A new type of superhydrophobic membrane seawater desalination device

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Abstract. In response to the existing problems of the current seawater desalination equipment, this project designed a new type of super-hydrophobic membrane tangential distillation seawater desalination device with simple structure, low energy consumption, high seawater conversion rate, operation and reduced maintenance costs. The successful implementation of the project will not only provide economical and applicable freshwater equipment for the living water of island residents, but also have potential application value for China's coastal defense construction and offshore development.

Keywords: Desalination, superhydrophobic membrane, distillation.

1. Introduction

Based on the background of high energy consumption, expensive components, and complicated operation of the current domestic small-scale seawater desalination devices, this project proposes to build a new type of membrane distillation seawater desalination device that adapts to the island environment and meets the needs of island residents. In view of the high energy consumption of traditional solar seawater desalination devices due to poor solar energy collection and the upward diffusion of steam affecting energy input downwards, the multi-layer structure is designed to force the steam to diffuse downwards to the bottom to condense, and a special structure is used to enhance latent heat recovery for preheating. Methods such as hot sea water minimize heat loss and improve energy utilization. Aiming at the problem of membrane pollution, this project proposes a pretreatment method integrated with the device: the capillary force of the fiber material is used to transport seawater tangentially above the membrane surface, which not only prevents the seawater from contacting the membrane surface completely, but also filters the seawater. Treatment can reduce membrane pollution, extend membrane life, and reduce maintenance costs. This method is economical and simple, and is suitable for small seawater desalination devices for island residents.

2. Research background

2.1. Current status of seawater desalination

Seawater desalination is currently an important means to solve the problem of shortage of freshwater resources. Compared with groundwater exploitation, seawater desalination has the advantages of abundant original water resources and less likely to cause environmental problems. It is considered to
be the most practical and sustainable way to provide freshwater sources. At present, the global annual output of seawater desalination is about $9000 \times 10^4 \text{m}^3$, and the annual consumption of crude oil exceeds 850 million m$^3$. Due to the shortage and non-renewability of fossil fuels and the deterioration of the natural environment caused by their mining, the development of new energy-driven seawater desalination technology has become a major international issue that needs to be resolved.

### 2.2. Traditional solar seawater desalination device
Sunlight penetrates into the glass plate to input solar energy to heat up the device, the seawater is heated and evaporated, water vapor rises on the inner surface of the glass plate to condense, and fresh water flows into the water collecting tank for collection. But the device has no other heat collection equipment, so the solar energy collection effect is not good. At the same time, the unreasonable position of the vapor liquefaction surface causes the condensed droplets to affect the light radiation, and the latent heat of condensation is not recovered, so the efficiency of fresh water production is low, only $0.3-0.4 \text{L/(m}^2\text{·h})$. However, traditional devices have simple and practical characteristics, which are worth learning from.

### 2.3. Membrane distillation
Membrane Distillation (MD) is a thermally driven membrane separation process that uses a porous hydrophobic membrane as the separation medium and the vapor pressure difference on both sides of the membrane as the driving force. The porous hydrophobic membrane acts as a thermal insulator and a physical barrier. Water vapor passes through the pores of the membrane and condenses in the cold, while other components are blocked on the hot side by the hydrophobic membrane.

In recent years, although a variety of new seawater desalination technologies have been developed at home and abroad, such as reverse osmosis technology, multi-stage flash evaporation, freezing method, etc., reverse osmosis technology requires high operating pressure, strict pretreatment requirements, complex equipment, and it is difficult to dispose of high-concentration salt solutions for discharge, and other new seawater desalination technologies such as multi-stage flash evaporation and freezing methods have complex processes and large equipment, which cannot be applied to small seawater desalination devices. Membrane distillation can not only make up for the shortcomings of reverse osmosis desalination technology that is difficult to deal with high-concentration salt solutions, but also membrane distillation has higher water distillation efficiency and purity, which can meet the WHO drinking water salinity standard of 1‰, which is convenient for island residents and offshore residents Use directly. In addition, the original solution does not need to be heated to the boiling point during membrane distillation, and it can be carried out at 60-90°C. Therefore, it can be combined with low-cost energy such as solar energy to solve the drinking and domestic water problems of residents.

### 2.4. Island desalination
Islands have a large demand for small seawater desalination devices, but there are few practical applications. The main factor restricting the promotion of small island seawater desalination devices is the high operating cost, which is caused by two aspects: (1) At present, small seawater desalination devices adopt engineering. The design does not form an integrated modular device, it occupies a large area, and the engineering cost is high. It is not suitable for the simple desalination needs of island residents; (2) Lack of suitable pretreatment equipment. The civil structure used in the clarification tank and valveless filter of the seawater desalination project requires too much transportation investment and is not suitable for small-scale seawater desalination on remote islands.

### 3. Technical route

#### 3.1. Installation innovation
This project proposes a membrane distillation seawater desalination device that can realize solar heat collection and latent heat recovery. Its innovations are reflected in the following three aspects:
(1) In view of the high energy consumption of traditional solar desalination devices, this project proposes a multi-layer structure to force vapor to diffuse down to the bottom to condense, reducing heat loss.

(2) Aiming at the problem of membrane pollution, this project proposes an integrated method of seawater supply and pretreatment: transport seawater tangentially above the membrane surface to avoid contact with the membrane surface, and pre-filter the seawater to reduce membrane pollution and extend membrane life. Reduce maintenance costs.

(3) Aiming at the problems of poor condensation effect and waste of latent heat in common devices, this project proposes a copper wire cluster structure imitating grass, so that the steam will form a drop-like condensation with a higher heat transfer coefficient, so as to efficiently recover the latent heat of condensation for seawater pretreatment. Heat, improve energy utilization.

3.2. Evaporative condensation structure
The improper location of water vapor condensation in traditional devices weakens the light radiation intensity of the light-to-heat conversion surface and affects the absorption of solar energy by seawater. If you want to solve this problem, you need to meet the following conditions:

(1) The heat-receiving part of seawater is separated from the condensation part of water vapor, that is, seawater needs to be transported between the light-to-heat conversion layer and the condensation surface, so that the solar energy input-evaporation-condensation process can be completed in one direction and from top to bottom.

(2) The water vapor diffusion path is separated from the light channel, that is, a desalination method is required to force the water vapor to diffuse down to the condensing chamber for liquefaction.

Therefore, the device structure of this project is shown in Figure 1, and the following measures are adopted: the glass shell prevents water vapor from overflowing above the light-to-heat conversion layer to reduce surface radiation and convective heat loss; the glass inner plate receives the distillation film, and the internal cavity is equipped with a vapor condensation chamber; The fibrous material passes between the light-to-heat conversion layer and the distillation membrane as a seawater transport layer; the working principle of membrane distillation is used, that is, the vapor pressure difference on both sides drives water vapor through the membrane pores, while the superhydrophobic membrane acts as a thermal insulator to prevent heat dissipation.

![Figure 1. Overall structure of the device.](image)

3.3. Device internal structure
Each part is shown in Figure 2. A cavity is formed between the glass shell and the glass inner plate, which is equipped with a light-to-heat conversion layer, a seawater transmission fiber layer, and a super-hydrophobic distillation film. The four-sided glass inner plate is a copper vapor condensation
chamber, and its bottom surface. It is a latent heat recovery board with a special copper wire cluster structure.

The light-to-heat conversion layer should be a light-to-heat conversion material with a broad spectrum and high-efficiency light absorption capability. Carbon-based materials have a good broad spectrum absorption capacity due to the loose π electron-intensive energy level, and the aromatic bond enables the material to exist stably at ambient temperature. Carbon-based composite materials with nanostructures (such as graphene, carbon nanotubes, etc.) will form a large number of optical microcavities on the reflective surfaces on both sides of the spacer layer, confine the light to the tiny space through resonant recycling, and enhance the interaction between light and material. Effect.

This project selects fiber materials to fill the cavity formed between the glass shell and the glass inner plate, and the gap between the light-to-heat conversion layer and the distillation film to form a seawater transmission fiber layer. The seawater transmission layer is connected to the external reservoir, and the good water transportation capacity of the capillary fiber material is used to realize the continuous supply of seawater to the device. In addition, the capillary force of the fiber material can thin the seawater, and the two-dimensional channel tangential transmission of the seawater between the light-to-heat conversion layer and the superhydrophobic distillation film can reduce the heat conduction loss, increase the heating area and improve the evaporation efficiency. At the same time, the fiber material transportation seawater also prevents the membrane material from directly contacting the liquid, reducing heat loss and protecting the membrane material. Experiments have verified that the water supply rate of the multi-layer cotton thread is sufficient to compensate the evaporation rate of the thin layer of water and improve the water production performance of the device.

The glass inner plate blocks the contact between the copper vapor condensation chamber and the seawater in the reservoir, and its top surface is a super-hydrophobic distillation membrane, which is a channel for vapor to enter the condensation chamber. Traditional seawater desalination methods are commonly used for direct evaporation and condensation without membranes, but the requirement to heat seawater to the boiling point limits its application in combination with solar energy. The use of hydrophobic membrane for distillation not only has higher distillation efficiency and cleaner products, but also does not need to heat the raw material liquid to the boiling point, so it can use cheap energy such as solar energy, geothermal heat, and factory waste heat to reduce the cost of seawater desalination. Compared with the original hydrophobic membrane, the superhydrophobic membrane material with a contact angle of 160° or more has a higher flux. The literature has pointed out that when 3.5wt% NaCl is used as the raw material, the flux of the superhydrophobic membrane is higher than that of the original hydrophobic membrane. By more than 30%.

When saturated vapor comes into contact with a surface below the saturation temperature, the vapor will release latent heat and condense into a liquid. Traditional seawater desalination devices have not recovered and reused the latent heat of condensation. Due to the high latent heat energy of water vapor (100°C, 2.257MJ/kg), if this part of energy can be reasonably reused, the water production efficiency will inevitably be effectively improved. Therefore, the device is designed with a latent heat recovery plate with a special copper wire cluster surface structure, so that when the vapor contacts the copper wire, a large number of small droplets are formed, which promotes dropwise condensation. Because the droplet condensation heat resistance is very small, and the heat transfer coefficient is more than 4 times higher than the common film condensation in the industry, it can strengthen the latent heat transfer to the seawater for preheating. The effective use of latent heat also helps increase the condensation rate.
4. Calculation and analysis
This paper provides heat loss calculations and energy utilization efficiency calculations.

4.1. Heat loss calculation
The main output forms of the solar energy input by this device are reflection loss, convection loss, system heating, and seawater evaporation. The theoretical calculation of the heat loss of each part is as follows.

(1) Reflection loss:
According to Stefan-Boltzmann law
\[ q_1 = \sigma \varepsilon (T^4 - T_\infty^4) \]  

Among them, \( \sigma \) is the black body radiation constant, \( \sigma = 5.669 \times 10^{-8} \text{W/(m}^2 \text{·K}^4) \); \( \varepsilon \) is the material emissivity, which can be derived from Kirchhoff’s law, \( \varepsilon = \alpha \), and \( \alpha \) is the light absorption ratio of the material.

(2) Convection loss:
According to Newton’s law of cooling
\[ q_2 = h(T - T_\infty) \]  

Among them, \( h \) is the convective heat transfer coefficient of the substance, which is related to the ambient wind speed \( v \)
\[ h = 5.7 + 3.8v \]  

(3) Increased temperature of the system:
Ignoring the energy absorbed by the heating of other materials except seawater, most of the energy input from the outside is absorbed by the seawater. It is known that the combination of heat conduction and radiation causes the water temperature to rise
\[ q_3 = \left( \frac{l}{k} + h_r^{-1} \right)^{-1}(T - T_\infty) \]  

Among them, \( l \) is the thickness of the thermally conductive material, and \( h_r \) is the heat transfer coefficient converted from radiation to convection.

4.2. Energy efficiency calculation
According to the calculation formula of energy utilization efficiency
Among them, \( Q_G \) is the mass flow of steam in kg/m\(^2\)·h, \( h_{fg} \) is the latent heat energy of water vapor, \( h_{fg} = 2.257 \text{MJ/kg} \) (at 100°C), \( q_{solar} \) is the solar power density, and \( A \) is the illuminated area.

4.3. Superhydrophobic membrane

When the water contact angle of a surface is greater than 150°, due to its super hydrophobicity, this type of surface has the characteristics of self-cleaning and pollution resistance. This type of surface is usually called a superhydrophobic surface, or it is considered to have a "lotus effect".

The self-cleaning and anti-fouling properties of the super-hydrophobic surface can effectively solve the problem of membrane pore wetting and membrane fouling of membrane distillation materials. Due to the rough structure and high hydrophobicity of the superhydrophobic surface, the air gap between the membrane surface and the liquid can be increased, that is, the effective evaporation area can be increased, the possibility of wetting of the membrane pores can be reduced, and the membrane flux can be increased.

In the membrane distillation process, the heat loss due to the heat conduction across the membrane will reduce the vapor pressure difference, reduce the driving force, and cause the gas flux to decrease. Studies have found that the surface of the superhydrophobic membrane has a micro-nano-scale rough structure and a strong repulsive force against liquids, which can increase the porosity and gaps, and reduce the heat loss of vapor during heat conduction across the membrane to a certain extent.

4.4. Fiber material

As a natural capillary material, cotton material has the advantages of wide sources, mature production technology, and low price. The experiment found that the initial water absorption rate of cotton thread is above 7cm/min, which is the best water absorption effect compared to other materials. And it has been verified by experiments that the water absorption efficiency of the multi-layer cotton thread is sufficient to compensate for the evaporation rate of the thin layer of water, indicating that the capillary water delivery can be increased by increasing the number of layers of cotton thread.

Since water in the pores of carbon materials will increase heat loss, Xiuqiang Li et al. used fiber materials to achieve seawater two-dimensional channel transmission, reducing heat loss by reducing the contact area between light-absorbing materials and seawater, thereby solving the problem of the introduction of seawater that affects energy utilization efficiency. Experiments under natural light revealed that the energy utilization efficiency of this method increased to 80%.

5. Conclusions

Through theoretical research and experimental proof, this thesis proposes a membrane distillation seawater desalination device that uses solar energy, condensation latent heat recovery, and seawater pretreatment. Effectively solve the problems of traditional methods and realize high-efficiency desalination of seawater with natural light, low cost and low energy consumption.

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