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Investigation of a floating solar desalination film

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ABSTRACT

In traditional solar desalination systems, the solar collector and demineralizer are separate components with a large thermal resistance and pipeline heat loss between them. This paper introduces the concept of a floating solar desalination film, which uses concentrated light to directly evaporate seawater. The greatest advantage of this design is that it combines solar energy collection and seawater demineralisation as an integrated system, eliminating pipeline heat losses and realising large-scale desalination on the surface of the sea, saving space on the land. This paper describes the operating principle of the floating solar desalination film, carries out an optical simulation for the light concentration process, analyses heat and mass transfer processes for theory calculation in the film's microstructure, and investigates optimisation of the device structure. A performance test was conducted on the device, showing water production and temperature measurements at different weather conditions. In addition, the average daily efficiency of the system was calculated. According to the test results, with comprehensive tracking of the sun, the water production per unit area of this test device reached 1.38 kg/m^2·day. With azimuth-only tracking of the sun, the water production was 1.19 kg/m^2·day, and the daily solar-thermal conversion rate reached 22.7%.

1. Introduction

According to predictions made by the United Nations, by 2025, 14% of the world's population will face water shortages [1], one billion people will lack clean drinking water, and about 663 million people will live in areas without a drinking water supply [2,3]. This lack of freshwater resources is a threat that cannot be ignored. Seawater desalination is a potential solution to these freshwater supply issues.

Since traditional seawater desalination requires a lot of energy, solar-powered desalination is a good alternative [4–7]. At present there is a trend towards combining modern industrial desalination technology with solar energy technology [8–10]. Many new types of solar desalination systems have been proposed [11–16], but these studies have encountered problems such as high costs and technical bottlenecks [17]. Solar desalination technology cannot yet be utilised at a large scale, as its economic feasibility is not comparable to that of traditional industrial desalination systems [18]. There are several reasons behind the economic issues that are hindering large-scale application of solar desalination systems, and these reasons can be broken down into three parts. (1) The traditional solar desalination system consists of three separate parts, the solar collector, the thermal reservoir and the desalter. These components need to be connected together by a lengthy pipeline, resulting in high heat transmission resistance and increasing pipeline heat loss. This means that the overall efficiency of the system is not high [19]. (2) The construction cost of the solar collector system is too high [20]. (3) The solar collector system covers a huge area, which results in additional high costs, which are especially adverse for regions already short of land resources [21]. Thus, the idea of a solar seawater desalination that combines the solar collector with the seawater desalter constitutes a promising idea for reducing the magnitude of these problems.

To that end, Wu et al. [22] proposes a direct-evaporation type of seawater desalination system. This uses the Fresnel lens to collect solar rays, thereby directly heating the humidification-dehumidification desalination system to produce fresh water. Experimental investigation shows that the efficiency of a single-effect device can reach as high as 69%. Chaouchi et al. [23] designed a desalination system device by combining the distiller and the receiver, with a parabolic concentrating function. The receiving surface is 0.013 m^2 and the geometric concentration ratio is 195. The test results, thus far, are not very satisfactory, but it constitutes a novel attempt in the study of the concentration of light and a direct heating desalination system. Joshua et al. [24] proposed the idea of installing a butterfly concentrator above the traditional solar still, and carried out a simulation study and economic cost analysis of such a system. The results show that the system cost increased by 10%, but the daily water yield per unit area increased by a

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factor of 3, indicating that a direct heating desalination system has great developmental potential and good prospects for application.

In the process of utilizing sunlight to direct heat seawater and generate evaporation, it is necessary to utilise functional materials that enhance the evaporation of seawater. Zeng et al. [25] used carbide to synthesise Fe_3O_4 nanoparticles with an average diameter of 50 nm. These nanoparticles can be suspended on the surface of water to enhance the ability of the seawater to absorb sunlight. Experiments show that adding Fe_3O_4 nanoparticles to 3.5% saline water can increase evaporation efficiency by a factor of about 2.3. Zhou et al. [26] developed a porous structure of aluminium-based nanoparticles. The structure floats on water and promotes a sunlight absorption rate of up to 96%, and an energy conversion rate of over 90%, providing a potential mechanism for improvement of seawater evaporation efficiency. However, these studies do not discuss how to effectively collect the evaporated freshwater and lack a comprehensive overview of solar desalination system design, including light concentration, desalination, and seawater collection. Thus, further research is needed to achieve an efficient, industrial-scale solar desalination system.

Due to the shortage of land resources [27], it is especially critical to obtain freshwater from oceans with a system that does not take up precious space on land [28–30]. Therefore, if solar desalination can be carried out directly on the surface of the sea, not only can ocean resources be fully utilised but also land resources can be conserved. To this end, this paper introduces a new type of floating desalination film, which uses the micropore or microstructure of the film to concentrate light for direct heating seawater and evaporating seawater to achieve solar-powered desalination. The greatest advantage of this system is that it combines solar energy collection and seawater demineralisation into an integrated device, eliminating the need for heat transfer in a pipeline, and increasing energy transfer efficiency. In addition, since this device floats directly on the sea, it conserves land resources. The film is made of non-metallic materials, which are corrosion-resistant and relatively inexpensive. Multiple films can be joined together, enabling large-scale desalination.

2. Unit structure and operating principle of the floating solar desalination film

The overall structure of the floating solar desalination film proposed in this paper is shown in Fig. 1. The system includes a concentrator, seawater filler groove, and condensation cavity. The system operating principle is shown in Fig. 2. When the device is operating, sunlight passes through the top transmitting film and illuminates the reflecting surface of the concentrator inside the unit. The light is then reflected onto the secondary reflection panel that reflects the light to the upper end of the water-absorbing filler. Seawater is absorbed by the water-absorbing filler and heated by the concentrating light to generate water vapour. The water vapour condenses in the condensation cavity, mainly on the inner surface of the underlying film where direct contact with cold seawater occurs. To avoid steam entering the concentration space, a transparent cover is installed at the light outlet of the concentrator. The film is made of transparent organic materials. Pressure within the cavity prevents seawater from entering.

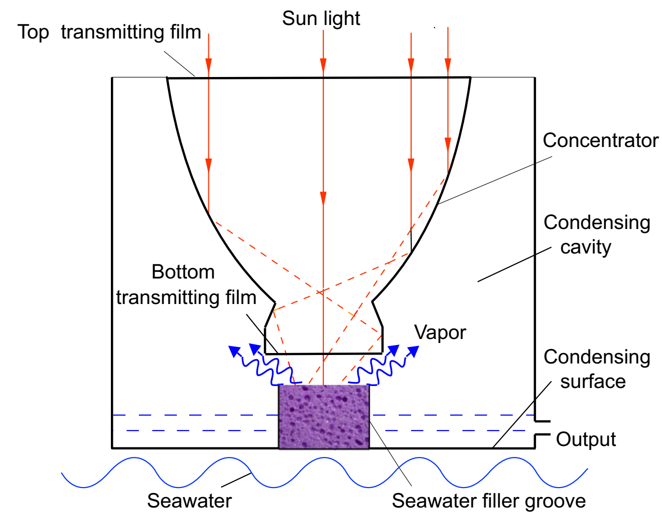

Fig. 2. Light concentration and evaporation processes in the microstructure of the film.

3. Microstructure design

3.1. Light concentration system design

To enable adaption to sea surface conditions, a compound parabolic concentrator (CPC) with a large concentrating angle was selected to construct the concentration unit. The CPC chosen for this study uses the parabolic equation $x^2 = 23.5y$. The CPC has the following specifications: a light inlet size of 42.2 mm, a light outlet size of 10 mm, height of 50 mm, concentration ratio of 4.2, and maximum acceptance angle of 10°.

The selected CPC concentrator is simulated with Lighttools optical simulation software to analyse its light concentration performance at different angles of incidence θ. Curve 'a' in Fig. 3a shows the variation of the light receiving rate on the receiving surface under different angles of incidence. When the angle of incidence is < 6°, the concentration ability of the system is maximised, and the receiving rate of the receiving surface reaches about 75%. However, when the angle of incidence is > 6°, the entire system receiving rate drops sharply, which

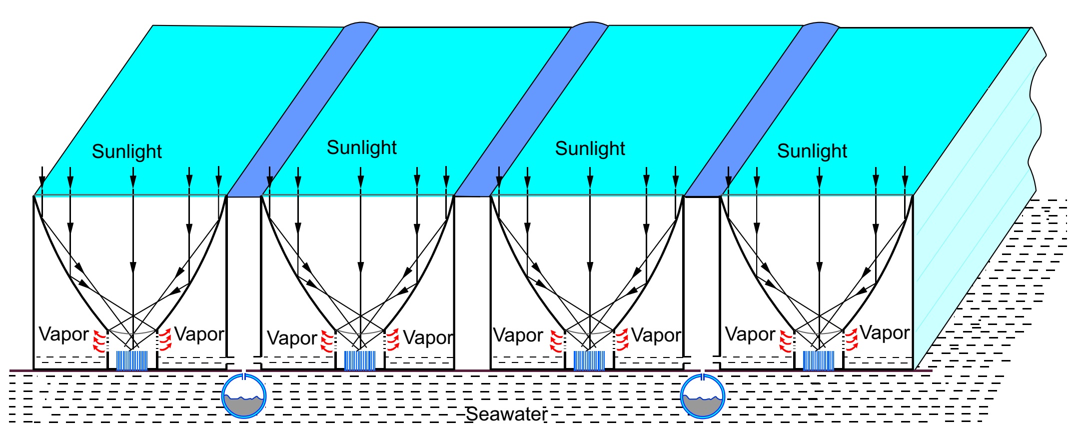

Fig. 1. Diagram of the floating solar desalination film.