Design and Research of a Portable Seawater Desalination Device System Based on Membrane Distillation Technology

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Keywords: Desalination, membrane distillation technology, portable unit, solar energy

Abstract: With regard to the increasingly insufficient global water resources and the ever-increasing demand for offshore operations and emergency rescue, this paper is devoted to the analysis and design of a portable desalination device system, suitable for sea rescue and remote areas through effectively integrating various functional modules. It focuses on compactness, light weight, and excellent sealing performance with a design for stable operations in such complex and variable marine environments. Simultaneously, it is easily portable and rapidly deployable on both land and sea. The design core is to adopt advanced membrane distillation technology, enhancing a desalination solution that caters to the needs of offshore activities through technological innovation, which is highly portable and practical, ensuring a safe and reliable source of fresh water for offshore workers while maximizing operational benefits.

1. Introduction

With the shortage of water resources and more frequent maritime activities, there is an emerging demand for a supply of fresh water in emergencies like sea rescue and remote drought disaster areas. According to the United Nations Convention to Combat Desertification (UNCCD) projection, the shortage of water is likely to affect 24 to 700 million persons by the year 2030 in arid regions[1]. However, traditional sources of freshwater normally fail to meet immediate and sustained needs in such scenarios. This leads to the need for the need for developing efficient, portable desalination devices that are reliable. In this paper, a portable desalination device using membrane distillation technology tailored for such emergencies is presented, which adopts solar energy and wind energy to generate electricity by promoting practicality and environmental friendliness. The objective of this paper is to develop a highly mobile and practical desalination method to serve sea-going applications as well as efficiently supply fresh water to victims of disasters for furthering the development and application of desalination technology.

2. Research Review on Desalination Technology

2.1. Overview of Seawater Desalination Technology

Seawater desalination technology has become an urgent way to solve the global lack of water. In the early times, thermally driven solutions (MED, MSF) were historically the first techniques adopted, whereas currently the technologies based on membranes (mainly RO) are quickly spreading worldwide[2]. Using mathematical statistics, this paper analyzes the recent research trend by using the China National Knowledge Internet (CNKI) database.

The statistical analysis in Figure 1 highlighted many research hotspots, such as desalination technology, reverse osmosis, water treatment, multi-effect distillation, and new desalination materials. These keywords signify current and future trends in seawater desalination. Widely used technologies like multi-stage flash, multi-effect distillation, and reverse osmosis are unsuitable for small-scale rescue devices due to issues such as high electricity consumption, large size, and complex processes. Conversely, membrane distillation is a relatively new process under worldwide investigation due to its low cost and energy-saving alternative to conventional separation processes such as distillation and reverse osmosis[3].

  DOI: 10.25236/iwmecs.2024.005

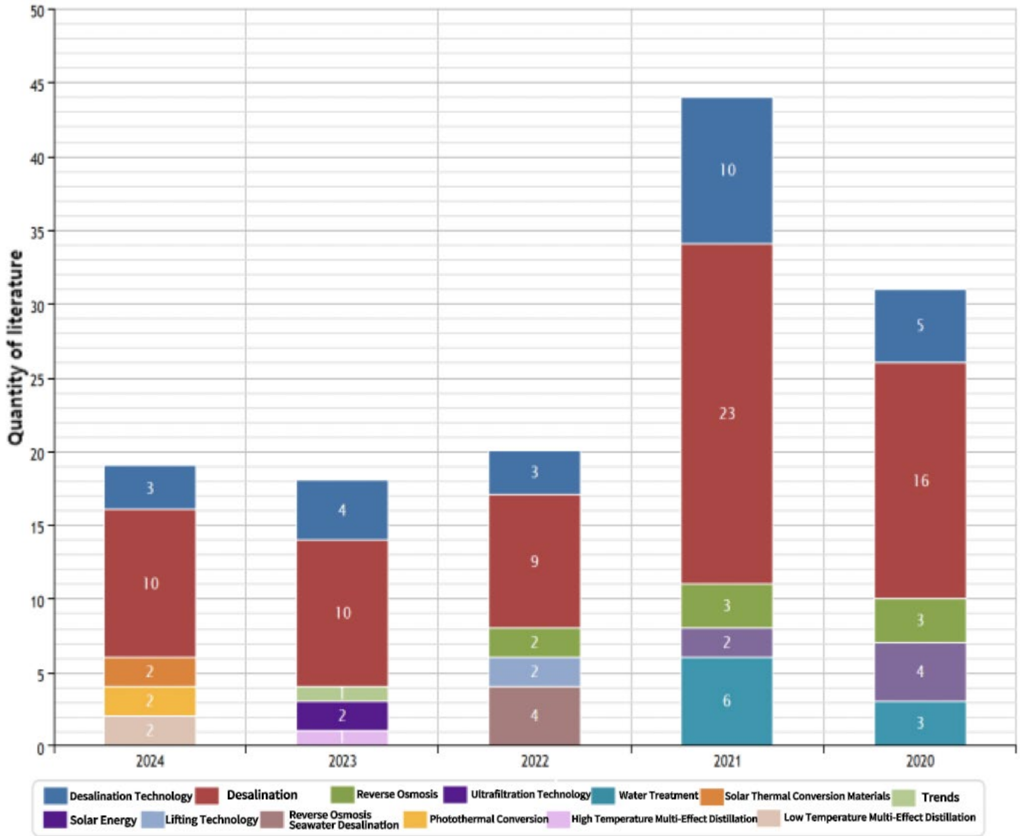

Figure 1 Analysis of research topics related to seawater desalination.

2.2. Membrane Distillation Technology

Membrane distillation technology is a newly developed liquid separation technique that couples membrane separation with the principle of distillation. However, the working mechanism of this technology is mainly supported by the principles of mass transfer and heat transfer.

1) Working mechanism: In the membrane distillation process, the hot feed solution vapor produced heats up and diffuses through the membrane pores due to the gradients of either concentration or pressure. Only water vapor can permeate through the membrane while impurities like salts and organics are withheld by it. Condensation on the cold side results in the solution's purification.

2) Mass transfer and heat transfer processes: In the case of mass and heat transfer, membrane distillation is a process in which water vapor diffuses through membrane pores, where the nature of membrane material, pore structure, solution concentration, temperature, and pressure prevail. The heat transfers between the membrane and feed solution, with condensation on the cold side. Then, condensation heat could be recovered to enhance energy efficiency.

3) The membrane material: The properties of membrane material play a crucial role in MD technology, mainly by its process performance. The common materials used are PTFE, PP, PE, and ceramics, all possessing different properties such as chemical and thermal stability, mechanical strength, and wetting characteristics. PTFE is one of the most chemically stable materials and hydrophobic; therefore, it is widely used in desalination and wastewater applications. Ceramic membranes show outstanding performance in extreme conditions due to their stability at high temperatures and strength.

4) Various technologies in the membrane distillation: Depending on the contact mode of membrane, feed solution, and condensing medium, generally, it is possible to divide membrane distillation technologies into several categories like direct contact, air gap, gas sweep, and vacuum. For the three configurations, increasing inlet temperatures enhances the thermal efficiency, and inlet concentration of the saline solution has no significant effect on process parameters[4].

3. Design of Portable Desalination Device System

3.1. Design of the Pre-treatment Process

This design focuses on enhancing the efficiency of the pretreatment step involved in membrane distillation seawater desalination, ensuring the stability and longevity of the operation through the use of membrane components, particularly hydrophobic membranes, which effectively prevent possible damage or blockage of the membranes by impurities or microorganisms present in seawater. The pretreatment process used in this design consists of a three-stage progressive filtration system, equipped with high-efficiency power equipment for highly efficient and reliable pretreatment. The detailed steps are shown in Figure 2 below.

1) First stage filtration: It makes use of a 5 μ m precision polypropylene (PP) cotton filter element to effectively block the large-sized suspended substances in seawater, such as sand particles and shell fragments. By doing so, it avoids the damage of these particles to the subsequent equipment and membrane components and reduces the possibility of blockage.

2) Second-stage filtration: Inside which was a silver-loaded activated carbon filter element, using its excellent adsorption property, all kinds of harmful gases such as chlorine, hydrogen sulfide, organic compounds, and pigments were removed. Meanwhile, the antibacterial property of silver ions inhibits bacterial growth effectively, reducing the possibility of biological contamination.

3) Three-stage filtration: It uses a high-precision ultrafiltration membrane filter element to intercept the suspended solid, microparticle, colloid, and part of the bacterium larger than 0.01 μ m, to further guarantee the clarity of the water quality entering the membrane distillation system, and delay the fouling of the membrane, and improve the distillation efficiency and service life of the membrane component.

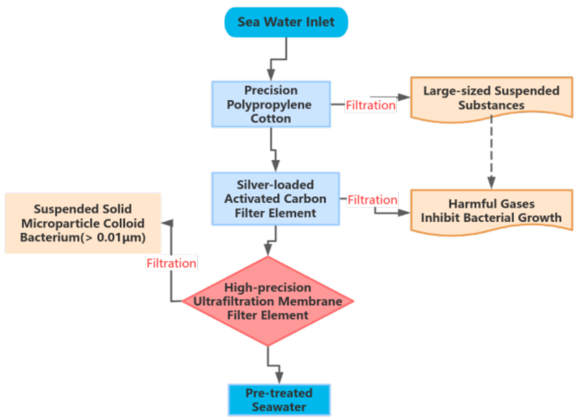

Figure 2 The schematic diagram of three-stage progressive filtration system

A peristaltic pump was selected as the power device to ensure smoothness in the operation process by providing stable water flow. Based on the calculation involving the flow rate of the peristaltic pump, in combination with the physical properties of the activated carbon and specifications of the activated carbon filter, with a diameter of 57mm, the flow rate falls within a range of 153～468 mL/min. This allows for a balance in assurance between processing efficiency and energy consumption.

3.2. Process Design of Water Production

The design uses one variety of segmented membrane distillation technologies AGMD (Air Gap Membrane Distillation) and DCMD (Direct Contact Membrane Distillation). The system also involves a thermal and cold circulation system, which has been carefully designed to raise the effective transference rate across the membrane. Hot seawater is pumped into the heating tank by the peristaltic pump for heating up to optimum temperature before passing into the membrane distillation module for desalination. Condensed freshwater is stored in the water storage tank for later use.

Given the particularity of the offshore rescue environment, it will be equipped with solar panels and batteries as an energy supply. The power of the solar panels and the capacity of the battery will be rationally matched, with detailed energy calculation, to ensure the device can work stably under bad conditions offshore. Meanwhile, precise energy consumption estimates by major components will ensure that the system can cover all its needs with energy.

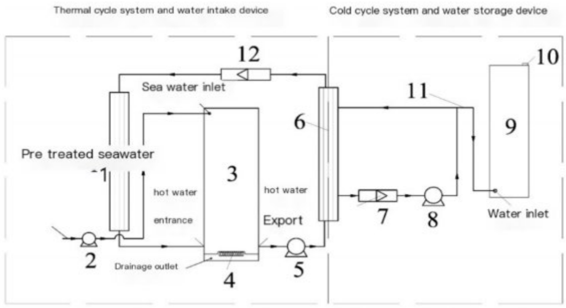

Figure 3 Membrane distillation seawater desalination process flow diagram

Figure 3 illustrates a typical water treatment and distribution system, both thermal and cold cycles, inclusive of integral water intake and storage facilities[5]. A general description of the working principle follows, together with numbered components:

·Water intake and pre-treatment: The first intake of seawater is made through the seawater inlet. The sea water is usually first pre-treated by successive steps of filtration, and in Figure 2, these steps have been labeled in detail.

·High-temperature resistant ultrafiltration unit 1: Seawater after being treated with pretreatment, passes through this unit for finer particle removal and impurities to result in higher quality feed into successive stages.

·Water intake peristaltic pump 2: It presses and gives the flow rate to circulate the pretreated seawater into the system.

·Heating water tank 3: Seawater is passed into this heating water tank to raise the temperature of the water to the desired temperature for membrane distillation.

·Heating element 4: The water in the tank is heated up to the required temperature with the help of a heating element.

·Water and gas dual-purpose pump 5 and hydrophobic membrane element 6: Under the drive of the water and gas dual-purpose pump, hot seawater enters inside the membrane filaments through the water inlet of the hydrophobic membrane element. Water vapor passes through the small pores of the membrane filaments into the cold circulation system where it is condensed into freshwater.

·Thermal cycle: The thermal and cold cycles operate in a joint fashion, and the vapor produced by the thermal cycle undergoes condensation either through the cold cycle or through natural cooling. All the pumps, membrane elements, and flow meters are connected in a way that the water flows in a continuous manner.

·Flowmeter 7: This measures the rate of fluid flow into and out of the membrane distillation unit.

·Water and gas dual-purpose pump 8: The process is AGMD before the freshwater condensation fills the housing of the hydrophobic membrane module. The process of membrane distillation becomes DCMD when the freshwater will fill the housing of the hydrophobic membrane module. The cold circulation system utilizes a dual-purpose water and gas pump for circulating the water and gas within the system.

·Storage tank 9: The distilled water is collected in a storage tank for later use.

·Safety valve 10: Constructed to prevent overpressure of the system, and it protects against uncontrolled operations.

·Overflow pipeline 11: The overflow pipeline acts if water starts collecting too much in the system; it carries away the surplus water safely outside the system.

·Additional flowmeter 12: Additional flowmeter for more measurement capability, probably at some different location in the system.

3.3. Device Structure Design

The device will employ a modular design concept, divided into the pretreatment module, membrane distillation module, energy recovery and control module, etc. Each module is fixed through sturdy brackets and sealed enclosures to prevent displacement and collision during transportation. An integrated propulsion and buoyancy device will be designed for convenient carrying and use on both land and sea. It can be seen in Figure 4. There are four wheels on the right side of the housing for the propulsion device, together with a pull bar at the back end, so that the device is easily movable either on land or aboard ships. The buoyancy device was made from polyvinyl chloride foam plastic mounted at the front and rear end in the housing of the device in order to meet requirements for its floating up to a height of the water surface.

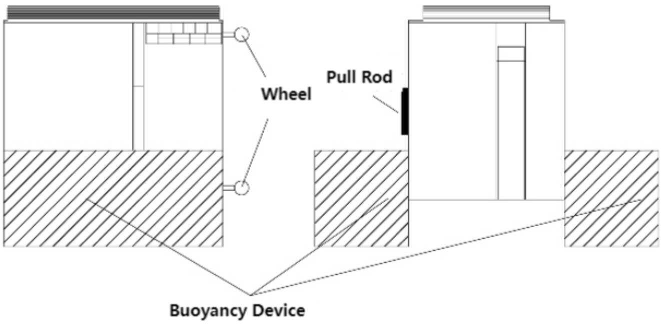

Figure 4 Schematic diagram of the exterior of the device.

Furthermore, the device will also make full use of PLC, sensors and indicators to make the real-time monitoring of the operating process and one-button automatic operation come true by using programmed procedures. When the battery is sufficient and the water production conditions are met, the system starts automatically; when the battery is low or a fault occurs, it immediately sends out an alarm and shuts down.

3.4. Potential Directions for Improvement

Although this portable seawater desalination device system has striven for perfection in its design concept, there is still room for further enhancement. The following are several potential directions for improvement:

1) Improve membrane distillation efficiency: By optimizing membrane materials and structures, such as adopting new membrane materials with higher water permeability and selectivity, or designing more efficient membrane distillation component structures, it is possible to further enhance membrane distillation efficiency and reduce energy consumption.

2) Enhance pretreatment capability: Tailoring the parameters and configuration of the pretreatment process to the characteristics of seawater in specific ocean areas can be achieved by increasing the number of pretreatment stages, selecting more suitable filter materials and filter element precision, in order to more effectively remove impurities and contaminants from seawater, protect the membrane elements, and extend their service life.

3) Optimize energy management: Although this design already employs solar panels and batteries as the energy supply, in practical applications, it may be necessary to optimize the energy management strategy based on specific circumstances. For example, the energy consumption of the heating device and peristaltic pump can be controlled through intelligent algorithms to maximize energy utilization.

4) Increase intelligent functions: By introducing more sensors and intelligent control algorithms, the level of intelligence of the device can be further enhanced. For instance, real-time monitoring of water quality and membrane fouling can be implemented, with automatic adjustment of the parameters for the pretreatment and membrane distillation processes based on the monitoring results. Alternatively, remote monitoring and fault diagnosis functions can be integrated through a remote communication module.

4. Conclusion

The present paper contains research on development history and the current research status in seawater desalination technology for the satisfaction of freshwater needs under emergency conditions, such as maritime rescue and remote areas. During the device design process, many aspects have been taken into consideration, including pretreatment processes, water production processes, and device structure. This would be developed through a three-stage progressive filtration system, segmented membrane distillation technology, and modular design concept that would enhance the desalination efficiency, practicality, and reliability. Besides, it is intended that solar and wind power generation be used as the electrical energy sources for this system to address the environmental friendliness and practicality of the system. Although this research provided direction in the design of portable seawater desalination device systems, further improvements are still possible. Therefore, in the future, I would like to continue further research on membrane distillation technology and constantly seek new material membranes and efficient desalination techniques so that I could make greater contributions to solving the global water shortage problem with wisdom and strength.

Acknowledgements

This paper is the result of great guidance and support. I would like to extend my cordial thanks to my supervisor for his professional guidance and patience in the research of portable seawater desalination, which influenced me a lot. Besides, thanks to those who provided experimental conditions, data, and suggestions for my improvement of device design constantly.

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