameters on system performance.~~

53

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19

20 ~~combine the cooling tower and traditional SCPP technology for electricity generation~~ 21

22 ~~and seawater desalination. A bi-directional turbine was installed in the hybrid system,~~ 23

24 ~~allowing the system to operate as a cooling tower at night and as an SCPP during the~~ 25

26 ~~day. The theoretical calculation showed that the total utilization rate of the hybrid~~ 27

28 ~~system was 0.73%, 1.4 times that of the traditional SCPP.~~

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31 ~~At present, there are many theoretical studies on seawater desalination-SCPP~~

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33 ~~technologies and their optimization and improvement, indicating that the concept of~~

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35 ~~SCPP integrated with seawater desalination has received recognition and research~~ 36

37 ~~interest from scholars, but the experimental studies on this technology are relatively~~ 38

39 ~~few. Maia et al. [29] compared and summarized several seawater desalination-SCPP~~ 40

41 ~~technologies mentioned above and also pointed out that although this technology had~~

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44 ~~shown considerable commercial potential, there was still a lack of sufficient~~

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46 ~~experimental data to prove the authenticity of the simulation calculation results of the~~

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48 ~~proposed systems.~~

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50 At present, seawater desalination-SCPP technologies have shown considerable 51

52 commercial potential [34]. But most of the studies on these technologies are limited to 53

54 theoretical calculations and simulations, and the experimental studies are relatively few. Zuo et al. [~~30~~35] established a small experimental device of solar chimney power plant integrated with seawater desalination. The device was mainly composed of a chimney,

a heat collector roof and a solar still, and no wind turbine and generator were installed. An unsteady no-load test was carried out on the device to investigate the operation law of the airflow temperature in the device and freshwater production, as well as the energy utilization characteristics. Cao et al. [~~31~~36] proposed a solar humidification 8

9 dehumidification seawater desalination system combined with the chimney solely for

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11 freshwater production. Hot and humid air was generated by mixing the hot air from the 12

13 horizontal collector with the wet air from the inclined collector. It was then condensed 14

15 into freshwater by the condenser in the chimney. A small experimental device was

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18 designed and constructed to simulate the production of freshwater, and to explore the

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20 main factors affecting the freshwater production.

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22 In conclusion, the existing experimental devices for seawater desalination-SCPP

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24 technologies are small in size and simplified in structure, and more importantly, they 25

26 do not realize water-electricity cogeneration. ~~At present, in the actual weather, the~~ 27

28 ~~operation performance, water production laws and power generation laws of the SCPP~~

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31 ~~integrated with seawater desalination under load are still unknown. And there~~ There is

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33 ~~also~~ currently a lack of experimental results to confirm the function of water-electricity

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35 cogeneration of the integrated system. This hinders the verification and in-depth

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37 understanding of the system simulation calculation results, and is not conducive to the 38

39 optimal design and commercial application of seawater desalination-SCPP 40

41 technologies. In addition, the operation mechanism and performance, water production

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44 characteristics and power generation characteristics of the SCPP integrated with

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46 seawater desalination under load are still unknown.

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48 In this paper, a comprehensive test platform for solar chimney power plant 49

50 combined with distillation (SCPPCD) that can realize water-electricity cogeneration 51

52 was designed and built. The wind turbine and generator were installed in the SCPPCD 53

54 of the test platform. Multiple independent basin solar stills were arranged radially inside

the heat collector in a modular design, so as to provide a reference for the modular design, manufacture and installation of solar stills in large-scale SCPPCD. The measured data of SCPPCD under actual meteorological conditions were analyzed, and the following research was done.

(1) The variation and distribution characteristics of the temperature inside the heat collector and hot airflow temperature rise were explored.

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9 (2) The temporal characteristics and radial distribution characteristics of freshwater

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11 production in solar stills were studied. 12

13 (3) The variation law of system power output and energy conversion conditions in the

14

15 system were explored.

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18 (4) The interaction mechanism between parameters such as seawater temperature,

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20 airflow temperature, temperature difference between seawater and solar still cover,

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22 freshwater yield and generated power was revealed.

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# 24 2. Experimental setup and measuring instruments

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26 *2.1 Experimental site*

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28 Fig.1 shows the physical figure of the comprehensive test platform, including three

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31 test devices of SCPPCD and three independent basin solar stills used for comparative

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33 study. The test platform was installed at Hohai University, Nanjing, China.

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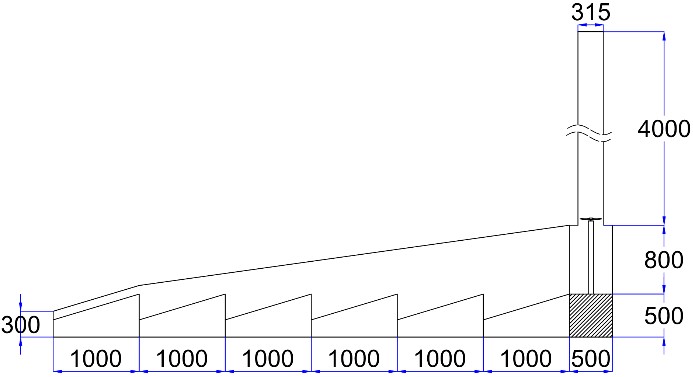
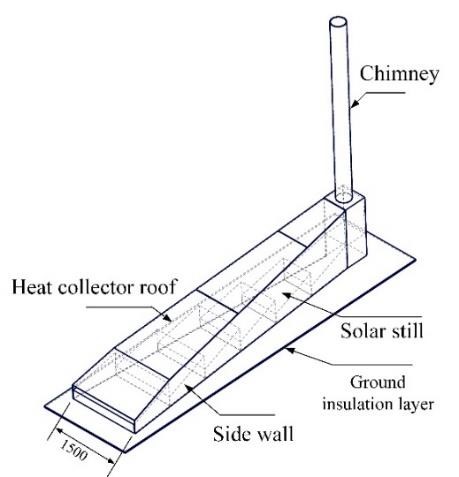
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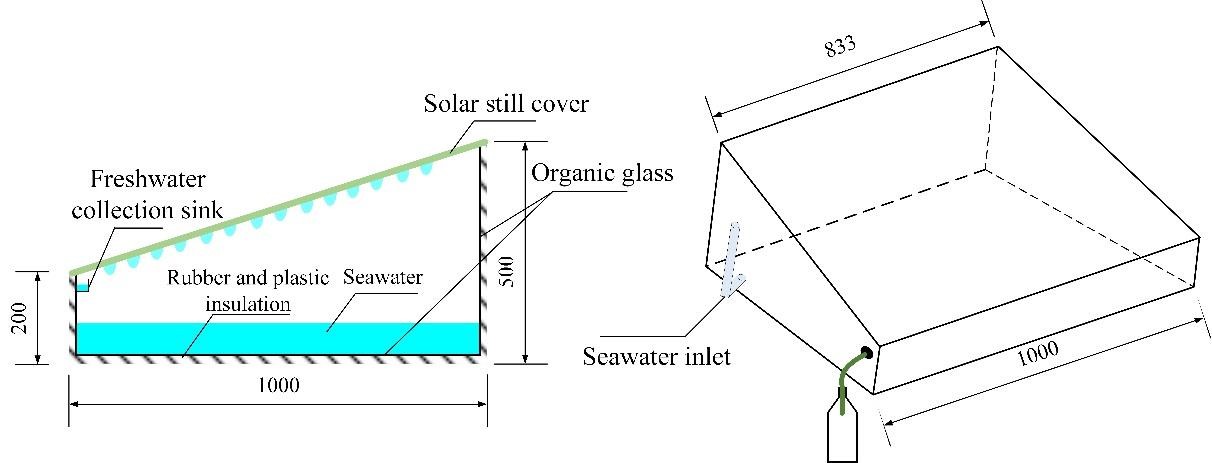
52 Fig.1 Test devices of SCPPCD and independent basin solar stills

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54 *2.2 Device structure and dimensions*



(a) Structural composition of SCPPCD (b) Dimensions of SCPPCD



(c) Structure and dimensions of the independent basin solar still

Fig.2 Structure and dimensions of test devices (unit: mm)

The basic structure and main dimensions of the SCPPCD test device and the independent basin solar still are shown in Fig.2. The SCPPCD is mainly composed of seven parts:

1. Heat collector roof: The material used is 5 mm thick transparent polycarbonate hollow sheet. The density is 1200 kg/m3, the thermal conductivity is 0.19 W/(m∙K), the specific heat capacity is 1170 J/(kg∙K), the transmittance is 0.8 and the emittance is 0.9.
2. Ground insulation layer: The materials used are 5 mm thick polyvinyl chloride (PVC) plate and 20 mm thick black rubber and plastic insulation material. The density of the PVC plate is 1380 kg/m3, and the thermal conductivity is 0.16 W/(m∙K). The thermal conductivity of the rubber and plastic insulation material is 0.034-0.041

W/(m∙K).

1. Side walls: The material used is double glazing with air gap. The glass thickness is 3.5 mm×2 and the air gap thickness is 3 mm. The outer side of the side wall was insulated with a 30 mm thick polystyrene foam plate.

Fig

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~~Fig.4~~

~~S~~

~~hape and dimension~~

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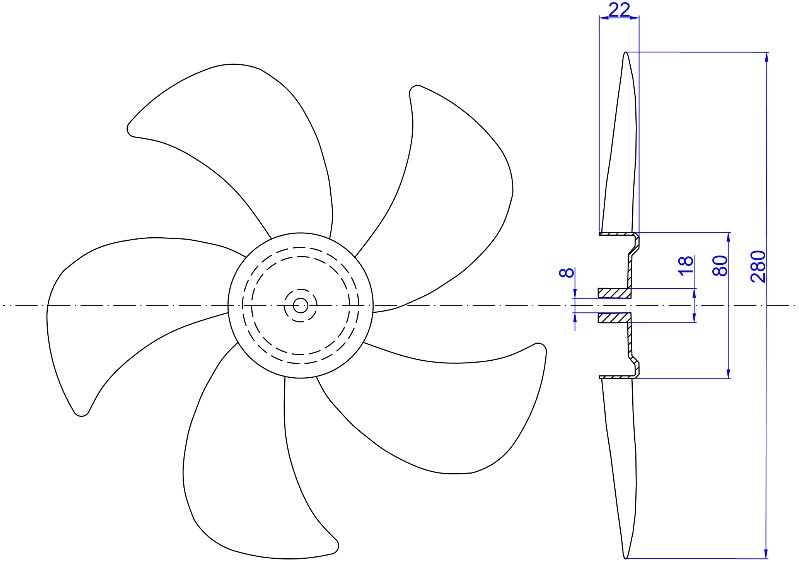
~~of~~

~~wind~~

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~~unit:~~

~~mm)~~



1. Solar stills: The material used for the bottom plate and walls of the solar still is 8 mm thick organic glass. 20 mm thick black rubber and plastic insulation material was laid on the periphery and bottom of the solar still. Six solar stills of different sizes were set up in the integrated system, numbered 1-6 from the collector entrance to the bottom of the chimney. The structure and dimensions of the No. 4 solar still is the same as that of the independent solar still, as shown in Fig.2(c). The seawater in the distiller was made by mixing water and sea crystals.
2. Solar still cover: The material used is 3.5 mm thick ordinary transparent glass. The density is 2500 kg/m3, the thermal conductivity is 0.75 W/(m∙K), the specific heat capacity is 837 J/(kg∙K), the transmittance is 0.8 and the emittance is 0.9.
3. Chimney: The material used is a grey PVC water pipe with an outer diameter of 315 mm and a length of 4 m. To prevent rainwater from entering the chimney, the

chimney was equipped with an umbrella-like rain cap on top.

1. Wind turbine and generator: Fig.3 shows the wind turbine set and generator.  ~~Fig.4 shows the shape and dimensions of the wind turbine.~~ The number of turbine blades is 5 and the diameter of the turbine is 280 mm. The output of the generator was 8

9 terminated with a 5 V regulator module and a LED (or a resistance of 150 Ω) to facilitate

10

11 reading the voltage across the resistor and testing the output power. 12

13 *2.3 Data measurement*

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1516 The solar irradiance, ambient temperature and humidity, ambient wind speed,

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18 airflow velocity in the chimney and the temperature of each measuring point in the

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20 system were collected by automatic measurement system. The solar irradiance, ambient 21

22 temperature and humidity and ambient wind speed were measured by photoelectric 23

24 solar radiation sensor, temperature and humidity transmitter and three-cup wind speed 25

26 sensor, respectively. The platinum resistance with high precision for low temperature 27

2829 measurement was selected to measure the air temperature and seawater temperature in

30

31 the device. The sensor information used in the test is shown in Table.1.

32

33 Six solar stills were set up under the heat collector of each integrated system,

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35 numbered 1-6 from the collector entrance to the bottom of the chimney. A temperature 36

37 measuring point system (six in total) was arranged in the center of each solar still. The 38

39 measurement point arrangement of the acquisition system is shown in Fig.~~5~~4. The 40

41 temperature measurement point systems were numbered ①-⑥ from the collector inlet

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44 to the bottom of the chimney.

## 45 Table.1 Sensor information

|  |  |  |  |
| --- | --- | --- | --- |
| Equipment | Model | Measuring range | Accuracy and error |
| Solar radiation sensor | RS-RA-\*-JT | 0~1800 W/m2 | 1 W/m2, ±2% |
| Temperature and humidity transmitter | RS-WS-N01-SMG | −40  ~+120  0% RH~80% RH | ±0.5  , (25  )  ±3% RH |
| Three-cup wind speed sensor | RS-FSJT-\* | 0~30 m/s | ±(0.2+0.03V) m/s |
| Pipeline wind speed transmitter | RS-FS-\*-9TH | 0~15 m/s | ±(0.2+2%FS) m/s |
| Temperature sensor | WZP-PT100 | −40  ~+200 | ±(0.15+0.002T) |

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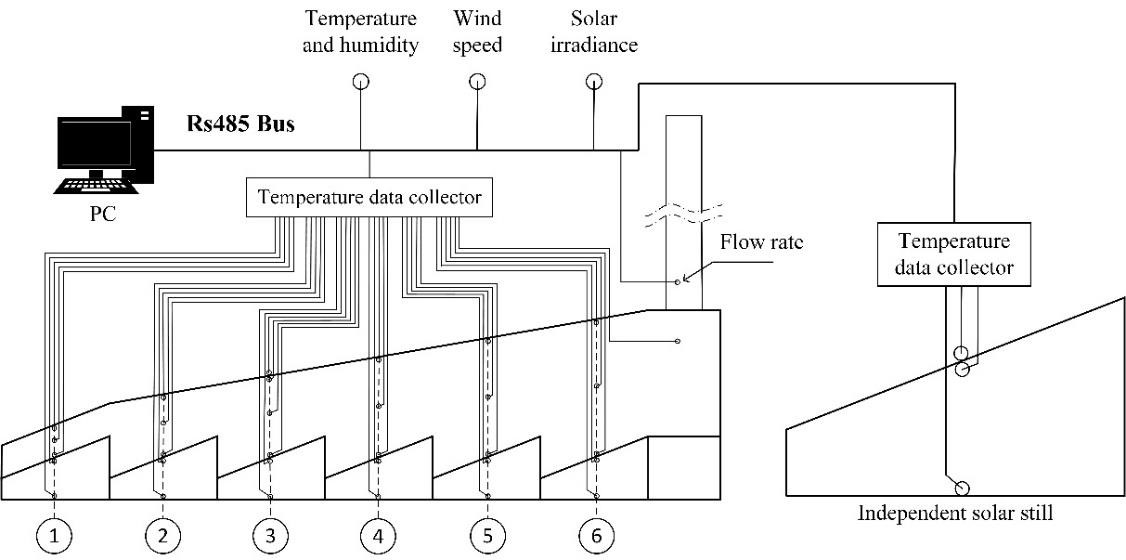
Each temperature measuring point system is composed of the temperature

measuring point of each thermometric layer arranged on the vertical line in the center of the solar still. The thermometric layer includes the inner surface of the cover plate of the heat collector, the hot airflow, the outer surface and inner surface of the glass cover of the solar still and seawater. In addition, an airflow temperature measurement point

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9 was also arranged at the chimney base.

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28 Fig.~~5~~4 Measuring point arrangement and the composition of acquisition system

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31 The output signals of all sensors were converted to digital signals and connected

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33 to an RS485 communication bus, which was then connected to the monitoring computer

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35 via a USB converter. The measured data were recorded in real time by the self36

37 developed performance testing software. The above parts constitute a real-time data 38

39 acquisition system. In this experiment, the interval of automatic data collection was 5 40

41 minutes.

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44 The freshwater produced in the test flowed into a mineral water bottle with a

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46 capacity of 500 ml and a mass of 18 g through a drainage tube. The water bottle was

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48 weighed with an electronic scale every 60 min, and the freshwater was sent back to the 49

50 solar still after the measurement, keeping the brine concentration and seawater layer 51

52thickness in the solar still unchanged. The electronic scale has a measuring range of 053

54 5000 g and an accuracy of 1 g.

The voltage across the generator load and the current through the load were measured with a multimeter every 60 minutes.

*2.4 Uncertainty analysis*

The experiment was conducted from July to August 2021, during the summer in Nanjing, China. The work done during the test included the calibration and installation of measuring instruments, the operation of the test equipment and the data acquisition. 8

9 To ensure the accuracy of the measurement results, the data were measured 10

11 continuously for 4 days after the stable operation of the device under each working 12

13 condition.

14

15 All measurement results were inevitably uncertain, so uncertainty analysis of the

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18 measured parameters in the test was carried out to verify the accuracy of measured

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20 parameters. The arithmetic mean of N numbers is:

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1. 1 *N*
2. *~~x~~*  *N* *i*1 *xi* (1)

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26 In turn, the standard deviation is:

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1. 1 *N xi*  *~~x~~*2 (2)
2.  *N* 1*i*1 

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33 The standard error of the mean is:

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1. *S*  (3)
2. *N*1

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## 39 Table.2 Uncertainty analysis results of the experimental data

|  |  |
| --- | --- |
| Parameters | Standard error |
| Ambient temperature | ±0.117 |
| Ambient humidity | ±0.461 |
| Pt100 temperature | ±0.254 |
| Ambient wind speed | ±0.025 m/s |
| Airflow velocity in chimney | ±0.028 m/s |
| Solar irradiance | ±14.625 W/m2 |

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51 Uncertainty analysis was performed on the parameters measured in the test, 52

1. including temperature, flow rate, and solar irradiance. The data used were the measured
2. data from 6:00 to 18:00 on August 1, 2021. The results of uncertainty analysis are shown in Table.2.

# 3. Results and discussion

*3.1 Weather conditions*

The daily operating characteristics of the integrated system were analyzed using the experimental data of August 1 and 2, 2021 as an example. The seawater thickness

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9 *hw* in the solar still was 8 cm.

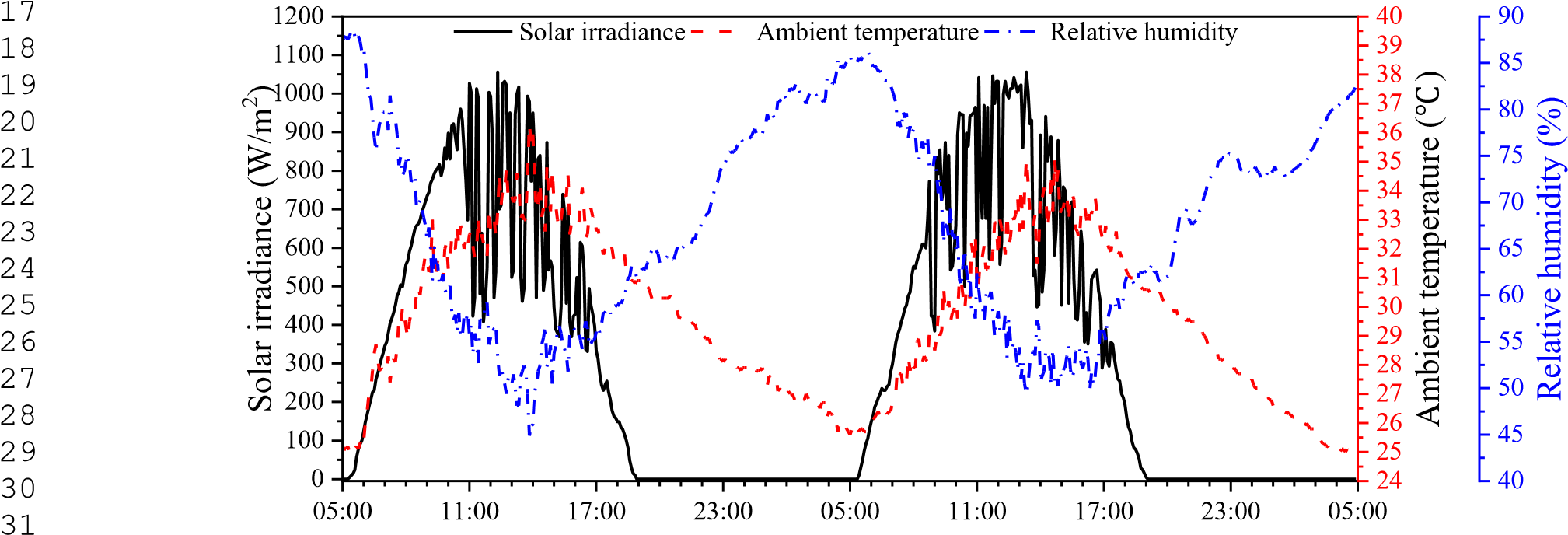
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11Fig.~~6~~ 5 shows the variation curves of solar irradiance *I*, ambient temperature *Ta*

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13and relative humidity from August 1 to 2. From the figure, the selected test days 14

1516 were typical sunny days in summer.



## 32 Time (h)

33 Fig.~~6~~ 5 Variation curves of solar irradiance, ambient temperature and relative humidity

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35 *3.2 Temperature variation and distribution*

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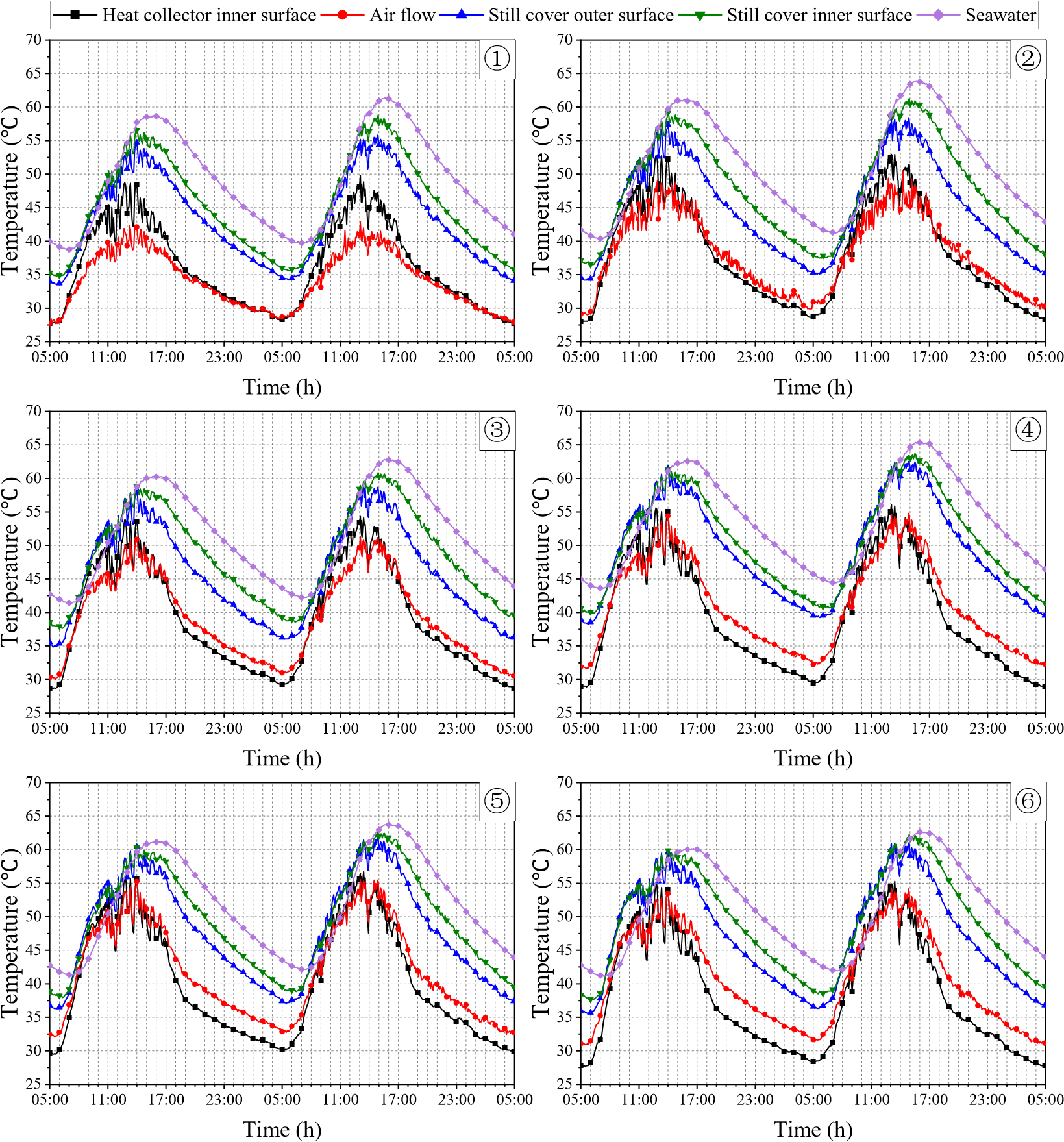
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39 Fig.~~7~~ 6 Temperature variation curves of the integrated system

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41 Fig.~~7~~ 6 shows the temperature change curves of the six temperature measurement

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43 point systems in the test device with time. Fig.~~8~~ 7 shows the radial distribution of 44

45 different thermometric layers every 3 hours. From Fig.~~7~~ 6 and Fig.~~8~~7, the temperature 46

47 change characteristics of the six measurement point systems (①-⑥) were similar, but 48

49 the temperature peak time was different. The airflow temperature and collector roof 50

51 temperature reached the peak first, and the seawater temperature reached the peak last.

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53

54 Along the radial direction from collector entrance to chimney, the temperature of each

thermometric layer was first increased and then decreased. And the seawater temperature and surface temperature inside and outside the still glass cover of the No.4 solar still were basically the highest. Most of the time the temperature of seawater was the highest of the five thermometric layers, and only around 9:00-12:00, it might be lower than the temperature of the solar still cover. The temperature of the inner and outer surfaces of solar still cover was almost the same during this period.

Along the radial direction, both the airflow temperature and collector roof 8

9 temperature rose first, reached the peak at position ⑤ and then decreased. In the 10

11 process of the air flowing along the radial direction, the airflow temperature rose greatly 12

13 from position ① to position ② and dropped significantly from position ⑤ to 14

15 position ⑥. As the cold air first entered the heat collector, its temperature was low,

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18 approximately equal to the ambient temperature. During the radial flow of air, it

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20 transferred very little heat to the environment by convection and absorbed more heat 21

22 due to the large temperature difference between the seawater and the airflow. Therefore, 23

24 the temperature rise range in the flow segment from position ① to position ② was 25

26 the largest. In the area of position ⑥, the heating surface of the airflow was greatly

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28 reduced, and the flow section was reduced, resulting in an increase in flow velocity.

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31 As a result, the heating time of the airflow was shortened, and the heat loss of the hot

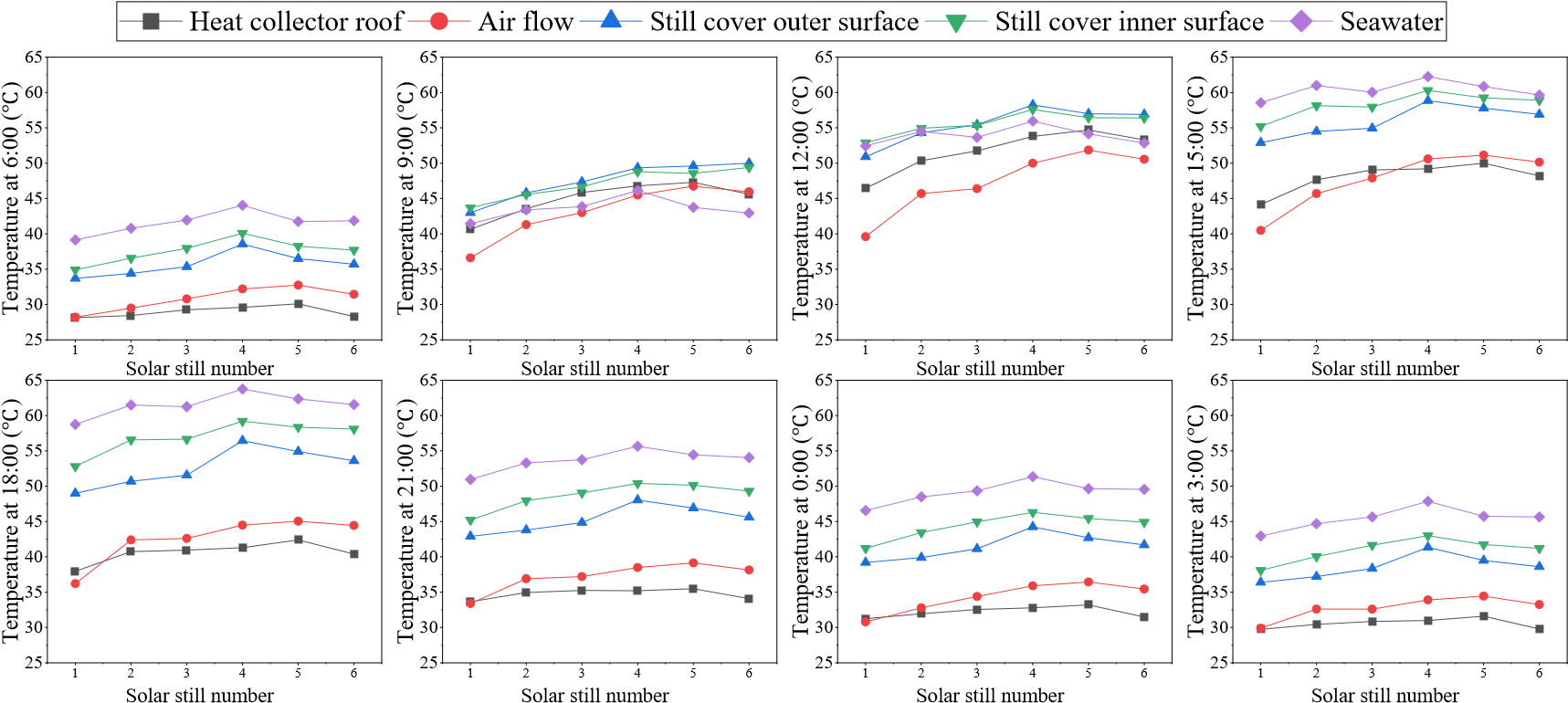
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33 air flowing from position ⑤ to position ⑥ was greater than the heat gain. Therefore,

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35 the temperature of the airflow fell back and there was a significant cooling.

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Fig.~~8~~ 7 Temperature radial distribution of the integrated system

Between 9:00 and 15:00, the hot airflow temperature was lower than the seawater temperature and collector roof temperature. This meant that the airflow was heated by both seawater and collector roof during this period, so it was heated up rapidly and it had a higher temperature. In other periods, the airflow temperature was higher than the collector roof temperature, and the collector roof was heated by the airflow. The airflow lost the heat it carried through the collector roof, so its temperature was at a medium or 8

9 low level. The temperature difference between the airflow and collector roof gradually 10

11increased along the radial direction, and it reached the maximum in position ⑥. This 12

13 showed that the heat loss of the airflow in position ⑥ was the most serious, and the

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1516 airflow in this position was significantly affected by environmental factors.

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18 It can also be found from Fig.~~7~~ 6 and Fig.~~8~~ 7 that the temperature of each

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20 thermometric layer in each measuring point system was much higher than the ambient 21

22 temperature, even at night. For one thing, the seawater in the solar still had a good heat

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24 storage effect. It released a lot of heat at night to maintain the temperature of the system.

25

26 For another, the test device had a good thermal insulation performance and this reduced 27

2829 the heat loss of the system at night.

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31 Then, the measurement point system ④ is used as an example to analyze the

32

33 temperature change characteristics of each thermometric layer, as shown in Fig.~~7~~ 6 and

34

35 Fig.~~8~~7. The overall temperature change trend of each thermometric layer in the 36

37 measurement point system ④ showed a sinusoidal distribution, and it was similar to 38

39 the change characteristics of solar radiation. However, the temperature peak time of 40

41 seawater and solar still cover was later than that of solar radiation, and the delayed time

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43

44 of seawater temperature was longer. On August 1, the peak time of the seawater

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46 temperature was 16:00, and the peak time of the internal surface temperature of solar

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48 still cover was 14:00. This was because most of the solar radiation after sunrise was 49

50 absorbed by the bottom plate of the solar still. Seawater absorbed only a small part of 51

52 the solar radiation, but it also absorbed the heat of the still bottom plate in the form of 53

54 convective heat transfer. So, most of the solar radiation was absorbed and stored in

seawater, resulting in the highest peak temperature of seawater. The seawater was heated up slowly due to its large specific heat capacity, which is 4096 J/(kg∙K), causing the peak time of seawater temperature to lag behind that of solar radiation. At noon, the heating of solar still cover mainly depended on the absorption of the latent heat of condensation released by water vapor. The specific heat capacity of the glass cover is

small, which is 837 J/(kg ∙K), so the heating time required for glass cover was shorter 8

9 than that of seawater, and the peak time of glass cover temperature was earlier than that

10

11 of seawater temperature.

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13 From the temperature change curves of the measurement point system ④ in 14

1516 Fig.~~7~~6, it was found that the temperature of the inner and outer surfaces of the glass

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18 cover was close during the period from 7:00 to 14:00 on August 1, and these two

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20 temperatures were higher than seawater temperature for a period of time. This was 21

22 because seawater temperature was low during this period and the evaporation of 23

24 seawater was small. So, little condensation heat was absorbed by the inner surface of 25

26 the glass cover, resulting in almost the same temperature on the inner and outer surface 27

2829 of the glass cover. In addition, the glass cover of the solar still had a small specific heat

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31 capacity. After absorbing solar radiation, the glass cover was heated up quickly and its

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33 temperature exceeded the seawater temperature. The temperature difference between

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35 the seawater and the inner surface of the glass cover became negative, which was not

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37 conducive to the evaporation of seawater in the solar still. After 14:00, the seawater 38

39 temperature exceeded the glass cover temperature, and a large amount of seawater 40

41 evaporated and condensed on the inner surface of the glass cover. The inner surface of

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44 the solar still glass cover absorbed a large amount of condensation latent heat, and its

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46 temperature was significantly higher than the temperature of the outer surface.

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48 After sunrise on August 1, the collector roof temperature and airflow temperature 49

50 rose rapidly. The airflow temperature was higher than the collector roof temperature, 51

52but the collector roof temperature rose faster. At about 9:00, the collector roof 53

54 temperature exceeded the airflow temperature, and it was not until 14:00 that the

collector roof temperature was lower than the airflow temperature again. The specific heat capacity of air can be calculated by equation (4). The specific heat capacity of the collector roof is 1170 J/(kg∙K), and it is slightly larger than that of air. During the period from 5:00 to 14:00, the temperature of the solar still cover was not high. The heat obtained by the airflow from the glass cover by convective heat transfer was less than the heat absorbed by collector roof from solar radiation. Therefore, although the 8

9 specific heat capacity of the airflow was a little smaller, the heating speed of the airflow 10

11 was less than that of the collector roof. After 14:00, the temperature of the solar still 12

13 cover was significantly increased, and it increased the convective heat transfer to the 14

15 airflow, resulting in a higher temperature of the airflow than that of the collector roof.

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18 From 14:00 to 8:00 the next day, the airflow temperature was higher than the collector

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20 roof temperature. At this time, the airflow heated the collector roof and lost heat to the 21

22 environment through the collector roof. This further exacerbated the reduction in the 23

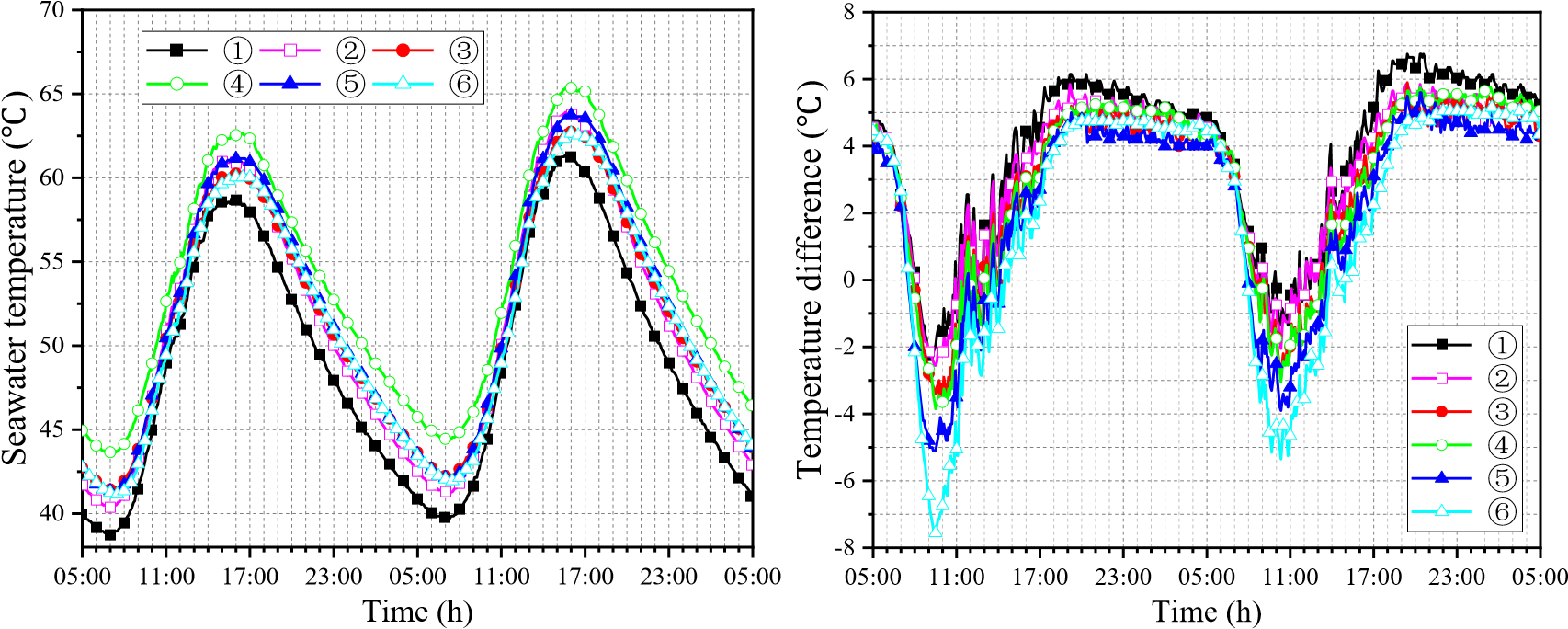
24 airflow temperature. The valley temperature of the airflow appeared at sunrise at 5:00.

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26 *Cp air*, 10070.04*Tair* (4)

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1. (a) Seawater temperature (b) Temperature difference between seawater and
2. inner surface of solar still glass cover
3. Fig.~~9~~ 8 Change curves of seawater temperature and the temperature difference between 48

49 seawater and inner surface of solar still cover

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51 Fig.~~9~~ 8 shows the change of the seawater temperature and the temperature

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54 difference between seawater and the inner surface of the solar still cover *Twc* of the

six temperature measurement point systems. The seawater temperature of the six solar stills basically exceeded 40 , as shown in Fig.~~9~~8(a). Along the direction from collector entrance to chimney, the seawater temperature rose first and then fell, and the seawater temperature of the No.4 solar still was the highest. There was little difference in seawater temperature in the No.2, No.3, No.5 and No.6 solar still. The seawater temperature in the No.1 solar still was the lowest. For one thing, it was located at the 8

9 collector entrance, and the airflow temperature above the solar still cover was the lowest. 10

11 So, the seawater transferred more heat to the airflow, and the seawater itself lost more 12

13 heat. For another, although insulation layer was laid outside the side walls of the solar 14

1516 still, the heat loss caused by the heat conduction from seawater to the external

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18 environment still existed.

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20 From Fig.~~9~~8(b), the positive temperature difference of the No.1 solar still was the 21

22largest. The maximum temperature difference *Twc* on August 1 reaches 6 , and the

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25 maximum *Twc* on August 2 exceeded 6 . The period with the positive temperature

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28 difference greater than 4 was the longest. The absolute value of the negative

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30 temperature difference in the No.1 solar still was the smallest, only 2.2 , and the 31

32 negative temperature difference lasted the shortest time. As the temperature difference 33

3435 *Twc* was less than or equal to 4 °C, the temperature difference line of the No.6 solar

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37 still was at the bottom of all the temperature difference lines. The absolute value of the 38

39 negative temperature difference in the No.6 still was much greater than that of other 40

41 stills, with a maximum of 7.5 °C, and its negative temperature difference lasted the

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44 longest time. In the period with the positive temperature difference greater than 4 ,

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46 the temperature difference *Twc* in the No.6 still was basically the same as that in the

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49 No.3 still, and was slightly higher than that in the No.5 still.

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51 It was also found from Fig.~~9~~ 8 that in the period with the positive temperature 52

53 difference greater than 4 , the difference in temperature difference *Twc* between the

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six solar stills was not large, and the difference between the maximum *Twc* and the minimum *Twc* was within 2 °C. But in the negative temperature difference period, the difference in temperature difference *Twc* between the six solar stills was large.

The difference between the maximum and the minimum negative temperature difference on August 1 reached 5.3 °C. The literature [~~30~~35] pointed out that only when

8 the water surface temperature exceeds 40 °C and the temperature difference *Twc* is

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10 positive, can seawater evaporate significantly, and a considerable amount of freshwater

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13 can be received. All six solar stills met the condition of water surface temperatures

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15 exceeding 40 °C, and the seawater temperature in the No.4 solar still was the highest.

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17 In addition, considering the analysis of the variation characteristics of temperature 18

19 difference *Twc* , the following conclusions can be drawn. The location of the No.1

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22 solar still is the most favorable for water production, and the water yield of the solar

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24 still in the position 4 is also considerable. But the location of the No.6 solar still is not 25

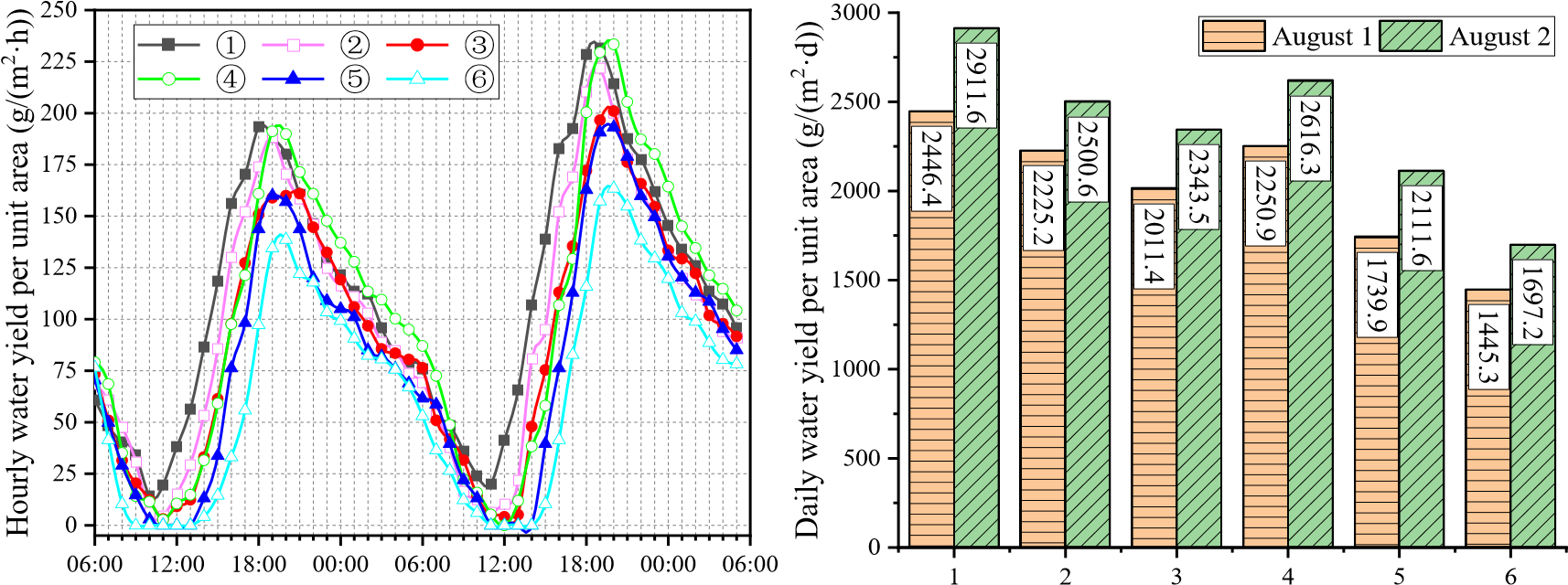
26 conducive to the water production of the still.

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29 *3.3 Water yield variation and distribution*

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44 Time (h) Solar still number

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46 Fig.~~10~~ 9 Variation curves of freshwater yield Fig.~~11~~ 10 Radial distribution of daily water yield

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1. per unit area
2. Fig.~~10~~ 9 shows the variation curves of the water yield of six solar stills in the

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52 integrated system. The variation characteristics of the freshwater yield of all the stills

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54 were similar, but the amount of the water produced was different. Along the radial

direction from the collector entrance to the chimney, the valley and peak value of the hourly water yield per unit area of the solar still gradually decreased. The valley value of the water yield even dropped to zero, which meant that no water was received. It was not desirable that the low water production period and no water production period of the solar still gradually increased along the radial direction.

The water yield of the six solar stills varied significantly during the recovery 8

9 period of water production. In the order of solar still number 1 to 6, the water yield of 10

11 the six solar stills began to rise sequentially. The No.1 solar still produced the most 12

13 freshwater per hour per unit area. It was the first to reach the peak water yield and the

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1516 peak value was the largest. Due to the superior seawater temperature and moderate

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18 temperature difference, the water yield of the No.4 still exceeded that of the No.2 and

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20 No.3 solar still, and its peak water yield was close to that of the No.1 solar still. The 21

22 No.5 solar still had a lower water yield than that of No.1-4 still, and the No.6 still had 23

24 the lowest water yield. The valley water yield of No.6 still was zero, and its period of 25

26 no water received was the longest.

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2829 During the decline period of water production after the peak water yield, the No.4

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31 solar still had the largest water yield, the No.1, No.2, No.3 and No.5 solar stills had

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33 little difference in water yield, and the No.6 solar still had the smallest water yield.

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35 Fig.~~11~~ 10 shows the radial distribution of the daily water yield per unit area of the

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37 six solar stills. From the figure, the daily water yield per unit area of the No.1 solar still 38

39had the most advantage. The daily water yield of the solar still showed an overall 40

41 decreasing trend with the increase of the solar still number, but there was a sudden

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44 increase in the water yield of the No.4 still, which even exceeded the water yield of the

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46 No.2 still. This was because the seawater temperature of No.4 still was high, and its

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48 hourly water yield per unit area in the peak water yield period was large. The daily 49

50 water yield per unit area of the No.1 solar still was 1.69 times and 1.72 times that of

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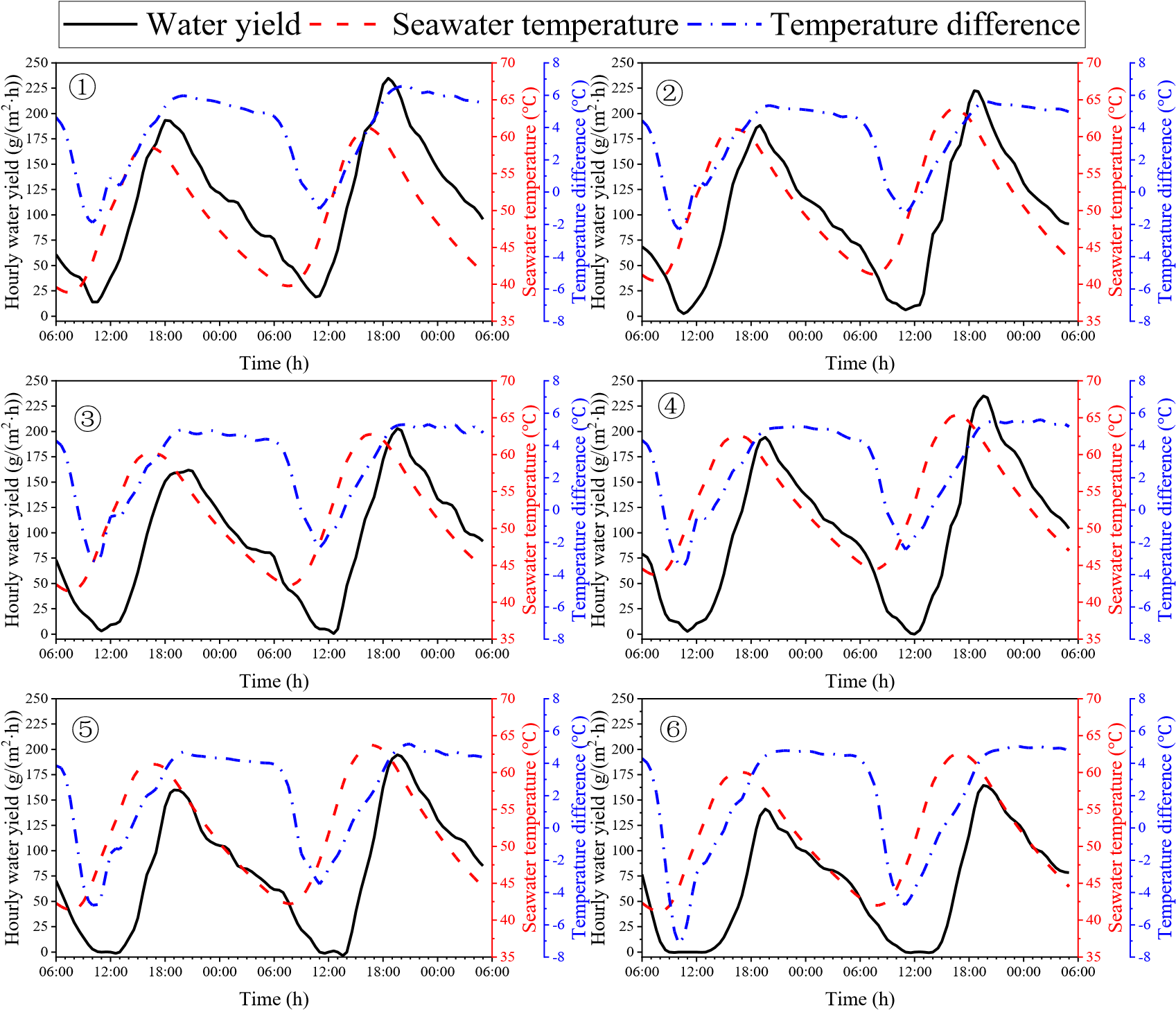
52No.6 still on August 1 and August 2, respectively. 53

54 In conclusion, solar stills should be arranged as far as possible in the area from the

collector inlet to the one-third radius of the heat collector.

*3.4 Analysis of the intrinsic relationship between freshwater yield, seawater*

*temperature and temperature difference* *Twc*

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1. Fig.~~12~~ 11 Hourly average variation curves of water yield per unit area, seawater temperature and temperature
2. difference between seawater and the inner surface of the solar still cover

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38 Although the water production of the solar still was mainly affected by seawater

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40 temperature and the temperature difference between the seawater and the inner surface 41

42 of solar still cover *Twc* , changes in seawater temperature and temperature difference

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45 *Twc* were not synchronized, as seen in Fig.~~9~~8. To understand the effect of the coupling

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48 of the two on the water yield of the solar still, these three parameters were plotted in 49

50 the same graph for re-analysis. Fig.~~12~~ 11 shows the hourly average variation curves of 51

52 water yield per unit area, seawater temperature and temperature difference *Twc* of the

53

54 six solar stills. Here are the common features shown in the six graphs. (1) During the recovery period of water production, seawater temperature and temperature difference

*Twc* were increasing, and the starting time of the recovery period of water production

coincided with that of *Twc* . (2) During the decline period of water production, the seawater temperature continued to drop. But the *Twc* changed very little at the beginning, and then it quickly decreased. (3) The valley value and peak value of water

8 yield appeared around the time corresponding to the valley value and peak value of the

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11 *Twc* .

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13 The differences shown in Fig.~~12~~ 11 are as follows. The No.1 solar still had the 14

15 lowest seawater temperature, but the highest water yield. The No.4 still had the highest

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18 seawater temperature, but produced slightly less water than the No.1 still. These

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20 features illustrated that although freshwater production was the result of a combination 21

22 of seawater temperature and temperature difference *Twc* , the extent of their effect on

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25 water production was different in different periods. Temperature difference was the 26

27 main factor affecting water production during the rising period of water production. As 28

29 the positive temperature difference during the rising period of water production 30

31 increased slightly, the water yield increased significantly. But the sharp increase in 32

33 seawater temperature had little impact on the increase in water yield. Seawater

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36 temperature was the main factor affecting water production during the decline period

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38 of water production. Especially at the beginning of the decline of water yield, the value 39

40 of temperature difference *Twc* was always large. But the freshwater yield in this

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43 period was decreasing, and the decreasing trend was consistent with the trend of 44

45 seawater temperature decline. This phenomenon and assertion can be further illustrated

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47 by the following correlation analysis in statistics. 48

49 In this paper, the correlation analysis method was used to study the intrinsic 50

51 relationship between the water yield, seawater temperature and temperature difference

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54 *Twc* . In correlation analysis, the correlation coefficient *r* was used to describe the

correlation between two variables. The meaning of the *r* is as follows.

(1) Positive correlation: If the variables *x* and *y* change in the same direction, it is

generally believed that if *r*  0.95, there is a significant correlation. If *r*  0.8，there is a high correlation. If 0.5 *r* 0.8, there is a moderate correlation. If 0.3 *r* 0.5, there is a low correlation. If *r*  0.3, the correlation is extremely weak and the two

8

9 variables are considered unrelated.

10

11 (2) Negative correlation: If the variables *x* and *y* change in the opposite direction, 12

13 *r* 0.

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15 (3) No linear correlation: *r* 0.

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18 Considering that seawater is the main energy carrier of the solar still, the seawater

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20 temperature has a great impact on the temperature of solar still cover. According to the 21

22 rise and decrease of seawater temperature, the water production period was divided into 23

24 rising period and falling period. In these two periods, the intrinsic relationship between 25

26 freshwater yield and seawater temperature and between freshwater yield and

27

28

29 temperature difference *Twc* was discussed. The experimental data were collected 30

31 from the six solar stills on August 1 and 2. Data points that did not meet the 32

33 requirements were eliminated. Since the experimental data did not meet the normal

34

35

36 distribution, Spearman correlation coefficient was used to describe the correlation of

37

1. variables, and the calculation formula is as follows.
2. *n*
3. 6(*Ri* *Qi* )2
4. *i*1  (5)
5. *rs*  1 *n n*( 2 1)

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45 Where, *Ri* represents the rank of *xi* , and *Qi* represents the rank of *yi* .

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48 Fig.~~13~~ 12 shows how freshwater yield varies with seawater temperature and 49

50 temperature difference *Twc* , respectively. From Fig.~~13~~12(a), freshwater yield was

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53 mainly affected by temperature difference during the rising period of seawater

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temperature, and the relationship between the two was a quadratic function. The fitting

formula between the two was *mw*  4.91*Twc*2 18.37 *Twc* 24.23 , R2  0.847 .

Where, *mw*represents the hourly freshwater yield per unit area, g/(m2∙h). The correlation coefficient *r* between *mw*and temperature difference *Twc* and between *mw*and seawater temperature *Tw* in this period was 0.891 and 0.544, respectively.

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9 This indicated that freshwater yield was highly correlated with the temperature 10

11 difference *Twc* , and moderately correlated with the seawater temperature. Therefore,

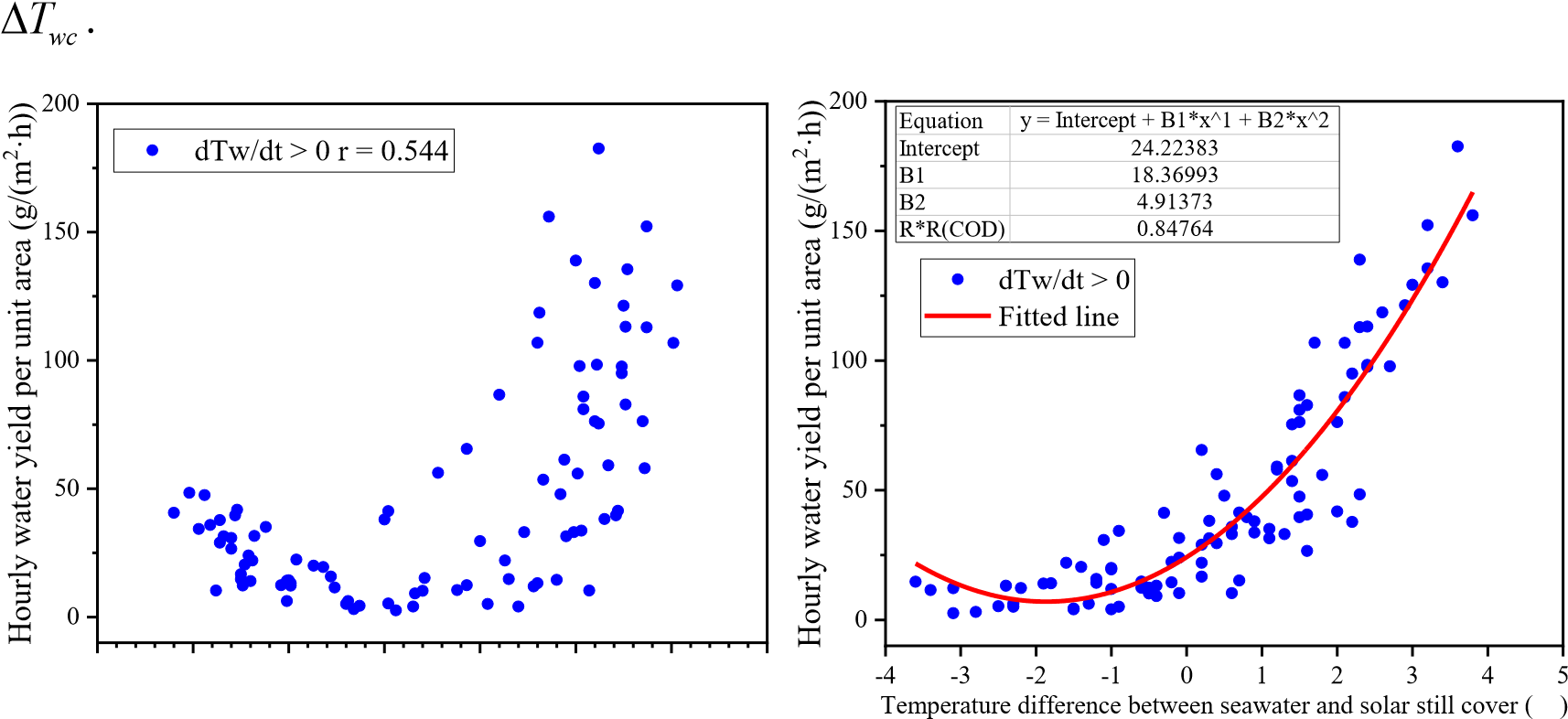
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14 the water yield in this period was mainly determined by the temperature difference

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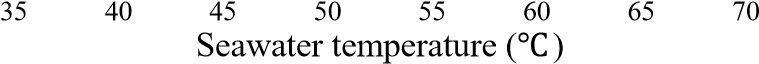
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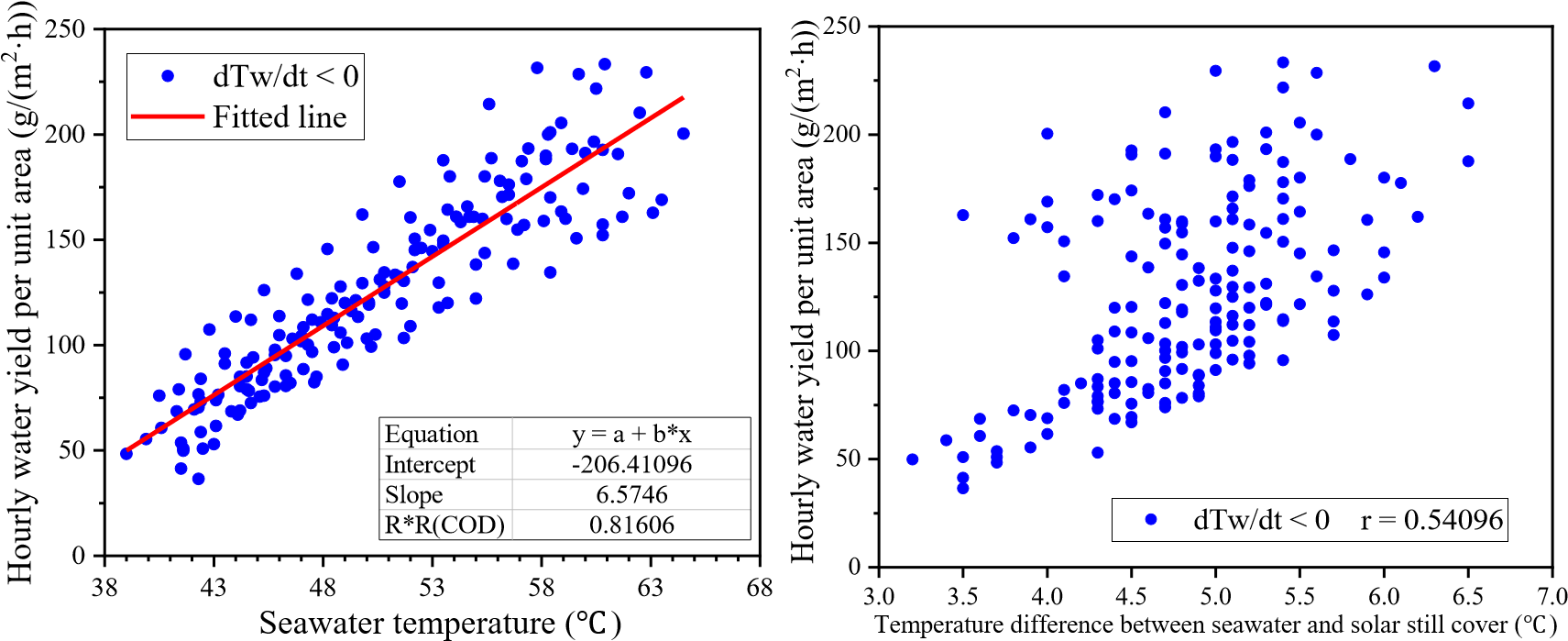
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34 (a) Rising period of seawater temperature

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1. (b) Falling period of seawater temperature
2. *Twc*
3. Fig.~~13~~ 12 Changes in freshwater yield with seawater temperature and temperature difference 

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From Fig.~~13~~12(b), the freshwater yield and seawater temperature showed an obvious linear relationship during the falling period of seawater temperature. The fitting formula was *mw*  6.57*Tw* 206.41, R2  0.816. The correlation coefficient *r* between *mw*and seawater temperature *Tw* and between *mw*and temperature difference

*Twc* in this period was 0.920 and 0.541, respectively. This indicated that freshwater yield was highly correlated with the seawater temperature, and moderately correlated

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9 with the temperature difference *Twc* . Therefore, the water yield in this period was

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11 mainly determined by seawater temperature.

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14 The above results show that the temperature difference *Twc* drives the 15

16 evaporation of seawater and is the driving force of water production. Also, seawater 17

18 temperature has an important influence on the amount of evaporation. During the test,

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21 seawater temperature in the integrated device maintained at a very high level (> 44),

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23 and evaporation occurred throughout. Therefore, maintaining a high temperature 24

25 difference *Twc* is a necessary condition for the system to produce a large amount of

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28 freshwater in summer.

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30*3.5 Temporal characteristics analysis of water production*

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32 It is of guiding significance for the operation and management of the integrated 33

34system to understand the characteristics of freshwater production in different periods.

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36 Fig.~~14~~ 13 shows the freshwater yield of the six solar stills (average value) in the system 37

3839 for one day and night. Taking the hourly water yield per unit area of 100 g/(m2∙h) as the

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41 dividing line, the water production period was divided into high-water yield period and

42

43 low-water yield period, as shown in Fig.~~14~~13. The high-water yield period on August 44

45 1 (17:00 to 1:00 the next day) accounted for only 33.3% of the total duration of the test 46

47 day, but it contributed 61.97% of the total water yield. The low-water yield period on 48

49 August 1 accounted for 66.7% of the total duration of the test day, but it only contributed 50

5152 37.03% of the total water yield. The high-water yield period on August 2 (16:00 to 3:00

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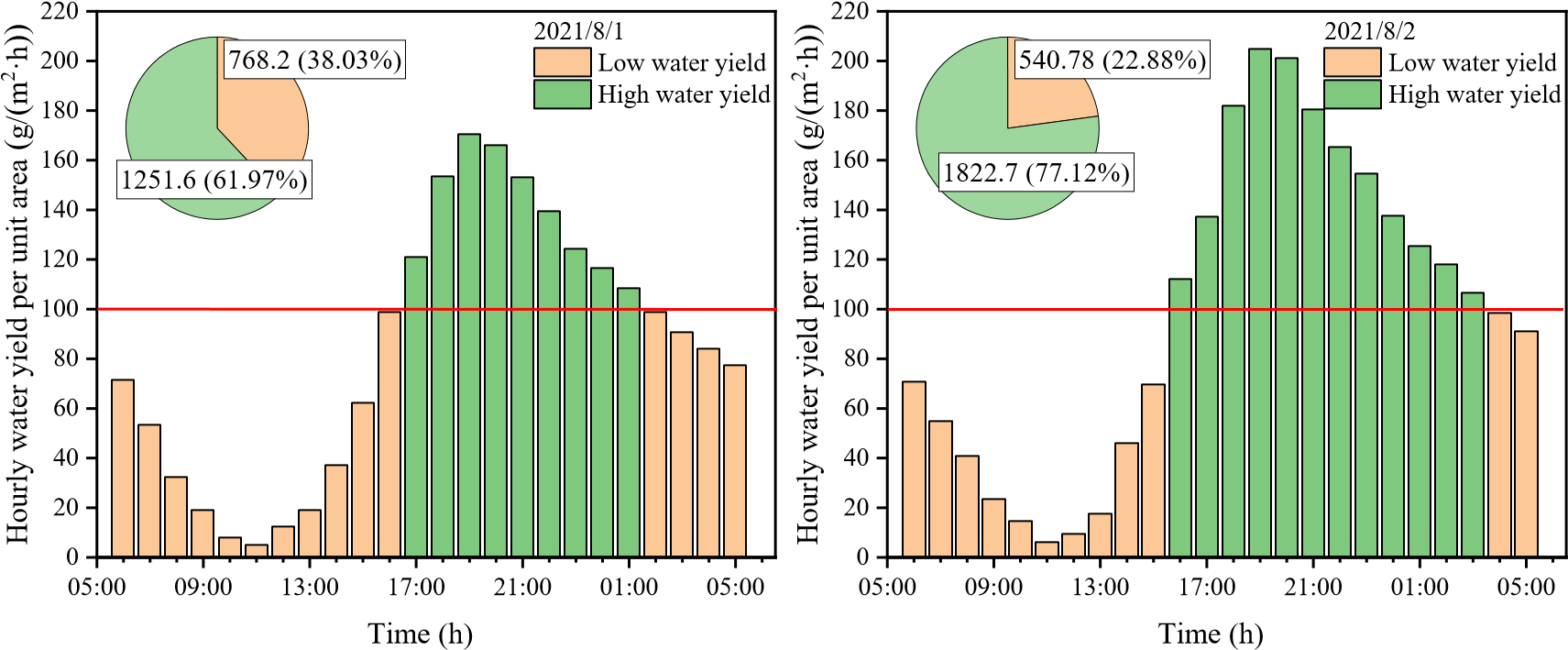
54 the next day) accounted for 45.83% of the total duration of the test day, and it

contributed 77.12% of the total water yield. The low-water yield period on August 2 accounted for 54.17% of the total duration of the test day, but it only contributed 22.88% of the total water yield. The operating characteristics in different water production periods showed that the high-water yield period generally occurred between sunset and 1-3 a.m. Although this period accounted for a small proportion of the day's operating time, it contributed most of the water produced. Therefore, it is necessary to strengthen the management of this operation period, reducing the failure rate of the device and

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9 manual error rate to ensure the efficient water production of the device.

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1. (a) High and low water yield period on Augest 1 (b) High and low water yield period on Augest 2
2. Fig.~~14~~ 13 Temporal characteristics of freshwater production of the integrated system

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31 Referring to Fig.~~12~~11, it was found that the seawater temperature and temperature

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33 difference *Twc* in the high-water yield period were both at a high level. This once

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36 again showed that a high seawater temperature and a high temperature difference *Twc* 37

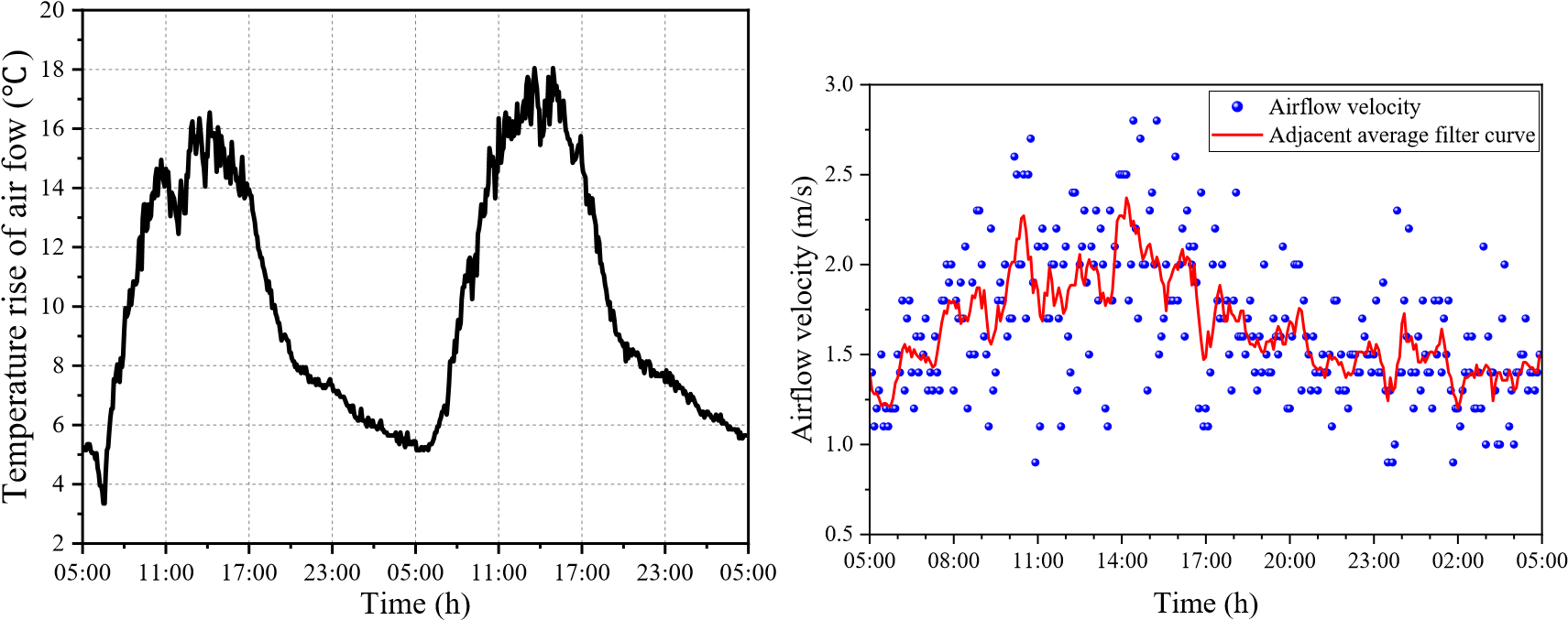
38 were the guarantee for the efficient water production of the device.

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41 *3.6 Power output*

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Fig.~~15~~ 14 Changes in airflow temperature rise Fig.~~16~~ 15 Variation curve of airflow velocity in the chimney

The airflow temperature rise is defined as the temperature difference between the airflow at the chimney base and the environment. Fig.~~15~~ 14 shows that the maximum and minimum temperature rise of the airflow in the chimney were 17  and 5 , respectively. The airflow temperature rise obtained was considerable, and the minimum 8

9 temperature rise was 5  even at night. This highlighted the advantage of the thermal

10

11 storage effect of seawater in the system. 12

13 Fig.~~16~~ 15 shows the change of airflow velocity in the chimney on August 1. The 14

1516 hot airflow in the chimney was affected by turbine rotation and ambient wind speed, so

17

18 the airflow velocity fluctuated greatly. The filtering curve of the airflow velocity

19

20 approximately conformed to the sine curve, and its distribution profile was 21

22 approximately a sinusoidal region. The peak period of the airflow velocity was at noon, 23

24 and the airflow velocity at night was maintained at about 1.5 m/s. The variation 25

26 characteristics of the airflow velocity during the daytime were similar to those of the 27

2829 solar irradiance. At night, the seawater in the solar still dissipated heat to the outside to

30

31 maintain a certain airflow temperature and airflow velocity.

32

33 The hot airflow in the chimney drove the wind turbine to rotate, which in turn

34

35 drove the DC generator to rotate and generate electricity. In order for the output power 36

37 to drive the LED, the output voltage of the generator was raised to 5 V through a 38

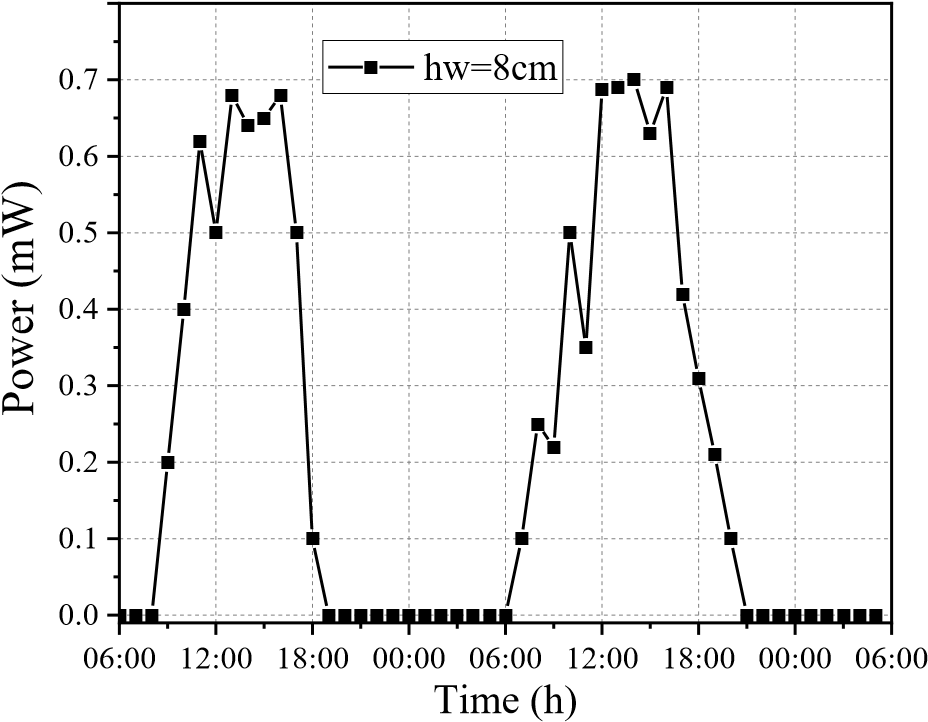
39 regulator module. During the test operation of the device, the turbine drove the 40

41 generator to light up the LED. This experimental phenomenon demonstrates that the

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1. SCPPCD can realize the water-electricity cogeneration.
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Fig.~~17~~ 16 Variation curve of generator power output

Fig.~~17~~ 16 shows the change curve of the generator power output. The change of generator power output was similar to that of the airflow temperature rise. The maximum generator power appeared at noon, about 0.70 ×10-3 W. Although the airflow 8

9 temperature rise was considerable at noon (Fig.~~15~~14), the output power of the test

10

11 device was small. This was because compared with the Spanish SCPP [2], the test 12

13 device constructed in this paper was still too small in scale, and the heat collector was 14

1516 only a fan-shaped area. The small size of the device resulted in increased heat

17

18 dissipation, shortened the time the air was heated in the collector and increased the

19

20 pressure losses in the system. After sunset, the airflow in the chimney was still flowing 21

22 due to the temperature rise. However, due to the small scale of the device and thin heat 23

24 storage water layer, the heat storage was insufficient, the airflow temperature rise 25

26 dropped a lot, and the airflow velocity was decreased. The pressure potential energy 27

2829 and kinetic energy of the airflow were not enough to overcome the energy consumption

30

31 caused by factors such as frictional resistance and generator electromagnetic resistance.

32

33 Therefore, the hot airflow could not drive the turbine to rotate in this period, and the

34

35 generator output power was 0 W.

36

37 The daily utilization efficiency of solar energy of the integrated system can be

38

39 calculated by the following formula: 40

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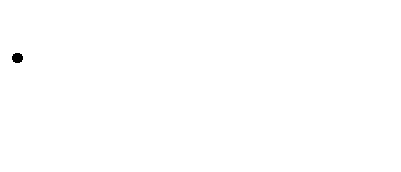
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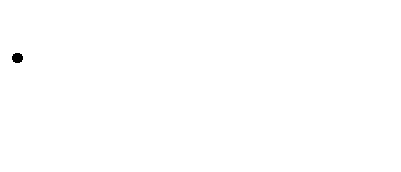
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4243 *i* 1 *j* 1 *S h ms j*, *fg e s i j*, , , *i*1 *Pe i*,

44 ~~~~*sol s*, ~~~~ 288  ~~(6)~~

4546 *Scol* *i*1 *Ii*

47

48 6 24

49

50

51 (6)

52

53

54

Where, *t* stands for an hour. The sampling interval for freshwater production

and power generation was one hour, and the sampling interval for solar irradiance was

five minutes. *hfg* represents the latent heat of water vaporization, J/g. *Scol* represents the area of the heat collector, m2. *Ss j*, represents the area of the No.j solar still, m2.

*me s i j*, , , represents the water yield of the No.j solar still, g/(m2·h). *I* represents the solar

8

9 10 irradiance, W/m2. *Pe* represents the output power of the generator, W.

11

12 It was calculated that the daily utilization efficiency of solar energy of the 13

14 integrated system on August 1 and 2 was 19.6% and 21.8%, respectively. Limited by

15

16 thermodynamic properties, the solar energy utilization efficiency of the conventional 17

18 solar chimney power plant is generally less than 1% [2,3,10,~~14~~25,~~32~~37]. Compared

19

20

21 with the traditional solar chimney power plants, the solar energy utilization efficiency

22

23 of SCPPCD was significantly improved.

24

25 In the SCPPCD, since the latent heat of vaporization released by the condensation 26

27 of water vapor was recycled and freshwater was produced, the solar energy utilization 28

29 efficiency and land utilization rate were greatly improved, which was the meaning of 30

31 integrating the freshwater generation with electricity generation. The SCPPCD is

32

3334 suitable for construction in desolate tidal flat areas along the coast.

35

# 364. Conclusion

37

38 In this paper, a comprehensive test platform for solar chimney power plant 39

40 combined with distillation (SCPPCD) that can realize water-electricity cogeneration 41

42 was designed and successfully built. The operation and output characteristics of 43

44 SCPPCD were tested and analyzed, and the following findings were obtained.

45

46 (1) The temperature variation of thermometric layers in each measuring point

47

48

49 system was similar, but the peak time of temperatures was different. The temperature

50

51 of each thermometric layer at the same moment increased first and then decreased from

52

1. the collector entrance to the chimney. The seawater temperature and solar still cover
2. temperature of the No.4 solar still were basically the highest. In the same measurement point system, seawater temperature was the highest most of the time. The airflow temperature was lower than collector roof temperature most of the time, and it lost heat

through the collector roof.

(2) Freshwater production was the result of a combination of seawater temperature

*Tw* and temperature difference *Twc* , but the extent of their effect on water production

8 was different in different periods. Temperature difference *Twc* was the main factor

9

10 affecting water production during the rising period of water production. Seawater

11

12

13 temperature *Tw* was the main factor affecting water production during the decline 14

15 period of water production.

16

17

18 (3) The daily water yield per unit area of the solar still basically decreased from

19

20 the heat collector entrance to the chimney. The No.1 solar still had the highest daily 21

22 water yield per unit area, and the water yield of the No.4 still was second only to the 23

24 No.1 still. The daily water yield of the No.1 still on August 1 and 2 was 1.69 times and 25

26 1.72 times that of the No.6 still, respectively. Solar stills should be arranged as far as 27

28 possible in the area from the collector inlet to the one-third radius of the heat collector.

29

30

31 (4) The high-water yield period generally occurs between sunset and 1-3 a.m. It

32

33 accounted for a small proportion of the day's operating time, but contributed most of

34

35 the water produced.

36

37 (5) The maximum temperature rise of hot airflow in the chimney was 17, and 38

39 the temperature rise was maintained above 5 during night operation. The variation 40

41 law of generator power was similar to that of airflow temperature rise, and the

42

43

44 maximum output power reached 0.71 mW in the daytime. But the power generation

45

46 could not be realized at night limited by the scale of the test device. The daily utilization

47

48 efficiency of solar energy on August 1 and 2 was 19.6% and 21.8%, respectively.

49

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51

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# 1 Experimental Research on the Operation Characteristics of Solar

2

3 **Chimney Power Plant Combined with Distillation (SCPPCD)**  4 [[2]](#footnote-2), a, Ziyang Yan a, Pengzhan Dai a, Tian Zhou a, Bo Qu a, Yue Yuan a, Yunting Ge b

5 Lu Zuo

6

7 a College of Energy and Electrical Engineering, Hohai University, Nanjing, China

8

## 9 b School of the Built Environment and Architecture, London South Bank University, London, UK 10

11 **ABSTRACT**: In this paper, a comprehensive test platform for solar chimney power 12

13 plant combined with distillation (SCPPCD) that can realize water-electricity 14

15 cogeneration was designed and built. Experimental research on SCPPCD was carried

16

17

18 out under actual meteorological conditions to explore the system operation performance

19

20 and the laws of freshwater production and power generation. The interaction 21

22 mechanism between parameters such as seawater temperature, airflow temperature, 23

24 temperature difference between seawater and solar still cover, freshwater yield and 25

26 generated power was revealed. The results show that the daily water yield of solar stills

27

28 decreases from the heat collector inlet to the chimney. Solar stills are recommended to

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31 be arranged in the area from collector inlet to the one-third radius of the collector. The

32

33 high-water yield period occurs between sunset and 1-3 a.m., and it contributes most of

34

35 the freshwater produced. Temperature difference is the main factor affecting water 36

37 production during the rising period of freshwater production, and seawater temperature38

39 is the main factor affecting freshwater production during the decline period. The 40

41 maximum temperature rise of airflow in the chimney is 17 , and the temperature rise

42

43

44 is maintained above 5 at night. The variation of generator power is similar to that of

45

46 airflow temperature rise, and the maximum power reaches 0.71 mW. This study

47

48 provides detailed experimental data and theoretical reference for future mathematical

49

50 simulation research and commercial application of SCPPCD.

51

52 **Keywords:** Solar chimney; Solar desalination; Water-electricity cogeneration; Freshwater yield; 53 54 Turbine

# 1. Introduction

The rapid growth of the world's population places a serious burden on the environment. The growing demand for energy and freshwater in developing countries results in even greater environmental damage. As a renewable energy generation 8

9 technology with simple structure and low operating cost, solar chimney power plant 10

11 (SCPP) technology [1-3] is particularly suitable for developing countries and regions. 12

13 It can make effective use of the abundant local solar energy resources and cheap land

14

15 to provide electricity to local residents in a clean way.

16

17

18 Many experimental studies on SCPP have been reported around the world, such as

19

20 in Florida, USA [4], Wuhan, China [5], University of Zanjan, Iran [6], Damascus 21

22 University, Syria [7], Aswan, Egypt [8], Warangal, India [9] and other regions. These 23

24 studies have proved the theoretical feasibility of SCPP technology and made some 25

26 optimizations on the influencing parameters of SCPP. But the studies also pointed out 27

28 that SCPP is too inefficient. Raising the chimney height is the key to improving the

29

30

31 efficiency of SCPP [10], but it brings construction difficulties and raise the investment

32

33 cost. Under the dual background of the difficulty in improving the efficiency of SCPP

34

35 and the global shortage of freshwater resources, the concept of SCPP technology for

36

37 seawater desalination has been put forward one after another, so that the system can 38

39 produce freshwater while generating electricity, and improve the utilization rate of solar 40

41 energy.

42

43

44 The concept of humidification-dehumidification is widely used in the desalination

45

46 process of integrated SCPP systems. Seawater desalination can be effectively achieved

47

48 by humidifying the hot air in the system and condensing the hot and humid air in the 49

50 chimney area. It is a common practice to arrange open seawater pools under the heat 51

52 collector of the SCPP. Wang et al. [11] designed to transform the ground below the heat 53

54 collector of SCPP into a large open seawater storage tank, and arranged a high-

efficiency condensing device on the chimney top to condense hot and humid air to produce freshwater by the way of indirect condensation. The feasibility of the water production principle was verified by simulation experiments of the condensing device. Zhou et al. [12] developed a mathematical model based on energy balance to evaluate the performance and economy of the system proposed by Wang et al. [11] and the conventional SCPP, and made a comparison. Azad et al. [13] also conducted a 8

9 numerical simulation research on such hybrid solar chimney systems. The genetic 10

11 algorithm optimization was used to determine the optimal geometric design variables. 12

13 Kiwan et al. [14] proposed to transform part of the ground thermal storage layer into an 14

15 open annular pool, so that the airflow carried water vapor after passing over the pool,

16

17

18 and then condensed on the inner wall of the chimney. A mathematical model was

19

20 established to explore the effect of operating parameters and geometric parameters on 21

22 system performance. Abdelsalam et al. [15] proposed to combine the cooling tower and 23

24 traditional SCPP technology for electricity generation and seawater desalination. A bi25

26 directional turbine was installed in the hybrid system, allowing the system to operate 27

28 as a cooling tower at night and as an SCPP during the day. The theoretical calculation

29

30

31 showed that the total utilization rate of the hybrid system was 0.73%, 1.4 times that of

32

33 the traditional SCPP. Abdelsalam et al. [16] explored the performance parameters of

34

35 the hybrid system, such as electricity output, freshwater production, and carbon dioxide 36

37 emissions, based on the environmental conditions in Doha, Qatar. The cash flow 38

39 analysis showed a high return on investment for the system. Abdelsalam et al. [17] also 40

41 analyzed the performance of the hybrid system in 16 cities in the Kingdom of Saudi

42

43

44 Arabia to select the optimal location for installation. Salameh et al. [18] studied the

45

46 electrical power and distilled water of the hybrid SCPP system under the geographic

47

48 location and metrological data of Sharjah and Alain (in UAE), and explored the effect

49

50 of wind speed on system performance.

51

52 In some systems, sprayers were designed to be installed at the entrance of the heat 53

54 collector or at the chimney base to increase the humidity of the hot air. Niroomand et

al. [19] designed to set up seawater sprayers and dehumidification tubes in the inlet section of the SCPP heat collector, so as to obtain freshwater in the humidification and dehumidification process of the airflow within the system. The feasibility of the system was verified by the established mathematical model. Ming et al. [20] proposed a SCPP system without heat collector by replacing the heat collector roof with black spiral pipes filled with hot water. The hot airflow in the system was humidified by a warm water 8

9 shower at the bottom of the chimney. Then the hot and humid air in the chimney reaches

10

11 the dew point and precipitation occurs if the chimney is high enough. The effectiveness 12

13 of freshwater generation of the system was evaluated by the developed flow and heat 14

15 transfer mathematical model. Subsequently, Ming et al. [21] considered adding air

16

17

18 turbine generators and water generators to the system to achieve power output, and

19

20 further analyzed the system performance parameters. It was found that the total energy

21

22 efficiency of the system was close to 7% when the chimney height was 3 km. Ming et 23

24 al. [22] designed to spray seawater droplets at the chimney base to humidify the thermal 25

26 airflow, thereby reducing the chimney height. Numerical simulation results showed that 27

28 humidification helped to improve the desalination efficiency.

29

30

31 Multi-stage flash technology and membrane distillation technology also have

32

33 certain applications in the desalination process of integrated SCPP systems. Méndez et

34

35 al. [23] proposed a multigeneration system with solar chimney and wind turbine 36

37 integration for hybrid desalination and power generation. In the system, multi-stage 38

39 flash technology was used in a cascaded manner to produce freshwater, utilizing the 40

41 heat source of the solar chimney thermal storage. Zuo et al. [24] designed an air gap

42

43

44 membrane distillation module and installed it vertically in the disc distiller of the SCPP

45

46 system. Water vapor could pass through the vertical hydrophobic membrane under the

47

48 action of pressure difference. It then passed through a narrow air gap to the surface of

49

50 the condensation plate and condensed into droplets.

51

52 Another commonly used method for seawater desalination of is to arrange closed 53

54 disc solar stills on the ground under the heat collector, and use the principle of disc

distillation to produce freshwater. Zuo et al. [25] designed to install closed solar stills under the heat collector roof, and proposed a solar chimney power plant combined with seawater desalination (SCPPCSD). This design realized the water-electricity cogeneration and the improvement of land resource utilization rate. The conventional SCPP and SCPPCSD were evaluated by the mathematical model based on energy balance and the economic analysis model. The results showed that SCPPCSD had a 8

9 higher solar energy daily utilization rate and better economic benefits. Asayesh et al. 10

11 [26] utilized the particle swarm optimization to optimize the design of the SCPPCSD, 12

13 and verified the existence of the optimal ratio between the seawater thermal storage 14

15 layer and the rock thermal storage layer in the system. Zuo et al. [27, 28] introduced a

16

17

18 wind supercharger device into the SCPPCSD to provide negative pressure for the

19

20 chimney outlet. It was found by numerical simulation that the wind supercharger device

21

22 made up for the loss of power generation caused by the coupling of seawater

23

24 desalination technology. For the purpose of reducing atmospheric pollution caused by 25

26 industrial waste heat and realizing energy recovery, Zuo et al. [29, 30] proposed to 27

28 combine the thermal power plant chimney with the solar chimney. High temperature

29

30

31 flue gas from the thermal power plant was introduced into the SCPPCSD through the

32

33 spiral heat exchange pipe under solar stills to heat the seawater in the solar still.

34

35 Theoretical analysis showed that the system power output and water production was 36

37 greatly improved, and the stability of system operation was also improved. Rahdan et 38

39 al. [31] utilized the CFD method to optimize the inclination angle of the chimney, heat 40

41 collector and solar still cover in a hybrid system of solar chimney and water desalination.

42

43

44 Rahbar et al. [32] proposed a solar chimney power plant integrated with transparent

45

46 photovoltaic cells and desalination (PVDSCP), and established a one-dimensional

47

48 mathematical model of the system. In the system, part of the solar radiation was

49

50 absorbed by the heat collector roof composed of transparent photovoltaic cells for 51

52 power generation, and the rest of the radiation energy was used to heat the seawater in 53

54 the solar still for desalination. The calculation results showed the heat collection

efficiency of the heat collector in PVDSCP was 26.13% higher than that in traditional

SCPP. Kiwan et al. [33] designed to install photovoltaic panels in the traditional SCPP

to increase the system power generation, and install solar stills to achieve freshwater production. The calculation results showed that the total utilization rate of the improved system increased from 0.51% to 4.37%, and the cost of producing freshwater was 1.6

US$/m3, 46.3% cheaper than other similar systems.

8

9 At present, seawater desalination-SCPP technologies have shown considerable 10

11 commercial potential [34]. But most of the studies on these technologies are limited to 12

13 theoretical calculations and simulations, and the experimental studies are relatively few. 14

15 Zuo et al. [35] established a small experimental device of solar chimney power plant

16

17

18 integrated with seawater desalination. The device was mainly composed of a chimney,

19

20 a heat collector roof and a solar still, and no wind turbine and generator were installed. 21

22 An unsteady no-load test was carried out on the device to investigate the operation law 23

24 of the airflow temperature in the device and freshwater production, as well as the energy 25

26 utilization characteristics. Cao et al. [36] proposed a solar humidification27

28 dehumidification seawater desalination system combined with the chimney solely for

29

30

31 freshwater production. Hot and humid air was generated by mixing the hot air from the

32

33 horizontal collector with the wet air from the inclined collector. It was then condensed

34

35 into freshwater by the condenser in the chimney. A small experimental device was

36

37 designed and constructed to simulate the production of freshwater, and to explore the

38

39 main factors affecting the freshwater production.

40

41 In conclusion, the existing experimental devices for seawater desalination-SCPP

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44 technologies are small in size and simplified in structure, and more importantly, they

45

46 do not realize water-electricity cogeneration. There is currently a lack of experimental

47

48 results to confirm the function of water-electricity cogeneration of the integrated system. 49

50 This hinders the verification and in-depth understanding of the system simulation 51

52 calculation results, and is not conducive to the optimal design and commercial 53

54 application of seawater desalination-SCPP technologies. In addition, the operation

mechanism and performance, water production characteristics and power generation characteristics of the SCPP integrated with seawater desalination under load are still unknown.

In this paper, a comprehensive test platform for solar chimney power plant combined with distillation (SCPPCD) that can realize water-electricity cogeneration was designed and built. The wind turbine and generator were installed in the SCPPCD 8

9 of the test platform. Multiple independent basin solar stills were arranged radially inside

10

11 the heat collector in a modular design, so as to provide a reference for the modular 12

13 design, manufacture and installation of solar stills in large-scale SCPPCD. The 14

15 measured data of SCPPCD under actual meteorological conditions were analyzed, and

16

17

18 the following research was done.

19

20 (1) The variation and distribution characteristics of the temperature inside the heat

21

22 collector and hot airflow temperature rise were explored.

23

24 (2) The temporal characteristics and radial distribution characteristics of freshwater 25

26 production in solar stills were studied.

27

28 (3) The variation law of system power output and energy conversion conditions in the

29

30

31 system were explored.

32

33 (4) The interaction mechanism between parameters such as seawater temperature,

34

35 airflow temperature, temperature difference between seawater and solar still cover,

36

37 freshwater yield and generated power was revealed.

38

# 39 2. Experimental setup and measuring instruments 40

41 *2.1 Experimental site*

42

43

44 Fig.1 shows the physical figure of the comprehensive test platform, including three

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46 test devices of SCPPCD and three independent basin solar stills used for comparative

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48 study. The test platform was installed at Hohai University, Nanjing, China.

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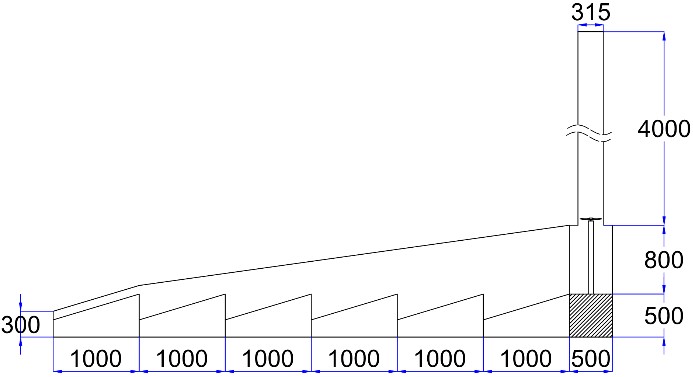
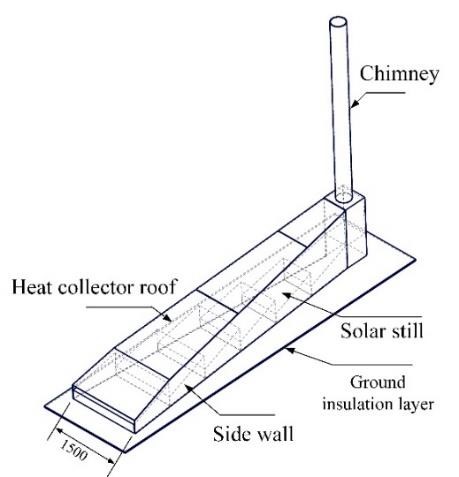
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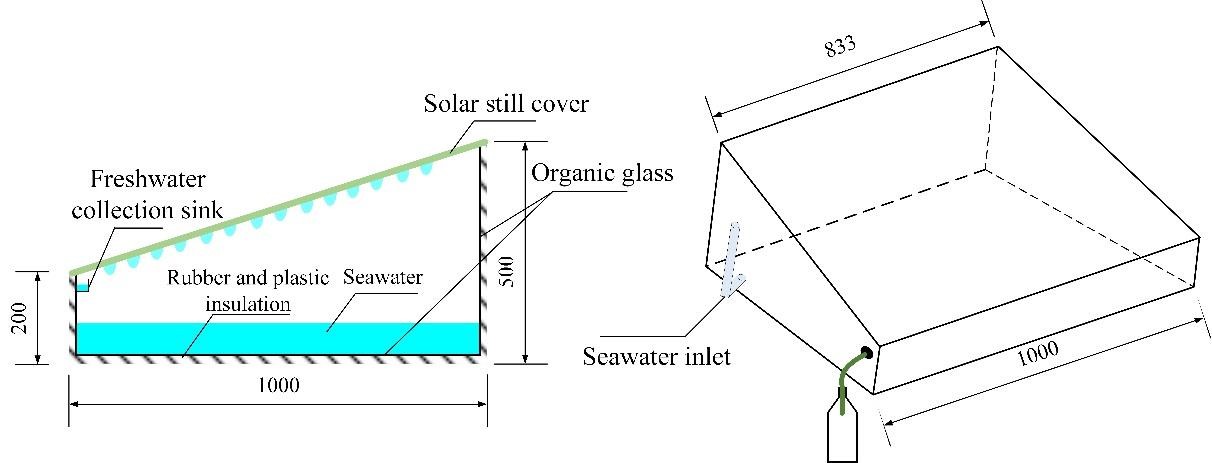


Fig.1 Test devices of SCPPCD and independent basin solar stills

*2.2 Device structure and dimensions*



(a) Structural composition of SCPPCD (b) Dimensions of SCPPCD



(c) Structure and dimensions of the independent basin solar still

Fig.2 Structure and dimensions of test devices (unit: mm)

The basic structure and main dimensions of the SCPPCD test device and the independent basin solar still are shown in Fig.2. The SCPPCD is mainly composed of seven parts:

* + 1. Heat collector roof: The material used is 5 mm thick transparent polycarbonate hollow sheet. The density is 1200 kg/m3, the thermal conductivity is 0.19 W/(m∙K), the specific heat capacity is 1170 J/(kg∙K), the transmittance is 0.8 and the emittance is 0.9.
    2. Ground insulation layer: The materials used are 5 mm thick polyvinyl chloride 8

9 (PVC) plate and 20 mm thick black rubber and plastic insulation material. The density 10

11 of the PVC plate is 1380 kg/m3, and the thermal conductivity is 0.16 W/(m∙K). The

12

13 thermal conductivity of the rubber and plastic insulation material is 0.034-0.041

14

15

16 W/(m∙K).

17

18 (3) Side walls: The material used is double glazing with air gap. The glass

19

20 thickness is 3.5 mm×2 and the air gap thickness is 3 mm. The outer side of the side wall

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22 was insulated with a 30 mm thick polystyrene foam plate.

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1. Fig.3 Wind turbine set and voltage regulator module
2. (4) Solar stills: The material used for the bottom plate and walls of the solar still is

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40

41 8 mm thick organic glass. 20 mm thick black rubber and plastic insulation material was

42

43 laid on the periphery and bottom of the solar still. Six solar stills of different sizes were 44

45 set up in the integrated system, numbered 1-6 from the collector entrance to the bottom 46

47 of the chimney. The structure and dimensions of the No. 4 solar still is the same as that 48

49 of the independent solar still, as shown in Fig.2(c). The seawater in the distiller was

50

51 made by mixing water and sea crystals.

52

53

54 (5) Solar still cover: The material used is 3.5 mm thick ordinary transparent glass. The density is 2500 kg/m3, the thermal conductivity is 0.75 W/(m∙K), the specific heat capacity is 837 J/(kg∙K), the transmittance is 0.8 and the emittance is 0.9.

1. Chimney: The material used is a grey PVC water pipe with an outer diameter

of 315 mm and a length of 4 m. To prevent rainwater from entering the chimney, the chimney was equipped with an umbrella-like rain cap on top.

1. Wind turbine and generator: Fig.3 shows the wind turbine set and generator.

The number of turbine blades is 5 and the diameter of the turbine is 280 mm. The output 8

9 of the generator was terminated with a 5 V regulator module and a LED (or a resistance 10

11 of 150 Ω) to facilitate reading the voltage across the resistor and testing the output 12

13 power.

14

15 *2.3 Data measurement*

16

17

18 The solar irradiance, ambient temperature and humidity, ambient wind speed,

19

20 airflow velocity in the chimney and the temperature of each measuring point in the 21

22 system were collected by automatic measurement system. The solar irradiance, ambient 23

24 temperature and humidity and ambient wind speed were measured by photoelectric 25

26 solar radiation sensor, temperature and humidity transmitter and three-cup wind speed 27

28 sensor, respectively. The platinum resistance with high precision for low temperature

29

30

31 measurement was selected to measure the air temperature and seawater temperature in

32

33 the device. The sensor information used in the test is shown in Table.1.

34

35 Six solar stills were set up under the heat collector of each integrated system, 36

37 numbered 1-6 from the collector entrance to the bottom of the chimney. A temperature 38

39 measuring point system (six in total) was arranged in the center of each solar still. The 40

41 measurement point arrangement of the acquisition system is shown in Fig.4. The

42

43

44 temperature measurement point systems were numbered ①-⑥ from the collector inlet

45

46 to the bottom of the chimney.

## 47 Table.1 Sensor information

|  |  |  |  |
| --- | --- | --- | --- |
| Equipment | Model | Measuring range | Accuracy and error |
| Solar radiation sensor | RS-RA-\*-JT | 0~1800 W/m2 | 1 W/m2, ±2% |
| Temperature and humidity transmitter | RS-WS-N01-SMG | −40  ~+120  0% RH~80% RH | ±0.5  , (25  )  ±3% RH |
| Three-cup wind speed sensor | RS-FSJT-\* | 0~30 m/s | ±(0.2+0.03V) m/s |
| Pipeline wind speed transmitter | RS-FS-\*-9TH | 0~15 m/s | ±(0.2+2%FS) m/s |
| Temperature sensor | WZP-PT100 | −40  ~+200 | ±(0.15+0.002T) |

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Each temperature measuring point system is composed of the temperature measuring point of each thermometric layer arranged on the vertical line in the center of the solar still. The thermometric layer includes the inner surface of the cover plate of the heat collector, the hot airflow, the outer surface and inner surface of the glass cover of the solar still and seawater. In addition, an airflow temperature measurement point was also arranged at the chimney base.

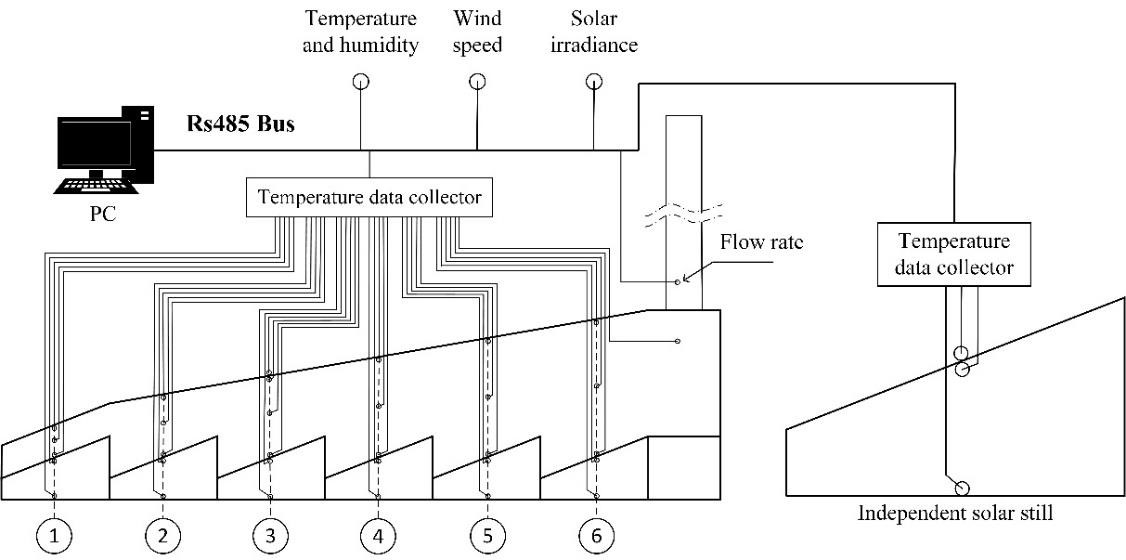


Fig.4 Measuring point arrangement and the composition of acquisition system

The output signals of all sensors were converted to digital signals and connected to an RS485 communication bus, which was then connected to the monitoring computer via a USB converter. The measured data were recorded in real time by the selfdeveloped performance testing software. The above parts constitute a real-time data acquisition system. In this experiment, the interval of automatic data collection was 5 minutes.

The freshwater produced in the test flowed into a mineral water bottle with a capacity of 500 ml and a mass of 18 g through a drainage tube. The water bottle was weighed with an electronic scale every 60 min, and the freshwater was sent back to the solar still after the measurement, keeping the brine concentration and seawater layer thickness in the solar still unchanged. The electronic scale has a measuring range of 05000 g and an accuracy of 1 g.

The voltage across the generator load and the current through the load were

measured with a multimeter every 60 minutes.

*2.4 Uncertainty analysis*

The experiment was conducted from July to August 2021, during the summer in

Nanjing, China. The work done during the test included the calibration and installation 8

9 of measuring instruments, the operation of the test equipment and the data acquisition. 10

11 To ensure the accuracy of the measurement results, the data were measured 12

13 continuously for 4 days after the stable operation of the device under each working

14

15 condition.

16

17

18 All measurement results were inevitably uncertain, so uncertainty analysis of the

19

20 measured parameters in the test was carried out to verify the accuracy of measured

21

22 parameters. The arithmetic mean of N numbers is:

23

1. 1 *N*
2. *~~x~~*  *N* *i*1 *xi* (1)

26

27

28 In turn, the standard deviation is:

29

30

1. 1 *N* 2
2.  *N* 1*i*1 *xi*  *~~x~~* (2)

33

34

35 The standard error of the mean is:

36

1. 
2. *S* (3)
3. *N*1

40

## 41 Table.2 Uncertainty analysis results of the experimental data

|  |  |
| --- | --- |
| Parameters | Standard error |
| Ambient temperature | ±0.117 |
| Ambient humidity | ±0.461 |
| Pt100 temperature | ±0.254 |
| Ambient wind speed | ±0.025 m/s |
| Airflow velocity in chimney | ±0.028 m/s |
| Solar irradiance | ±14.625 W/m2 |

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1. Uncertainty analysis was performed on the parameters measured in the test,
2. including temperature, flow rate, and solar irradiance. The data used were the measured data from 6:00 to 18:00 on August 1, 2021. The results of uncertainty analysis are shown in Table.2.

# 3. Results and discussion

*3.1 Weather conditions*

The daily operating characteristics of the integrated system were analyzed using the experimental data of August 1 and 2, 2021 as an example. The seawater thickness

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9 *hw* in the solar still was 8 cm.

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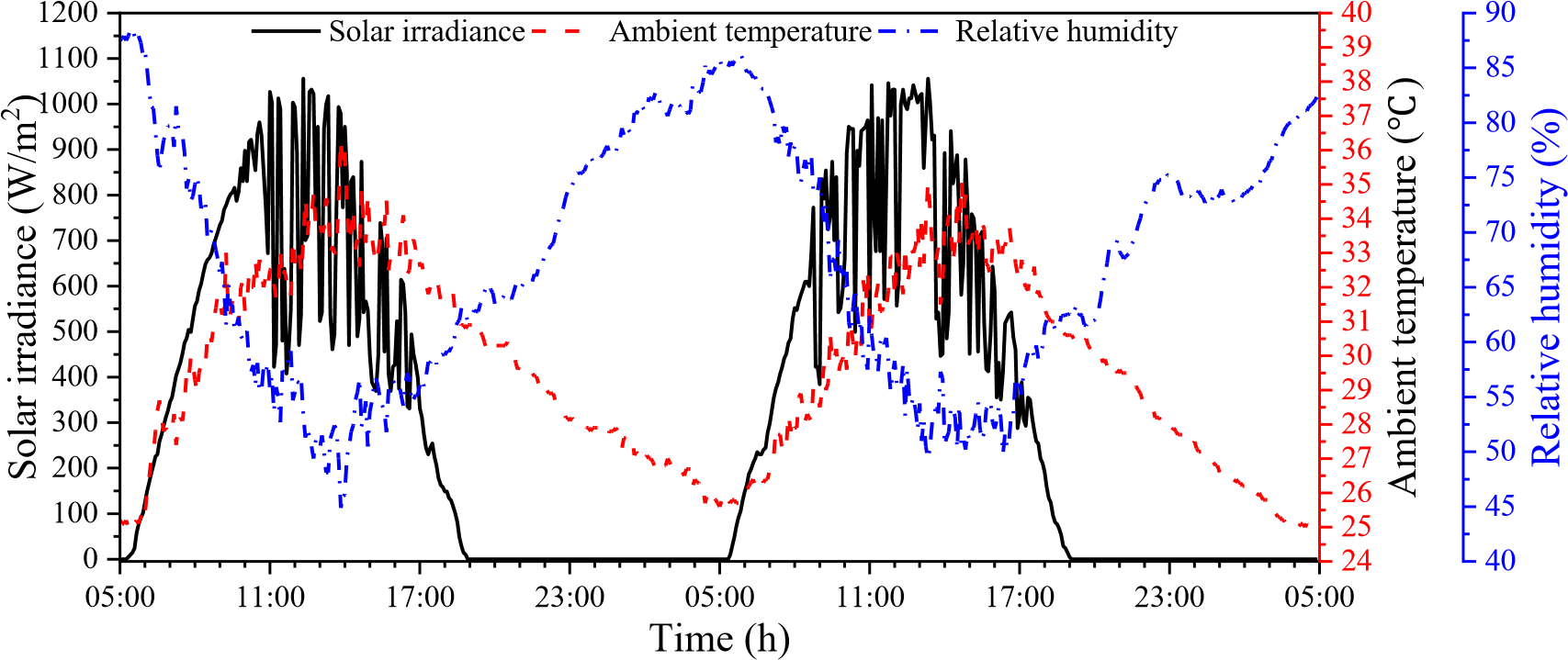
11 Fig.5 shows the variation curves of solar irradiance *I*, ambient temperature *Ta* and

12

13 relative humidity from August 1 to 2. From the figure, the selected test days were 14

15 typical sunny days in summer.

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33 Fig.5 Variation curves of solar irradiance, ambient temperature and relative humidity

34

35 *3.2 Temperature variation and distribution*

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37 Fig.6 shows the temperature change curves of the six temperature measurement 38

39 point systems in the test device with time. Fig.7 shows the radial distribution of different 40

41 thermometric layers every 3 hours. From Fig.6 and Fig.7, the temperature change

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43

44 characteristics of the six measurement point systems (①-⑥) were similar, but the

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46 temperature peak time was different. The airflow temperature and collector roof

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48 temperature reached the peak first, and the seawater temperature reached the peak last. 49

50 Along the radial direction from collector entrance to chimney, the temperature of each 51

52 thermometric layer was first increased and then decreased. And the seawater 53

54 temperature and surface temperature inside and outside the still glass cover of the No.4

solar still were basically the highest. Most of the time the temperature of seawater was the highest of the five thermometric layers, and only around 9:00-12:00, it might be

lower than the temperature of the solar still cover. The temperature of the inner and outer surfaces of solar still cover was almost the same during this period.

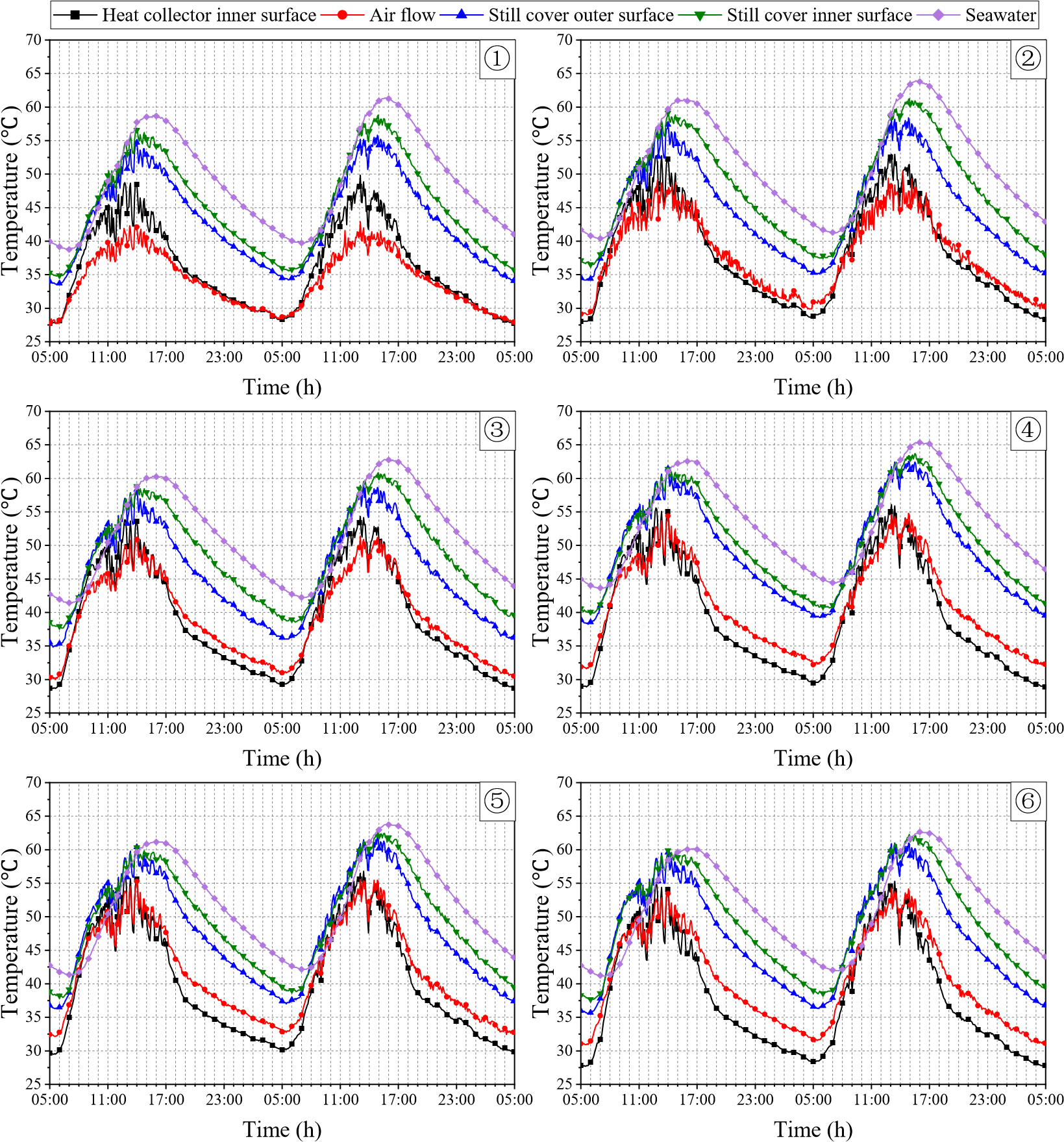


Fig.6 Temperature variation curves of the integrated system

Along the radial direction, both the airflow temperature and collector roof temperature rose first, reached the peak at position ⑤ and then decreased. In the process of the air flowing along the radial direction, the airflow temperature rose greatly from position ① to position ② and dropped significantly from position ⑤ to position ⑥. As the cold air first entered the heat collector, its temperature was low, approximately equal to the ambient temperature. During the radial flow of air, it transferred very little heat to the environment by convection and absorbed more heat due to the large temperature difference between the seawater and the airflow. Therefore, the temperature rise range in the flow segment from position ① to position ② was the largest. In the area of position ⑥, the heating surface of the airflow was greatly reduced, and the flow section was reduced, resulting in an increase in flow velocity. As a result, the heating time of the airflow was shortened, and the heat loss of the hot air flowing from position ⑤ to position ⑥ was greater than the heat gain. Therefore, the temperature of the airflow fell back and there was a significant cooling.



Fig.7 Temperature radial distribution of the integrated system

Between 9:00 and 15:00, the hot airflow temperature was lower than the seawater temperature and collector roof temperature. This meant that the airflow was heated by both seawater and collector roof during this period, so it was heated up rapidly and it had a higher temperature. In other periods, the airflow temperature was higher than the collector roof temperature, and the collector roof was heated by the airflow. The airflow lost the heat it carried through the collector roof, so its temperature was at a medium or low level. The temperature difference between the airflow and collector roof gradually increased along the radial direction, and it reached the maximum in position ⑥. This showed that the heat loss of the airflow in position ⑥ was the most serious, and the airflow in this position was significantly affected by environmental factors.

It can also be found from Fig.6 and Fig.7 that the temperature of each thermometric layer in each measuring point system was much higher than the ambient temperature, even at night. For one thing, the seawater in the solar still had a good heat

storage effect. It released a lot of heat at night to maintain the temperature of the system.

1

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3 For another, the test device had a good thermal insulation performance and this reduced

4

5 the heat loss of the system at night.

6

7 Then, the measurement point system ④ is used as an example to analyze the 8

9 temperature change characteristics of each thermometric layer, as shown in Fig.6 and 10

11 Fig.7. The overall temperature change trend of each thermometric layer in the 12

13 measurement point system ④ showed a sinusoidal distribution, and it was similar to 14

15 the change characteristics of solar radiation. However, the temperature peak time of

16

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18 seawater and solar still cover was later than that of solar radiation, and the delayed time

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20 of seawater temperature was longer. On August 1, the peak time of the seawater 21

22 temperature was 16:00, and the peak time of the internal surface temperature of solar 23

24 still cover was 14:00. This was because most of the solar radiation after sunrise was 25

26 absorbed by the bottom plate of the solar still. Seawater absorbed only a small part of 27

28 the solar radiation, but it also absorbed the heat of the still bottom plate in the form of

29

30

31 convective heat transfer. So, most of the solar radiation was absorbed and stored in

32

33 seawater, resulting in the highest peak temperature of seawater. The seawater was 34

35 heated up slowly due to its large specific heat capacity, which is 4096 J/(kg∙K), causing 36

37 the peak time of seawater temperature to lag behind that of solar radiation. At noon, the 38

39 heating of solar still cover mainly depended on the absorption of the latent heat of 40

41 condensation released by water vapor. The specific heat capacity of the glass cover is

42

43

44 small, which is 837 J/(kg ∙K), so the heating time required for glass cover was shorter

45

46 than that of seawater, and the peak time of glass cover temperature was earlier than that

47

48 of seawater temperature.

49

50 From the temperature change curves of the measurement point system ④ in Fig.6, 51

52 it was found that the temperature of the inner and outer surfaces of the glass cover was 53

54 close during the period from 7:00 to 14:00 on August 1, and these two temperatures 55

56 were higher than seawater temperature for a period of time. This was because seawater

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58

59 temperature was low during this period and the evaporation of seawater was small. So,

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little condensation heat was absorbed by the inner surface of the glass cover, resulting in almost the same temperature on the inner and outer surface of the glass cover. In addition, the glass cover of the solar still had a small specific heat capacity. After absorbing solar radiation, the glass cover was heated up quickly and its temperature 8

9 exceeded the seawater temperature. The temperature difference between the seawater 10

11 and the inner surface of the glass cover became negative, which was not conducive to 12

13 the evaporation of seawater in the solar still. After 14:00, the seawater temperature 14

15 exceeded the glass cover temperature, and a large amount of seawater evaporated and

16

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18 condensed on the inner surface of the glass cover. The inner surface of the solar still

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20 glass cover absorbed a large amount of condensation latent heat, and its temperature

21

22 was significantly higher than the temperature of the outer surface.

23

24 After sunrise on August 1, the collector roof temperature and airflow temperature 25

26 rose rapidly. The airflow temperature was higher than the collector roof temperature, 27

28 but the collector roof temperature rose faster. At about 9:00, the collector roof

29

30

31 temperature exceeded the airflow temperature, and it was not until 14:00 that the

32

33 collector roof temperature was lower than the airflow temperature again. The specific

34

35 heat capacity of air can be calculated by equation (4). The specific heat capacity of the

36

37 collector roof is 1170 J/(kg∙K), and it is slightly larger than that of air. During the period 38

39 from 5:00 to 14:00, the temperature of the solar still cover was not high. The heat

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41 obtained by the airflow from the glass cover by convective heat transfer was less than

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43

44 the heat absorbed by collector roof from solar radiation. Therefore, although the

45

46 specific heat capacity of the airflow was a little smaller, the heating speed of the airflow

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48 was less than that of the collector roof. After 14:00, the temperature of the solar still 49

50 cover was significantly increased, and it increased the convective heat transfer to the 51

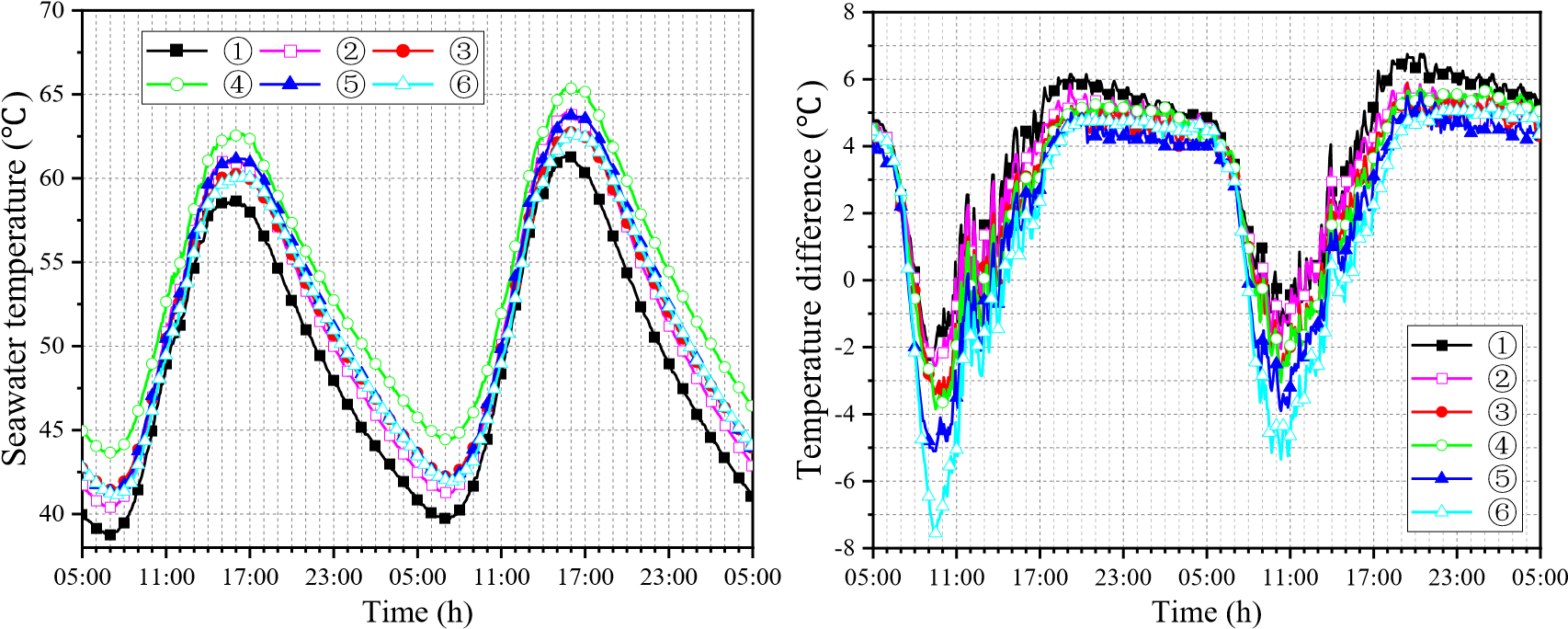
52 airflow, resulting in a higher temperature of the airflow than that of the collector roof. 53

54 From 14:00 to 8:00 the next day, the airflow temperature was higher than the collector

roof temperature. At this time, the airflow heated the collector roof and lost heat to the environment through the collector roof. This further exacerbated the reduction in the

airflow temperature. The valley temperature of the airflow appeared at sunrise at 5:00.

*Cp air*, 10070.04*Tair* (4)



(a) Seawater temperature (b) Temperature difference between seawater and inner surface of solar still glass cover Fig.8 Change curves of seawater temperature and the temperature difference between

seawater and inner surface of solar still cover

Fig.8 shows the change of the seawater temperature and the temperature difference between seawater and the inner surface of the solar still cover *Twc* of the six temperature measurement point systems. The seawater temperature of the six solar stills basically exceeded 40 , as shown in Fig.8(a). Along the direction from collector entrance to chimney, the seawater temperature rose first and then fell, and the seawater temperature of the No.4 solar still was the highest. There was little difference in seawater temperature in the No.2, No.3, No.5 and No.6 solar still. The seawater temperature in the No.1 solar still was the lowest. For one thing, it was located at the collector entrance, and the airflow temperature above the solar still cover was the lowest. So, the seawater transferred more heat to the airflow, and the seawater itself lost more heat. For another, although insulation layer was laid outside the side walls of the solar still, the heat loss caused by the heat conduction from seawater to the external environment still existed.

From Fig.8(b), the positive temperature difference of the No.1 solar still was the largest. The maximum temperature difference *Twc* on August 1 reaches 6 , and the

maximum *Twc* on August 2 exceeded 6 . The period with the positive temperature difference greater than 4 was the longest. The absolute value of the negative temperature difference in the No.1 solar still was the smallest, only 2.2 , and the

8 negative temperature difference lasted the shortest time. As the temperature difference

9

10 *Twc* was less than or equal to 4 °C, the temperature difference line of the No.6 solar

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13 still was at the bottom of all the temperature difference lines. The absolute value of the

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15 negative temperature difference in the No.6 still was much greater than that of other

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17 stills, with a maximum of 7.5 °C, and its negative temperature difference lasted the 18

19 longest time. In the period with the positive temperature difference greater than 4 , 20

21 the temperature difference *Twc* in the No.6 still was basically the same as that in the

22

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24 No.3 still, and was slightly higher than that in the No.5 still. 25

26 It was also found from Fig.8 that in the period with the positive temperature

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29 difference greater than 4 , the difference in temperature difference *Twc* between the

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32 six solar stills was not large, and the difference between the maximum *Twc* and the

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34 minimum *Twc* was within 2 °C. But in the negative temperature difference period,

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37 the difference in temperature difference *Twc* between the six solar stills was large.

38

39

40 The difference between the maximum and the minimum negative temperature 41

42 difference on August 1 reached 5.3 °C. The literature [35] pointed out that only when 43

44 the water surface temperature exceeds 40 °C and the temperature difference *Twc* is

45

46

47 positive, can seawater evaporate significantly, and a considerable amount of freshwater 48

49 can be received. All six solar stills met the condition of water surface temperatures 50

51 exceeding 40 °C, and the seawater temperature in the No.4 solar still was the highest.

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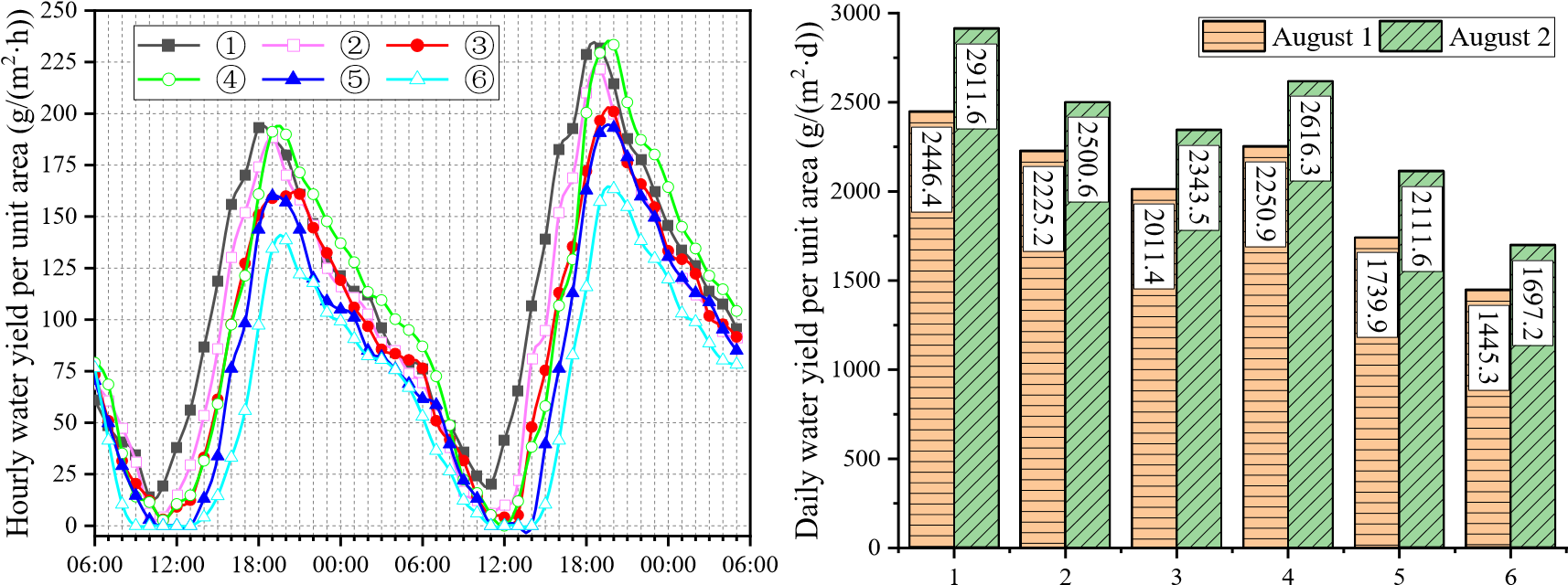
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54 In addition, considering the analysis of the variation characteristics of temperature

difference *Twc* , the following conclusions can be drawn. The location of the No.1 solar still is the most favorable for water production, and the water yield of the solar

still in the position 4 is also considerable. But the location of the No.6 solar still is not conducive to the water production of the still.

*3.3 Water yield variation and distribution*



Time (h) Solar still number

Fig.9 Variation curves of freshwater yield Fig.10 Radial distribution of daily water yield

per unit area

Fig.9 shows the variation curves of the water yield of six solar stills in the integrated system. The variation characteristics of the freshwater yield of all the stills were similar, but the amount of the water produced was different. Along the radial direction from the collector entrance to the chimney, the valley and peak value of the hourly water yield per unit area of the solar still gradually decreased. The valley value of the water yield even dropped to zero, which meant that no water was received. It was not desirable that the low water production period and no water production period of the solar still gradually increased along the radial direction.

The water yield of the six solar stills varied significantly during the recovery period of water production. In the order of solar still number 1 to 6, the water yield of the six solar stills began to rise sequentially. The No.1 solar still produced the most freshwater per hour per unit area. It was the first to reach the peak water yield and the peak value was the largest. Due to the superior seawater temperature and moderate temperature difference, the water yield of the No.4 still exceeded that of the No.2 and

No.3 solar still, and its peak water yield was close to that of the No.1 solar still. The

No.5 solar still had a lower water yield than that of No.1-4 still, and the No.6 still had

the lowest water yield. The valley water yield of No.6 still was zero, and its period of no water received was the longest.

During the decline period of water production after the peak water yield, the No.4 solar still had the largest water yield, the No.1, No.2, No.3 and No.5 solar stills had

8

9 little difference in water yield, and the No.6 solar still had the smallest water yield.

10

11 Fig.10 shows the radial distribution of the daily water yield per unit area of the six

12

13 solar stills. From the figure, the daily water yield per unit area of the No.1 solar still had 14

15 the most advantage. The daily water yield of the solar still showed an overall decreasing

16

17

18 trend with the increase of the solar still number, but there was a sudden increase in the

19

20 water yield of the No.4 still, which even exceeded the water yield of the No.2 still. This 21

22 was because the seawater temperature of No.4 still was high, and its hourly water yield 23

24 per unit area in the peak water yield period was large. The daily water yield per unit 25

26 area of the No.1 solar still was 1.69 times and 1.72 times that of No.6 still on August 1 27

28 and August 2, respectively.

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31 In conclusion, solar stills should be arranged as far as possible in the area from the

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33 collector inlet to the one-third radius of the heat collector.

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35 *3.4 Analysis of the intrinsic relationship between freshwater yield, seawater*

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37 *temperature and temperature difference* *Twc*

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40 Although the water production of the solar still was mainly affected by seawater 41

42 temperature and the temperature difference between the seawater and the inner surface

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45 of solar still cover *Twc* , changes in seawater temperature and temperature difference

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47 *Twc* were not synchronized, as seen in Fig.8. To understand the effect of the coupling

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49

50 of the two on the water yield of the solar still, these three parameters were plotted in 51

52 the same graph for re-analysis. Fig.11 shows the hourly average variation curves of 53

54 water yield per unit area, seawater temperature and temperature difference *Twc* of the

six solar stills. Here are the common features shown in the six graphs. (1) During the recovery period of water production, seawater temperature and temperature difference

*Twc* were increasing, and the starting time of the recovery period of water production coincided with that of *Twc* . (2) During the decline period of water production, the seawater temperature continued to drop. But the *Twc* changed very little at the

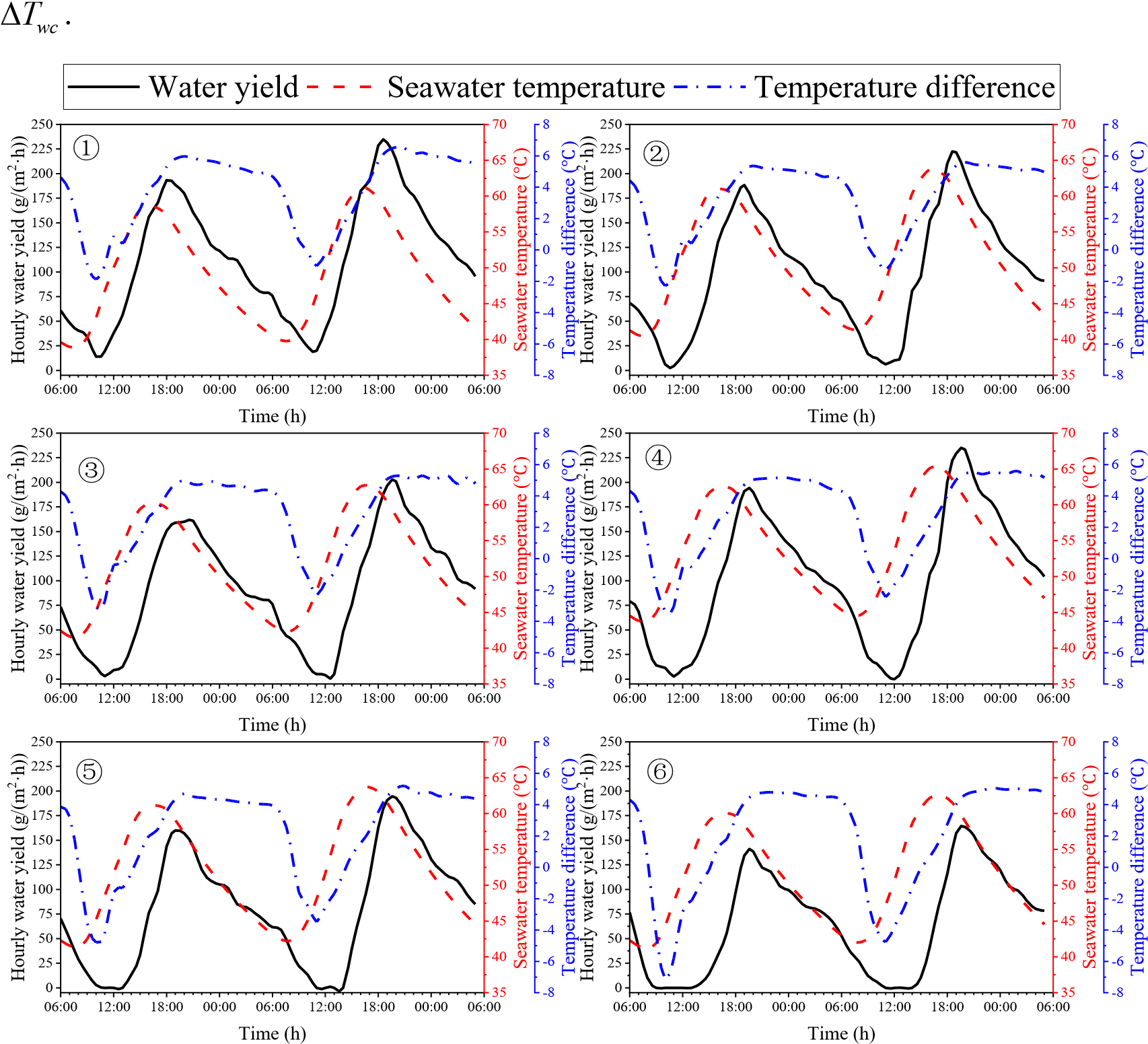
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9 beginning, and then it quickly decreased. (3) The valley value and peak value of water 10

11 yield appeared around the time corresponding to the valley value and peak value of the

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47 Fig.11 Hourly average variation curves of water yield per unit area, seawater temperature and temperature

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49 difference between seawater and the inner surface of the solar still cover 50

51 The differences shown in Fig.11 are as follows. The No.1 solar still had the lowest 52

1. seawater temperature, but the highest water yield. The No.4 still had the highest
2. seawater temperature, but produced slightly less water than the No.1 still. These features illustrated that although freshwater production was the result of a combination

of seawater temperature and temperature difference *Twc* , the extent of their effect on water production was different in different periods. Temperature difference was the main factor affecting water production during the rising period of water production. As

8 the positive temperature difference during the rising period of water production

9

10 increased slightly, the water yield increased significantly. But the sharp increase in

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12 seawater temperature had little impact on the increase in water yield. Seawater 13

14 temperature was the main factor affecting water production during the decline period 15

16 of water production. Especially at the beginning of the decline of water yield, the value

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19 of temperature difference *Twc* was always large. But the freshwater yield in this 20

21 period was decreasing, and the decreasing trend was consistent with the trend of 22

23 seawater temperature decline. This phenomenon and assertion can be further illustrated

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25

26 by the following correlation analysis in statistics.

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28 In this paper, the correlation analysis method was used to study the intrinsic

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30 relationship between the water yield, seawater temperature and temperature difference 31

32 *Twc* . In correlation analysis, the correlation coefficient *r* was used to describe the

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34

35 correlation between two variables. The meaning of the *r* is as follows.

36

37 (1) Positive correlation: If the variables *x* and *y* change in the same direction, it is 38

39 generally believed that if *r*  0.95, there is a significant correlation. If *r*  0.8，there

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41

42 is a high correlation. If 0.5 *r* 0.8, there is a moderate correlation. If 0.3 *r* 0.5,

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44

45 there is a low correlation. If *r*  0.3, the correlation is extremely weak and the two

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47

48 variables are considered unrelated.

49

50 (2) Negative correlation: If the variables *x* and *y* change in the opposite direction,

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52 *r* 0.

53

54 (3) No linear correlation: *r* 0.

Considering that seawater is the main energy carrier of the solar still, the seawater temperature has a great impact on the temperature of solar still cover. According to the rise and decrease of seawater temperature, the water production period was divided into rising period and falling period. In these two periods, the intrinsic relationship between freshwater yield and seawater temperature and between freshwater yield and

temperature difference *T*  was discussed. The experimental data were collected

8 *wc*

9

10 from the six solar stills on August 1 and 2. Data points that did not meet the

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12 requirements were eliminated. Since the experimental data did not meet the normal

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14 distribution, Spearman correlation coefficient was used to describe the correlation of

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16 variables, and the calculation formula is as follows.

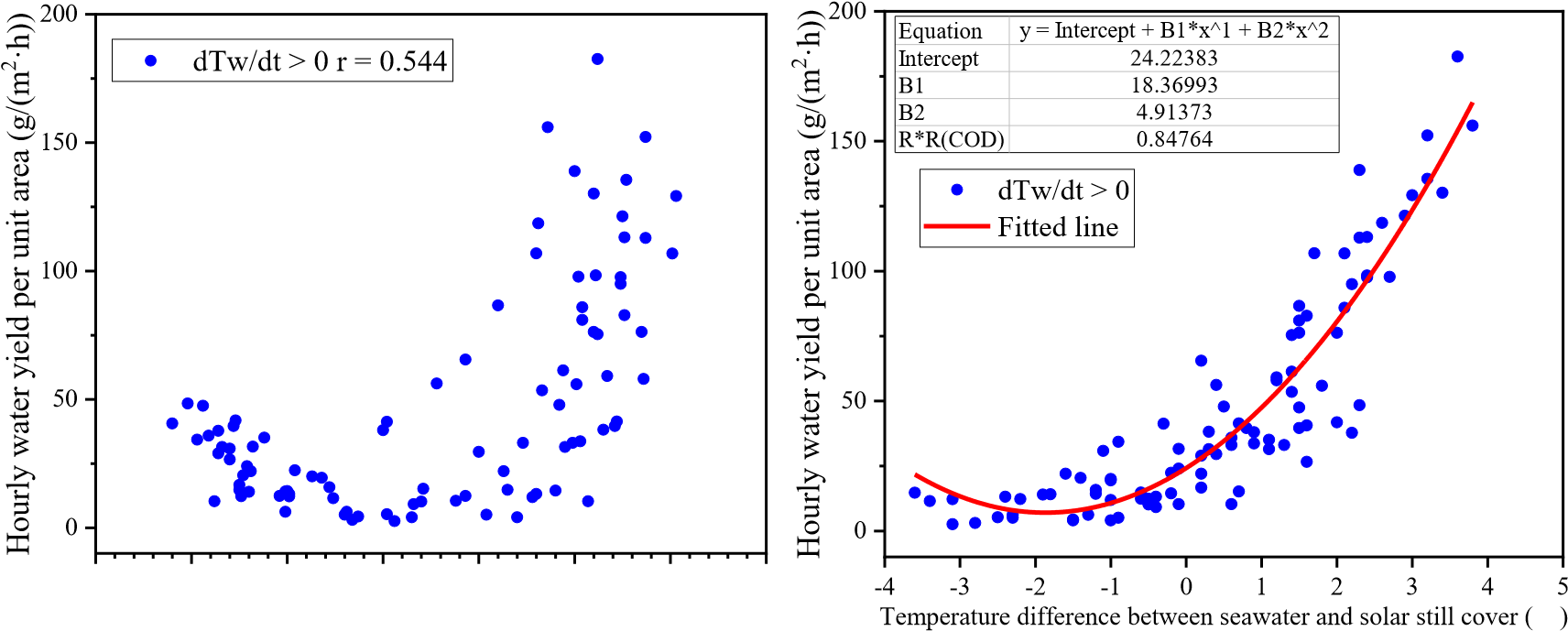
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1. *n* 2
2. 6(*Ri* *Qi* )
3. *rs*  1 *i**n n*1 ( 2 1)  (5)

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24 Where, *Ri* represents the rank of *xi* , and *Qi* represents the rank of *yi* .

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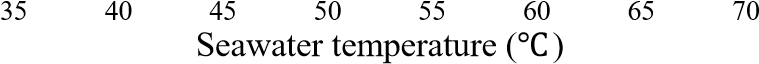
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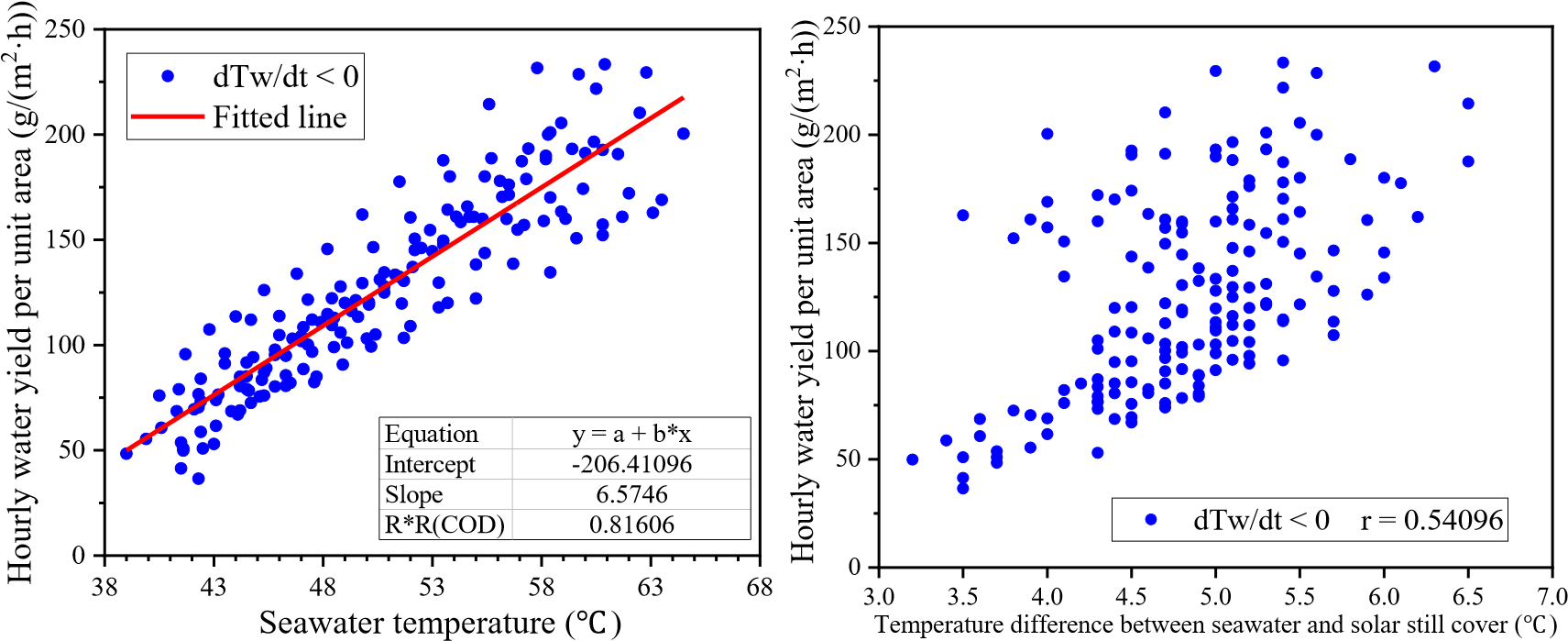
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41 (a) Rising period of seawater temperature

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(b) Falling period of seawater temperature

Fig.12 Changes in freshwater yield with seawater temperature and temperature difference *Twc*

Fig.12 shows how freshwater yield varies with seawater temperature and temperature difference *Twc* , respectively. From Fig.12(a), freshwater yield was mainly affected by temperature difference during the rising period of seawater

8 temperature, and the relationship between the two was a quadratic function. The fitting 9

10 formula between the two was *mw*  4.91*Twc*2 18.37 *Twc* 24.23 , R2  0.847 .

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13 Where, *mw*represents the hourly freshwater yield per unit area, g/(m2∙h). The

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15

16 correlation coefficient *r* between *mw*and temperature difference *Twc* and between

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19 *mw*and seawater temperature *Tw* in this period was 0.891 and 0.544, respectively. 20

21 This indicated that freshwater yield was highly correlated with the temperature

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23

24 difference *Twc* , and moderately correlated with the seawater temperature. Therefore, 25

26 the water yield in this period was mainly determined by the temperature difference

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28

29 *Twc* .

30

31 From Fig.12(b), the freshwater yield and seawater temperature showed an obvious 32

33 linear relationship during the falling period of seawater temperature. The fitting formula

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35

36 was *mw*  6.57*Tw* 206.41, R2  0.816. The correlation coefficient *r* between *mw*

37

38

39 and seawater temperature *Tw* and between *mw*and temperature difference *Twc* in

40

41 this period was 0.920 and 0.541, respectively. This indicated that freshwater yield was

42

43

44 highly correlated with the seawater temperature, and moderately correlated with the

45

46 temperature difference *Twc* . Therefore, the water yield in this period was mainly

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49 determined by seawater temperature.

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51 The above results show that the temperature difference *Twc* drives the

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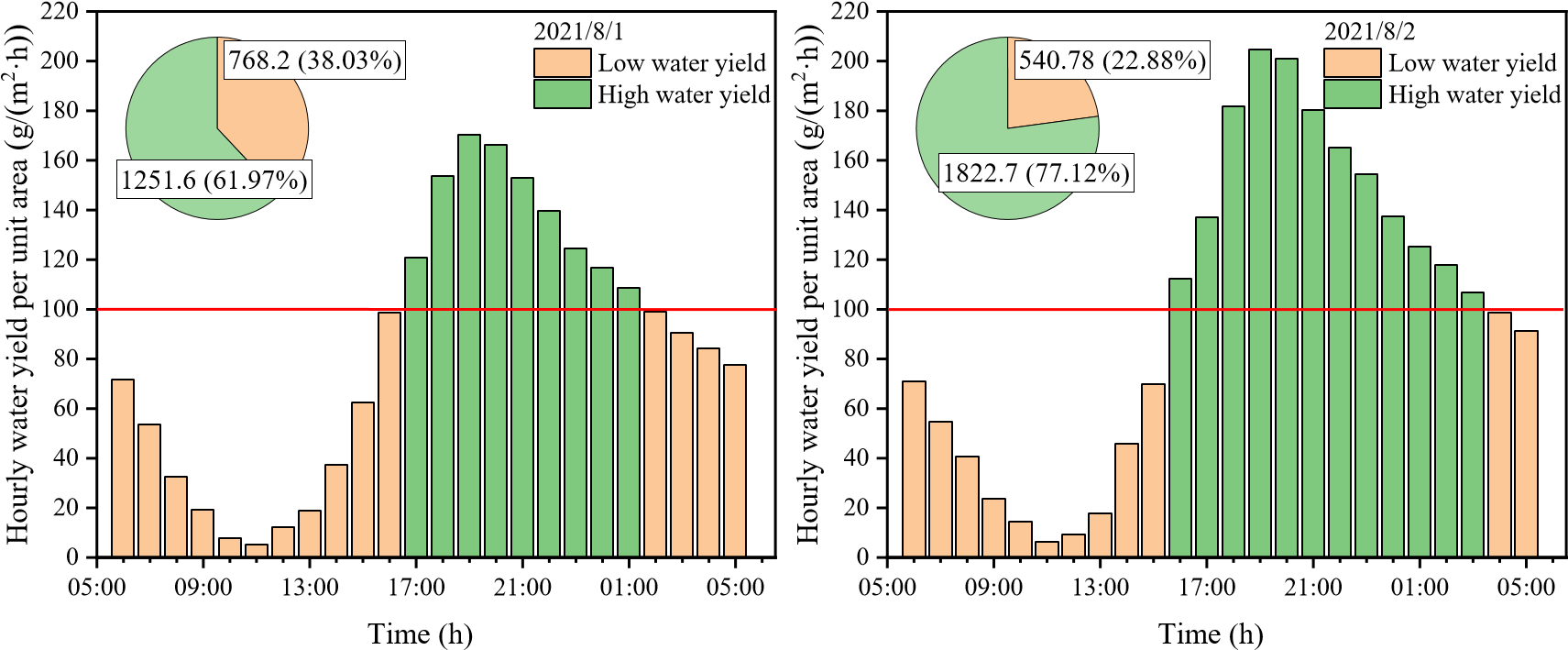
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54 evaporation of seawater and is the driving force of water production. Also, seawater

temperature has an important influence on the amount of evaporation. During the test, seawater temperature in the integrated device maintained at a very high level (> 44), and evaporation occurred throughout. Therefore, maintaining a high temperature

difference *Twc* is a necessary condition for the system to produce a large amount of freshwater in summer.

*3.5 Temporal characteristics analysis of water production*



(a) High and low water yield period on Augest 1 (b) High and low water yield period on Augest 2

Fig.13 Temporal characteristics of freshwater production of the integrated system

It is of guiding significance for the operation and management of the integrated system to understand the characteristics of freshwater production in different periods. Fig.13 shows the freshwater yield of the six solar stills (average value) in the system for one day and night. Taking the hourly water yield per unit area of 100 g/(m2∙h) as the dividing line, the water production period was divided into high-water yield period and low-water yield period, as shown in Fig.13. The high-water yield period on August 1 (17:00 to 1:00 the next day) accounted for only 33.3% of the total duration of the test day, but it contributed 61.97% of the total water yield. The low-water yield period on August 1 accounted for 66.7% of the total duration of the test day, but it only contributed 37.03% of the total water yield. The high-water yield period on August 2 (16:00 to 3:00 the next day) accounted for 45.83% of the total duration of the test day, and it contributed 77.12% of the total water yield. The low-water yield period on August 2

accounted for 54.17% of the total duration of the test day, but it only contributed 22.88% of the total water yield. The operating characteristics in different water production periods showed that the high-water yield period generally occurred between sunset and

1-3 a.m. Although this period accounted for a small proportion of the day's operating

time, it contributed most of the water produced. Therefore, it is necessary to strengthen the management of this operation period, reducing the failure rate of the device and manual error rate to ensure the efficient water production of the device.

Referring to Fig.11, it was found that the seawater temperature and temperature 8

9 difference *Twc* in the high-water yield period were both at a high level. This once

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12 again showed that a high seawater temperature and a high temperature difference *Twc*

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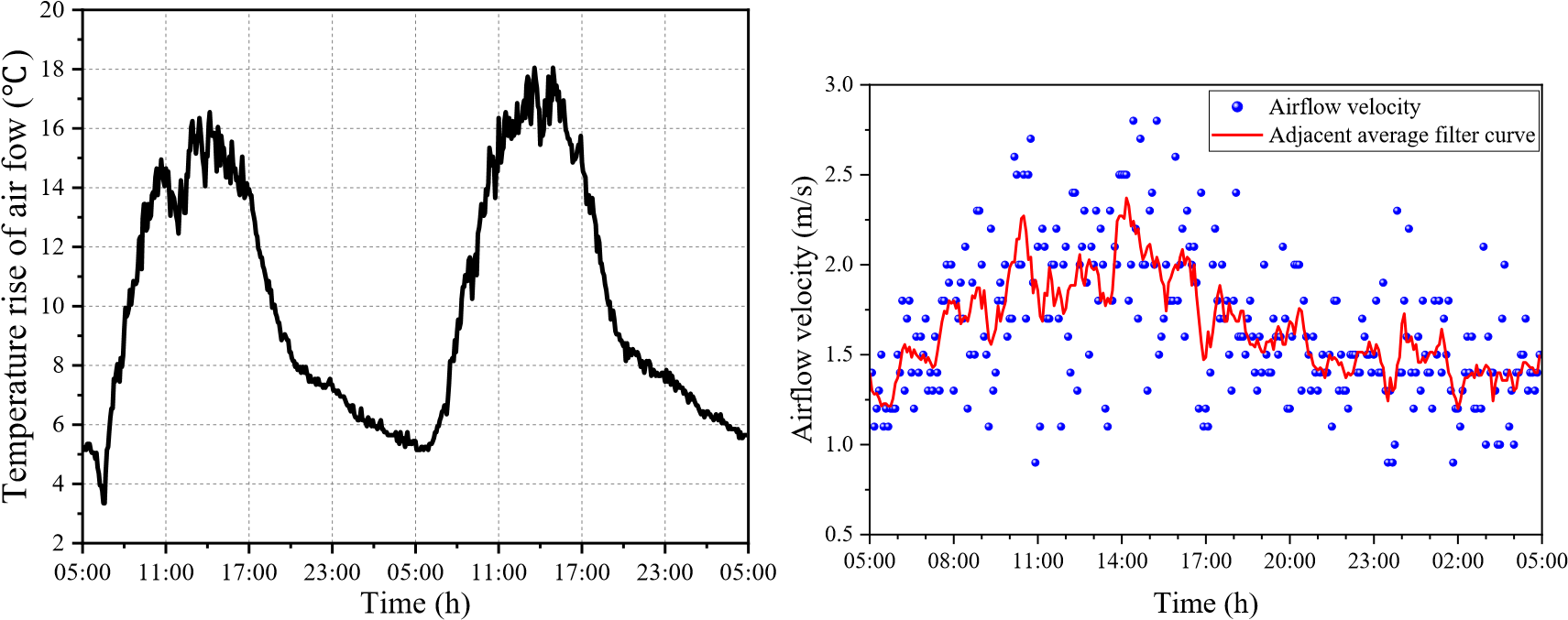
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15 were the guarantee for the efficient water production of the device.

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17 *3.6 Power output*

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35 Fig.14 Changes in airflow temperature rise Fig.15 Variation curve of airflow velocity in the chimney

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37 The airflow temperature rise is defined as the temperature difference between the 38

39 airflow at the chimney base and the environment. Fig.14 shows that the maximum and 40

41 minimum temperature rise of the airflow in the chimney were 17  and 5 ,

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43

44 respectively. The airflow temperature rise obtained was considerable, and the minimum

45

46 temperature rise was 5  even at night. This highlighted the advantage of the thermal

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48 storage effect of seawater in the system.

49

50 Fig.15 shows the change of airflow velocity in the chimney on August 1. The hot 51

52 airflow in the chimney was affected by turbine rotation and ambient wind speed, so the 53

54 airflow velocity fluctuated greatly. The filtering curve of the airflow velocity

approximately conformed to the sine curve, and its distribution profile was approximately a sinusoidal region. The peak period of the airflow velocity was at noon, and the airflow velocity at night was maintained at about 1.5 m/s. The variation characteristics of the airflow velocity during the daytime were similar to those of the solar irradiance. At night, the seawater in the solar still dissipated heat to the outside to maintain a certain airflow temperature and airflow velocity.

8

9 The hot airflow in the chimney drove the wind turbine to rotate, which in turn 10

11 drove the DC generator to rotate and generate electricity. In order for the output power 12

13 to drive the LED, the output voltage of the generator was raised to 5 V through a 14

15 regulator module. During the test operation of the device, the turbine drove the

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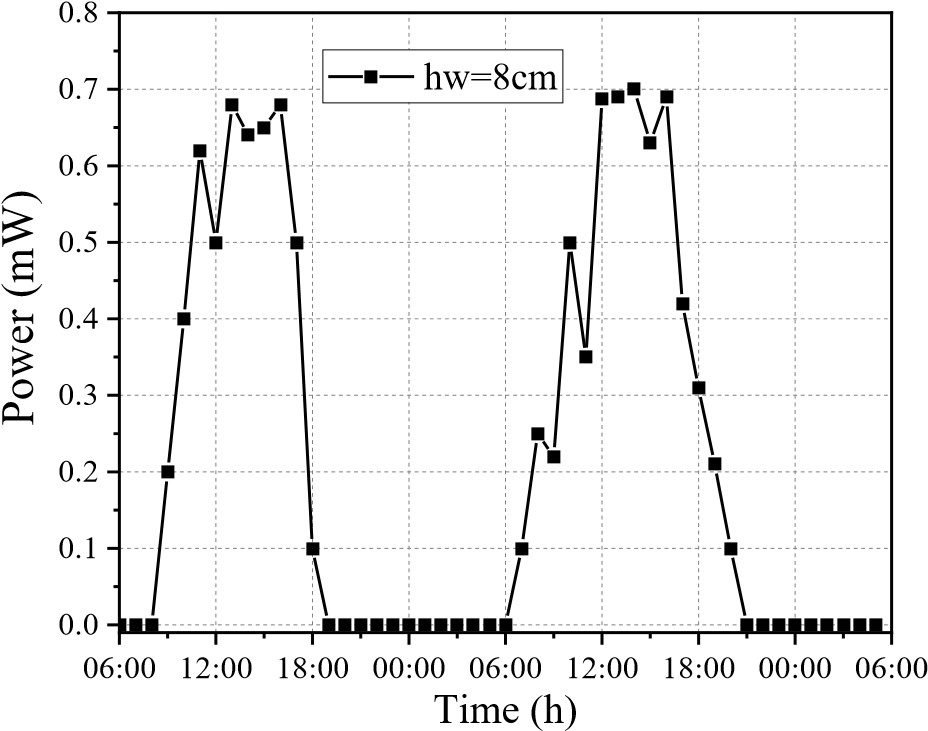
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18 generator to light up the LED. This experimental phenomenon demonstrates that the

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20 SCPPCD can realize the water-electricity cogeneration.

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37 Fig.16 Variation curve of generator power output

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40 Fig.16 shows the change curve of the generator power output. The change of 41

42 generator power output was similar to that of the airflow temperature rise. The 43

44 maximum generator power appeared at noon, about 0.70 ×10-3 W. Although the airflow 45

46 temperature rise was considerable at noon (Fig.14), the output power of the test device

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48

49 was small. This was because compared with the Spanish SCPP [2], the test device

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51 constructed in this paper was still too small in scale, and the heat collector was only a

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1. fan-shaped area. The small size of the device resulted in increased heat dissipation,
2. shortened the time the air was heated in the collector and increased the pressure losses in the system. After sunset, the airflow in the chimney was still flowing due to the temperature rise. However, due to the small scale of the device and thin heat storage

water layer, the heat storage was insufficient, the airflow temperature rise dropped a lot, and the airflow velocity was decreased. The pressure potential energy and kinetic energy of the airflow were not enough to overcome the energy consumption caused by factors such as frictional resistance and generator electromagnetic resistance. Therefore, 8

9 the hot airflow could not drive the turbine to rotate in this period, and the generator

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11 output power was 0 W.

12

13 The daily utilization efficiency of solar energy of the integrated system can be

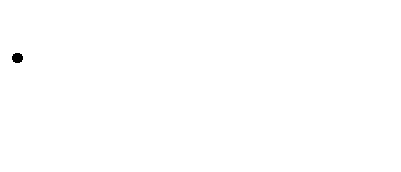
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15 calculated by the following formula:

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1. 24 6 24
2. *S h ms j*, *fg e s i j*, , ,  *t* *Pe i*, *t*
3. *sol s*,  *i* 1 *j* 1 288 *t i*1 (6)



2122 *Scol* *i*1 *Ii* 12

23

24

25 Where, *t* stands for an hour. The sampling interval for freshwater production 26

27 and power generation was one hour, and the sampling interval for solar irradiance was 28

29 five minutes. *hfg* represents the latent heat of water vaporization, J/g. *Scol* represents

30

31

32 the area of the heat collector, m2. *Ss j*, represents the area of the No.j solar still, m2.

33

34

35 *me s i j*, , , represents the water yield of the No.j solar still, g/(m2·h). *I* represents the solar

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37

38 irradiance, W/m2. *Pe* represents the output power of the generator, W.

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40

41 It was calculated that the daily utilization efficiency of solar energy of the

42

43 integrated system on August 1 and 2 was 19.6% and 21.8%, respectively. Limited by 44

45 thermodynamic properties, the solar energy utilization efficiency of the conventional 46

47 solar chimney power plant is generally less than 1% [2,3,10,25,37]. Compared with the 48

49 traditional solar chimney power plants, the solar energy utilization efficiency of

50

51 SCPPCD was significantly improved.

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54 In the SCPPCD, since the latent heat of vaporization released by the condensation

of water vapor was recycled and freshwater was produced, the solar energy utilization efficiency and land utilization rate were greatly improved, which was the meaning of integrating the freshwater generation with electricity generation. The SCPPCD is suitable for construction in desolate tidal flat areas along the coast.

# 4. Conclusion

In this paper, a comprehensive test platform for solar chimney power plant combined with distillation (SCPPCD) that can realize water-electricity cogeneration 8

9 was designed and successfully built. The operation and output characteristics of

10

11 SCPPCD were tested and analyzed, and the following findings were obtained.

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13 (1) The temperature variation of thermometric layers in each measuring point 14

15 system was similar, but the peak time of temperatures was different. The temperature

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18 of each thermometric layer at the same moment increased first and then decreased from

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20 the collector entrance to the chimney. The seawater temperature and solar still cover 21

22 temperature of the No.4 solar still were basically the highest. In the same measurement 23

24 point system, seawater temperature was the highest most of the time. The airflow

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26 temperature was lower than collector roof temperature most of the time, and it lost heat 27

28 through the collector roof.

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31 (2) Freshwater production was the result of a combination of seawater temperature

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33 *Tw* and temperature difference *Twc* , but the extent of their effect on water production

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36 was different in different periods. Temperature difference *Twc* was the main factor 37

38 affecting water production during the rising period of water production. Seawater

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41 temperature *Tw* was the main factor affecting water production during the decline

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44 period of water production.

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46 (3) The daily water yield per unit area of the solar still basically decreased from

47

48 the heat collector entrance to the chimney. The No.1 solar still had the highest daily 49

50 water yield per unit area, and the water yield of the No.4 still was second only to the 51

52 No.1 still. The daily water yield of the No.1 still on August 1 and 2 was 1.69 times and 53

54 1.72 times that of the No.6 still, respectively. Solar stills should be arranged as far as

possible in the area from the collector inlet to the one-third radius of the heat collector.

1. The high-water yield period generally occurs between sunset and 1-3 a.m. It

accounted for a small proportion of the day's operating time, but contributed most of the water produced.

1. The maximum temperature rise of hot airflow in the chimney was 17, and the temperature rise was maintained above 5 during night operation. The variation 8

9 law of generator power was similar to that of airflow temperature rise, and the 10

11 maximum output power reached 0.71 mW in the daytime. But the power generation 12

13 could not be realized at night limited by the scale of the test device. The daily utilization

14

15 efficiency of solar energy on August 1 and 2 was 19.6% and 21.8%, respectively.

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# 18 Acknowledgment

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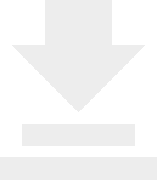
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