System Design of Small-scale Seawater Desalination Device

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Abstract. Water is of great significance to the subsistence and development of human beings. As we all know, fresh water issues have always been a major problem to the ocean navigation, as the existing desalination devices generally have the disadvantages of large volume, high-energy consumption, which would bring pollution to the environment. Basing on the study results in existence, this paper presents a new system design of small-scale seawater desalination device, which founds on the enhanced heat transfer processes of fluid phase change, including loop heat pipe technology, new type of heat-sink type spoiler evaporator and integrated soaking plate fin condenser to implement the low-power and low-temperature system. This system covers an area of only 1.8m², as the energy consumption is 62.5% of the reverse osmosis desalination method and 20% of the multistage distillation desalination method under the same conditions. What’s more, the system consists of the loop heat pipe based on the phase change thermal principle, integrated soaking plate fin condenser and the new type of heat-sink type spoiler evaporator, improves the heat transfer efficiency, besides it has low pollution.

1. Introduction
Plenteous fresh water is the basis and guarantee of the subsistence of human beings. Nowadays, as the explosive growth of the population and improvement of the industrialization level, the demand for water increases day by day. Meanwhile, with the development of the shipping industry, the navigation distance is getting further and further and the operation time is becoming longer and longer, resulted in the
correspondingly increasing demands to fresh water. Generally, it is suggested by statistical analysis that the large ships consume about 200 tons of fresh water per day.

Due to the low economic benefits and low safety of water transportation and storage of ocean-going ships. Seawater desalination becomes an important supplement of the fresh water to these ships. Conventional commercial marine desalination mainly uses reverse osmosis method and distillation method. The reverse osmosis method doesn’t need to provide heat resource, but the cost of operation and maintenance is high. Moreover, it requires high quality of seawater. Besides, the brine contains a large number of chemical agents, and the direct emissions of which can lead to water pollution. The distillation method has low requirements for seawater quality and the produced water is in high quality. Although the initial investment cost is high, the post-maintenance cost is low. For these reasons mentioned above, distillation has become the mainstream marine desalination technology[6]. At present, the research on seawater desalination mainly uses system calculation and small-scale experimental methods to determine the performance of seawater desalination system. And there are few studies on the structure characteristics of the desalination device itself and the designed devices are large in size and insufficient in compactness. In view of the above problems, a new system design of small-scale seawater desalination device is presented, which founds on the enhanced heat transfer processes of fluid phase change, including loop heat pipe technology, new type of heat-sink type spoiler evaporator and integrated soaking plate fin condenser. This system has lots of advantages, such as small in size and high conversion efficiency and so on.

2. System design

2.1. Design ideas
As shown in figure 1, aiming at improving the heat transfer efficiency, this paper innovatively puts forward a small-scale seawater desalination device, including a loop heat pipe that can transfer a large amount of heat over a long distance with a small temperature difference, which adopts a plate design. In order to make the device more simplified and efficient, this paper designs a desalination device including an evaporation system, a condensation system, and a fresh water collection system. The seawater evaporates in the evaporation system and produces vapor, which is then condenses in the condensation system to produce fresh water. And after that the fresh water is collected through the fresh water collection system, and the outflow of the waste liquid is discharged in the feedback system.

![Flow chart of the design](image)

2.2. Integral design
This work mainly consists of evaporation system, condensation system, vacuum maintenance system, circulating sprinkler system, fresh water collection system, including power-supply and control system and a base and limit device are also designed, as shown in Figure 2. This desalination device has the advantages of low energy consumption, low cost, small footprint, energy and environmental protection, and it can be used for vessels and water-deficient islands as well as for certain waterways. Our domestic islands are mainly distributed in the South China Sea, where there exists long illumination time and strong radiation, which is suitable for the development and promotion of solar desalination devices and the application of solar energy is non-polluting and in line with national environmental policy guidelines[7]. The chassis and the limit device can improve the stability of the platform by improving the buoy type desalination device.
3. System introduction

3.1. Evaporation system
The evaporation system is composed of a plate type loop heat pipe[5], a solar heat collecting plate, a hot plate and a heat-sink type spoiler evaporator. The heat collecting systems is formed by the solar collector plate and the electric heating plate, which are distributed on both sides of the plate type loop heat pipe, and the electric heating plate is disposed on the backlight side. The heat source is mainly based on solar heat collection. The electric heating plate provides electric auxiliary heating when necessary. The heat transfer medium in the loop heat pipe is transformed to a heat-sink type spoiler evaporator placed inside the tank to evaporate seawater[3][4].

- Design of plate type loop heat pipe. Utilizing the phase change heat transfer principle, the evaporator absorbs heat during operation, so that the liquid medium inside the capillary core evaporates, and the evaporated gas diffuses through the fine pores on the capillary core and passes through the evaporation loop to the condensation end. The vapor is liquefied by at the condensation end, and the liquefied medium is returned to the capillary core by the capillary force to realize heat transfer. Compared with traditional single-phase heat transfer, two-phase heat transfer can improve the heat transfer efficiency and reduce the heat loss during heat exchange[8][4].

- Design of heat sink type spoiler evaporator. In the evaporation system, the evaporator adopts 15 single-piece heat sinks placed in parallel at intervals of 2cm gap, and the total size is 30cm×30cm×20cm, which is connected in parallel by the main tubes, and finally fixed by the heat sink frame into groups, and the single-chip heat sink is disturbed. The monolithic fins spoiler evaporator is produced by laser welding and bulging technology. The fluid flow path in the evaporator has a U-shaped structure, and small particles are distributed on the U-shaped path to spoil the flow path, so that the inner wall of the evaporator is in full contact with the fluid heat conduction medium, thereby the heat transfer efficiency can be proved. The structure is shown in Figure 3[1][2].
3.2. Design of condensation system

The main part of the condensation system is composed of cold-water inlet, cold water outlet and an integrated uniform temperature plate finned condenser. The flow rate of the cold-water inlet and outlet is controlled by the throttle valve. The integrated uniform temperature plate finned condenser is autonomously processed by aluminium, and is composed of ribs, a uniform temperature plate and a self-made spoiler pipe, as shown in Figure 4.

Vapor chamber is shown in Figure 5. The sintered mesh structure is attached to the inner side of the cavity, and each of the upper and lower layers has a layer spacing of 200μm. The liquid medium at the bottom of the vacuum chamber absorbs the heat from the water vapor to the fin at the bottom of the temperature equalizing plate during operation. The vapor evaporates and diffuses into the vacuum chamber, and transfers the heat to the condensation pipe. The condensed liquid is then refluxed through a sintered web attached to the inner wall of the temperature equalizing plate by capillary force.

*The red arrow in the figure is the vapor medium after evaporation and the blue arrow is the liquid medium after condensation.
The vapor chamber is similar to the heat pipe in principle, but the conduction mode is different. The heat pipe is a bunch of linear heat conduction, and the vapor chamber is conducted on a two-dimensional surface, so it is more power-efficient and energy-efficient.

The spoiler pipeline is composed of the outer wall pipeline, five isolation cross plates and six spoilers. The specific structure is shown in Figure 6. The six isolated horizontal plates are evenly distributed in parallel, and the seven spoilers are interspersed between the isolated horizontal plates to flow around. And the cold seawater inside the spoiler pipe is in full contact with the upper and lower vapor chamber to increase the heat exchange efficiency.

![Figure 6. Sketches of the spoiler pipeline structure.](image)

The design of the fin structure greatly increases the contact area between the condenser and the vapor, which also increases the heat transfer rate. The condensed liquefied vapor adheres to the surface of the fin and then drops to enter the fresh water collecting tank by gravity.

4. Circuits design

This system chiefly uses environmental energy to generate electricity, and then forms a stable charging current through MPPT charger controller to charge the powered lithium ion battery through this current. Aimed to create a ‘reservoir’ of electrical energy, the electrical energy is stored when external sources of energy are sufficient, so that the normal supply of electricity can be realized when external sources of energy are insufficient. After voltage stabilization, the storage battery and the built-in inverter of the conduct current boost and inversion to obtain 220V AC power supply; After the inversion is completed, the circuit is divided into two parts: one part is used for direct power supply of AC electrical apparatus such as high-power centrifugal pump; the other part is for power supply of the DC logic control circuit and DC sensor after rectifying by the switching power supply and step-by-step isolation and voltage stabilization.

The design sketches of the overall circuit model is shown in Figure 7.

![Figure 7. Overall circuit model connection diagram.](image)

Some specific modules are demonstrated as follows:
Figure 8. Sketches of switching power supply

As shown in Figure 8, this is a switching power supply design principle diagram. 220V alternating current provided by the inverter, after reduction voltage by passing transformer and rectification by passing rectifier bridge, will be changed into direct current, then through a capacitor filter, using the LM317 voltage chip, by adjusting the resistance of variable resistor R1, this module can realize the stable and adjustable direct current output, from 0V to 24V.

Figure 9. Sketches of inverter.

As shown in Figure 9, this is the design schematic diagram of the inverter. The 12V direct current provided by the storage battery is changed into square wave through the NE555 chip, and through two complementary triodes, it is changed again into alternating current, under the effect of the booster transformer, 220V alternating current will be output.

5. Theoretical analysis of seawater desalination

Table 5-1. The meanings and values of the constants.

| symbols | meanings                                | values             |
|---------|-----------------------------------------|--------------------|
| m       | quality of a single water molecule      | $3 \times 10^{-26}$kg |
| kB      | Boltzmann constant                      | $1.38 \times 10^{-23}$J/K |
| NA      | Avogadro constant                       | $6.02 \times 10^{23}$ |
| R       | ideal gas constant                      | $8.314$J·mol⁻¹·K⁻¹ |
| S*1 | relative heat exchange area of the evaporation section | 0.327 |
|-----|-----------------------------------------------------|-------|
| S*2 | relative heat exchange area of the condensation section | 0.340 |
| T1  | operating temperature of the evaporation section     | 90℃   |
| T2  | operating temperature of the condensation section     | 15℃   |

Table 5-2. The meanings and values of the symbols in theoretical analysis.

| variable symbol | variable | meaning |
|-----------------|----------|---------|
| [a]             | sea water | evaporates involved in the reaction in a seawater desalination unit |
| [b]             | water vapor | water vapor that involves in the reaction of seawater evaporation in a seawater desalination unit |
| [c]             | fresh water | fresh water produced after condensation |
| [b’]            | other gases | gases that do not involve in the reaction in a seawater desalination unit |
| ya              | water vapor ratio | proportion of water vapor in all gases in seawater desalination plant |
| yb              | other gases ratio | ratio of other gases in seawater desalination plant in all gases |
| x               | solute ratio | ratio of other solutes in evaporation |

The steady process of seawater input, the theoretical process of heat transfer-based kinetics is as follows:

The amount of seawater is maintained at $[A]_0$, that is, $[A] \sim N([A]_0, \sigma)$ is stable, and the analytical process of the dynamic process of the reaction system is solved.

The seawater is continuously input, the quantity remains unchanged, and the series system of the first-order reaction is:

$$\frac{d[A]}{dt} = e$$

$$\frac{d[B]}{dt} = k_1[A] - k_2[B]$$

$$\frac{d[C]}{dt} = k_2[B] + l(t)$$

Suppose the amount of seawater remains unchanged at the level of $[A]_0$, that is, $[A] \sim N([A]_0, \sigma)$, then solve the above equation, here is the result

$$[B] = -\frac{k_1[A]_0}{k_2} e^{-k_2t} + \frac{k_1[A]_0}{k_2}$$
The final differential equation of desalinated water is:

\[
\frac{d[C]}{dt} = -k_1[A]_0 e^{-k_1t} + k_1[A]_0
\]

The time-varying function of desalinated water after solving the equation above is:

\[\begin{align*}
[C] &= \frac{k_1[A]_0}{k_2} e^{-k_2t} + k_1[A]_0 t - \frac{k_1[A]_0}{k_2}
\end{align*}\]

Given the nature of the analytic solution function, it is observed that the total amount of seawater in the device has been stable, the water vapor stabilizes at \(k_1[A]_0/k_2\) over time, and stable yield of fresh water will be realized at \(k_1[A]_0\).

According to (Table 5-2), substitute the parameters into

\[
k = \frac{y_A P N_A}{2R} \sqrt{\frac{2k_B T}{m n}} S^*
\]

the result is \(y_A = 710\) on the basis of (Table 5-2). The reaction rates of the evaporation segment and the condensation segment are as follows:

\[k_1 = 0.274, \quad k_2 = 0.116\]

Given the corresponding reaction rate, substitute them into the kinetic model, the theoretical result is 1.096 l/10 min in terms of stable fresh water yield. Next, the system will be analysed as a whole with the help of the parameters just calculated. Through simulation analysis of the obtained calculation, it is showed that, as demonstrated in Figure 10, the final seawater desalination tends to be stable, indicating that the designed device is stable and reliable.
6. Conclusion
This device could be used on ships or islands with less space occupancy by reducing the volume of seawater desalination device. On this basis, it could be modified into a buoy-like seawater designated device, enabling it to be used on the channel. At the same time, a plate condensing heat exchanger is provided, and the spoiler is inserted between the isolation plates to realize the full contact between the cold seawater inside the spoiler pipeline and the upper and uniform plates, so as to increase the heat exchange efficiency. Based on mathematical analysis of Kinetics model, theoretical analysis and calculation and empirical numerical simulation were carried out by using the ideal gas-wall collision probability formula and Raoult's theorem in physics, and it could be concluded that, the fresh water yield would be stable at 1.096 l/10min.

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