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The study of a novel light concentration and direct heating solar distillation device embedded underground

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ABSTRACT

A novel light concentration and direct heating solar distillation device embedded underground is proposed in this paper. The device is placed under the transparent pavement, which can resist typhoon and doesn't occupy any area of land surface. A method of light path simulation for solving light reception rate is developed. As the result, the reception rate is > 95% when the light incidence angle is < 25°. A theoretical model of heat and mass transfer is established. Calculation results show that the theoretical efficiency could reach 57%. An experimental device is developed and tested in Nanning city (longitude 108°, latitude 23°), China. The water yield and temperature curves are obtained in actual weather. Experiment results show that the daily water yield of the device on a sunny day reaches 2.95 kg/m^2 per unit aperture solar collector area and the water production efficiency is 28.3%, while the effective evaporation efficiency could reach 42.1%.

1. Introduction

Nowadays all over the world, many regions are in a bad situation of being short of fresh water, especially regions near the sea and islands where the seawater is abundant but cannot be directly utilized. Actually in most cases, there is also enough solar radiation in regions that are rich in seawater [1,2]. Therefore, it is of great significance to desalinate seawater utilizing solar energy in those regions.

In the early days, many scholars have conducted a great deal of research on basin solar still (one of the simplest solar desalination devices) [3–5]. This kind of low cost solar still has a simple structure, but the water yield is not satisfactory. Therefore, in the last few years, some researchers have again worked out several new approaches of making use of collector to promote water yield of distillers [6–9]. However, due to long pipelines and complex systems which restrain the promotion of the economy and efficiency, this type of solar desalination device was not popularized on a large scale. Large floor space of solar collector could also not be accepted for regions like islands and reefs where land area is of severe shortage. In addition, distillers combined with collectors could not greatly promote the evaporation temperature.

Owing to these reasons, some scholars proposed new structures of distillers integrated with concentrators [10–12]. Béchir Chaouchi et al. [13] designed a distillation system, using a solar dish concentrator with concentration ratio 195 to concentrate solar radiation and heat seawater directly. Although such concentration approach enhanced evaporation temperature, it made the system structure comparatively complex. Z.M. Omara and Eltawil [14] also used a solar dish concentrator to improve system performance, employing a two-axis automatic tracking system. However, the cost of the system increased accordingly, while additional energy was also consumed. Then, T. Arunkumar et al. [15] placed a solar dish concentrator below the distiller to promote water yield without employing a tracking system. Experimental results showed that the evaporation temperature of the system was higher than that of traditional basin solar stills, but the acceptance angle of the solar dish concentrator is not big, adversely affecting the concentration effect for a whole day.

In fact, compared with dish concentrator, compound parabolic concentrator (CPC) has better optical performance [16]. Due to the non-imaging characteristic of CPC [17], it has a bigger acceptance angle than other types of concentrators, so it is widely used in the field of solar energy utilization [18–20]. Joshua et al. [21] proposed a solar desalination system combining trough-type compound parabolic concentrator (TCPC) with basin solar still. Numerical simulation results showed that the water yield was markedly enhanced compared with single basin solar still. Nevertheless, this structure is only a simple combination of CPC with a single basin solar still and could not achieve the purpose of large-scale desalination and lack value for engineering application.

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Therefore, to improve on the weakness of current solar distillers, especially complex structure, large floor space, inapplicability for large-scale desalination, a novel light concentration and direct heating (LCDH) solar distillation device embedded underground is proposed and studied in this paper. The device has a simple structure and is made of low cost material, integrating heat collection with evaporation. The cost of the device and the thermal resistance in the system decreased due to the removal of solar collectors and long pipelines. The system also needs no tracking with a big acceptance angle, and could achieve large-scale desalination on account of the structural features. In addition, since the device is embedded underground, the top surface could still be used for other purposes, for example, serving as a transparent road, which means it could occupy no area of land surface. Again because of being embedded underground, the device has comparatively big condensation area and low condensation temperature which could improve the water production performance. Furthermore, compared with traditional desalination devices, this placement mode of being embedded underground make the device capable of fighting typhoons, so the service life is increased.

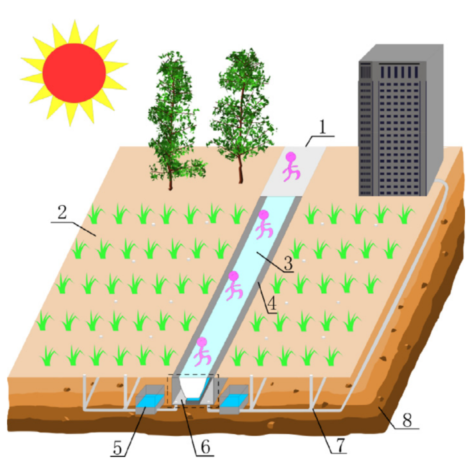
2. Working principle and system design

2.1. Working principle

The operation diagram of the device is shown in Fig. 1. The transparent glass at the top of the device serves as the road, while the main body of the device is embedded underground. When there are no pedestrians and other shields on the road, the solar radiation will be emitted into the device and heat the seawater in the seawater trough. The seawater evaporates into water vapor once heated. Then, the vapor condenses and turns into fresh water collected into the water tanks on both sides of the device. The fresh water could be used for watering the lawn or being transported to residential buildings to supply drinking water.

Fig. 2 shows the section diagram of the internal distiller structure, while the entire device is formed into a grooved structure by the stretch of the section.

The distiller is composed of top transparent glass, concentrator, bottom transparent glass, seawater trough and device shell. Among them, the top transparent glass, the bottom transparent glass and the concentrator are together coiled into a sealed light concentration cavity. The gas in the concentration cavity is air. At the bottom of the seawater trough, there is a seawater inlet hole, and the bottom surface of the trough is coated with a black absorptive insulating layer, which is designed to reduce the heat conduction loss at the bottom of the seawater trough and promote the absorptivity to the solar radiation. The bottom and side surface of the device are condensation surfaces and a fresh water outlet hole is opened at the bottom surface. The bottom and side surfaces of the device, the seawater trough and the concentrator are coiled into the condensation cavity. The water vapor evaporated from the seawater trough flows into the condensation cavity and condenses at the bottom and side surfaces of the device.



1-road，2-sod，3-glass，4-device shell，5-fresh water tank，6-solar still，7-pipeline，8-soil layer

Fig. 1. Operation diagram of the solar distillation unit.
1-road, 2-sod, 3-glass, 4-device shell, 5-fresh water tank, 6-solar still, 7-pipeline, 8-soil layer.

Working principle: during a sunny day, when no pedestrians walk above the device, the sun shines directly into the light concentration cavity through the top transparent glass. One part of solar rays are directly emitted to the seawater through the bottom transparent glass without reflection. Another part of solar rays are reflected by the concentrator and then gather at the seawater surface. The solar radiation concentrated on the seawater would heat the seawater in the trough. Then the seawater evaporates into water vapor, and flows into the condensation cavity through the narrow passage above the seawater trough. Next, the water vapor exchanges heat with the soil outside the distiller through the side and bottom surfaces of the distiller, and condenses into fresh water. Finally, the fresh water is gathered into the water tank via the valve under the device.

2.2. Structure size of the concentrator

Concentrator is the most important component of light concentration solar still, and the effect of concentration directly influences the water production performance of the distiller.

The concentrator designed in this paper belongs to TCPC type. To insure that the concentrator can achieve concentration effect and a certain concentration multiple for a whole year, a truncated CPC concentrator is selected in Fig. 3. The (light) incidence angle θ is defined as the angle formed by the incident light ray and vertical line under planar condition (for a triaxial condition, θ is defined as the angle formed by vertical line and the projection line of incident light ray on the CPC cross profile). The sizes of the truncated concentrator are as follows: light ray inlet width d_1 = 49 cm (d_1 = 50 cm before truncation), light ray outlet width d_2 = 30 cm, height h_0 = 39.09 cm (h_0 = 53.3 cm before truncation), the concentration ratio C = 1.63 (C = 1.67 before truncation). The acceptance angle θ_{max} of the initial CPC is 36.9°.

The focal length of the parabola is 24 cm. Eq. (1) is the equation of the CPC curve in a rectangular coordinate system when setting the center point of the CPC outlet as the origin point.

$$(0.6y - 0.8x)^2 = 96(0.8y + 0.6x),\ -24.5 \le x \le -15$$
$$(0.6y + 0.8x)^2 = 96(0.8y - 0.6x),\ 15 \le x \le 24.5 \quad (1)$$

2.3. Structure design of the distiller

The distiller structure is designed according to Figs. 2 and 3. The whole distiller is a seal cuboid structure with the length 2.01 m, width 0.62 m and height 0.517 m, containing: top transparent glass, concentrator, bottom transparent glass, seawater trough, condensing surface, etc. Among them, the top transparent glass is located at the device top as a light ray inlet, with the length 2 m, width 0.49 m and height 0.008 m. A TCPC concentrator with the longitudinal length 2 m and the reflection area 1.616 m^2 is just below the top transparent glass. The inner curve size of the concentrator section is the same as the curve size in Fig. 3, while the outer curve is linear. The minimum and maximum thickness values of the concentrator are 0.014 m and 0.035 m, respectively. The bottom transparent glass below the concentrator serves as the light ray outlet, with the length 2 m, width 0.3 m and thickness 0.003 m. The top transparent glass, CPC concentrator and bottom transparent glass together form into the light concentration cavity with