Design and research of the heat collecting system for a seawater desalination device driven by solar energy and wave energy

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Abstract. The seawater desalination device driven by solar energy and wave energy is a new unit designed for solving the global shortage of freshwater with new energy. The solar collecting system of the device was designed and researched in this paper through presenting the model selection and the structural design of the solar collecting system and a theoretical governing equation of the solar collecting system was purposed based on theoretical analysis. Meanwhile, Guangzhou was taken as an example to verify the heat collecting capacity of the system via calculation.

1. Introduction
Seawater desalination is one of the important means to solve the global shortage of freshwater. Seawater desalination refers to the use of distillation and infiltration to obtain freshwater by eliminating the salts in seawater. Traditional seawater desalinating technology is an energy-intensive industry. Under the requests of the energy crisis and sustainable development, seeking the application of seawater desalination devices and technologies using new renewable energy sources is imperative. A seawater desalination device driven by solar energy and wave energy was proposed against the above problems to provide freshwater for isolated islands and offshore platforms. A heating process is adopted in this device to desalinate seawater, that is, heat is collected through the solar energy for evaporating seawater; while the wave energy drives the inflow of seawater and the outflow of freshwater.

2. Model selection of the heat collecting system
Since the heat-pipe evacuated tube features fast starting speed, fast heat transfer, effective heat gain, high efficiency, and easy maintenance, bi-pass collector tubes were adopted in the seawater desalination device driven by solar energy and wave energy designed in this paper (see figure 1 for structure details).

The heat pipe is made of copper. And pure water was selected as the liquid working medium due to its good compatibility with the copper shell, simple purification, low saturated vapor pressure, and large specific heat capacity.
Figure 1. Structural diagram of the heat-pipe evacuated tube (bi-pass).

As the steam flow rate in the heat pipe evaporating section cannot be increased further and would be blocked after reaching a certain level, or even leading to overheating in the evaporating section, or a burnout accident in a serious situation, the liquid level in the case of using water as working medium should be a quarter of the vertical height of the heat pipe in accordance with a quarter of the volume of the heat pipe cavity [1].

3. Working process of the heat collecting system

Figure 2. Structural design of the heat collecting system.

A number of heat-pipe evacuated solar collector tubes in the heat collecting system of the seawater desalination device driven by solar energy and wave energy are installed on the stand in a row at a certain angle (as shown in figure 2). When a lot of sunlight radiates on the heat collecting system, the solar radiation is received by the metal fins that are equipped in the glass tube via the transmission of the glass tube. The temperature of metal fins will be raised after absorbing solar radiation and convert the solar radiation into heat. The heat is firstly transferred to the heat pipe by means of heat conduction so that the liquid working medium in the evaporation section of vacuum heat pipes is rapidly
vaporized through heat absorption under low pressure. Secondly, the generated gaseous working medium rises to the upper outlet of the heat collector. And then, all the working mediums are gathered with a pipe to enter the distiller for heat exchanging. After the heat exchange, the temperature of the working mediums is changed from the gaseous working mediums to the liquid working mediums and flow back to the bottom of the heat collector through the pipe to prepare for the next circulation. In this way, the liquid-vapor-liquid circulating process is repeated constantly over all the liquid working mediums in the heat pipe of the heat collecting system, so as to quickly and efficiently output the absorbed solar energy to the liquid to be heated [2-4].

4. Performance analysis of the heat collecting system

4.1. Modeling of the heat collecting system

Based on the diagram of energy flow of the collector tube shown in figure 3:

![Diagram of the energy flow driven by solar energy.](image)

Notes: $Q_{pg}$ is the radiation heat exchanging between the absorbent plate and the glass tube; $Q_s$ is the heat absorbed by the absorbent plate; $Q_{ga1}$ is the radiation heat exchanging between the glass tube and the environment; $Q_{ga2}$ is the heat convection between the glass tube and the environment; $Q_{cf}$ is the heat convection between the condensation section of the collector tube and the fluid; $Q_{hp}$ is the heat exchanging between the evaporation section and the condensation section of the collector tube; $Q_u$ is energy obtained by the heated fluid; $Q_{fa}$ is the heat convection between the heated fluid and the environment.

**Figure 3.** Diagram of the energy flow driven by solar energy.

According to the energy flow model in figure 3, the relation of energy balance can be established as follows:

Glass tube:

$$Q_{pg} = Q_{ga1} + Q_{ga2}$$

(1)

Absorbent plate:

$$Q_s = Q_{pg} + Q_{hp}$$

(2)

Fluid (liquid working medium):

$$Q_{hp} = Q_{cf} + Q_u + Q_{fa}$$

(3)
Heat loss:

\[ Q_{\text{loss}} = Q_{pg} + Q_{fa} \]  \hspace{1cm} (4)

4.1.1. Basic assumptions. In the heat collecting process of the collector tube, the absorbent plates, and the heat pipes are bound to lose energy in various ways. In order to avoid the effect from certain secondary factors in the analyzing process of heat transmission for better research, the following assumptions are made:

- Thermal resistances including the thermal resistance induced by the pressure drop when the steam flows in the heat pipes, the contact thermal resistance between the absorbent plate and the thermal evaporation section, and the conductive heat resistance of the glass tube and the selective absorbing coating are neglected;
- Air convection and loss of conductive heat in the evacuated collector tubes, as well as the glass tube's absorption of solar radiation, are neglected.
- The non-uniformity of the axial temperature in each section of the metal heat pipe is neglected, that is, the temperature of each part of the evaporation section and the condensation section is consistent;
- Steam temperatures of working mediums of the heat pipe are consistent;

4.1.2. Governing equations. According to the law of conservation of energy, the useful energy output by the evacuated collector tubes per unit time = solar radiation energy absorbed by the collector tubes - the collector tube's energy lost to the surroundings, namely:

\[ Q_u = Q_s - Q_{loss} = (\tau \alpha)_{e} A_p I - U_L A_p (T_p - T_a) \]  \hspace{1cm} (5)

In equation, \( A_p \) is the area of the absorbent plate, m\(^2\); \( (\tau \alpha)_{e} \) is the product of the effective transmission and the absorptivity; \( I \) is the average solar irradiance (W/m\(^2\)); \( U_L \) is the total heat loss coefficient (W/m\(^2\)·°C); \( T_p \) is the average temperature of the absorbent plate (°C); \( T_a \) is the environment temperature (°C).

The thermal loss coefficient \( U_t \) is an important thermal performance index for describing the thermal insulation property of the collector tubes. The coefficient \( U_L \) of the overall heat loss and the heat loss coefficient \( U_t \) of the collector tubes are approximately equivalent.

The heat loss coefficient \( U_t \) of the heat-pipe evacuated collector tubes can be expressed as:

\[ U_L = U_t = (\frac{1}{h_{pg}} + \frac{1}{h_{ga}})^{-1} \]  \hspace{1cm} (6)

In equation, \( h_{pg} \) is the heat transfer coefficient between the absorbent plate and the glass tube (W/m\(^2\)·°C); \( h_{ga} \) is the heat transfer coefficient between the glass tube and the surrounding environment (W/m\(^2\)·°C).

According to the principle of radiation heat transfer, it can obtain:
\[ Q_{pg} = \frac{2A_p \sigma (T_p^4 - T_g^4)}{1 + \frac{2A_p}{A_g} \left( \frac{1}{\varepsilon_g} - 1 \right)} \]  \hspace{1cm} (7)

\[ Q_{pg} \] is expressed by \( T_p - T_g \):

\[ Q_{pg} = h_{pg} A_p (T_p - T_g) \]  \hspace{1cm} (8)

According to simultaneous equations, \textit{错误!未找到引用源。} and \textit{错误!未找到引用源。}, it can obtain:

\[ h_{pg} = \frac{2\sigma (T_p + T_g)(T_p^2 + T_g^2)}{1 + \frac{2A_p}{A_g} \left( \frac{1}{\varepsilon_g} - 1 \right)} \]  \hspace{1cm} (9)

The heat loss coefficient can be also expressed as:

\[ U_t (T_p - T_a) = h_{pg} (T_p - T_g) \]  \hspace{1cm} (10)

where \( \sigma \) is the Stephen-Boltzmann constant (W/m\(^2\)·K\(^4\)); \( T_g \) is the temperature of the glass tube (°C); \( A_g \) - the surface area of the glass tube (m\(^2\)); \( \varepsilon_p \) - the emissivity of the absorbent plate; \( \varepsilon_g \) - the emissivity of the glass tube.

The heat loss coefficient \( U_t \) of the evacuated collector tubes, that is, the overall heat loss coefficient \( U_L \) of the collector tubes, can be calculated with the simultaneous equations \textit{错误!未找到引用源。}, \textit{错误!未找到引用源。}, and \textit{错误!未找到引用源。}. (To be specific, \( h_{ga} \) can find empirical data from the manual, \( A_g \), \( A_p \), \( \varepsilon_p \) and \( \varepsilon_g \) are known, only \( T_g \), \( h_{pg} \) and \( U_t \) are unknown when the specific values of \( T_a \) and \( T_p \) are set).

4.2. Calculating example

Taking the finned evacuated collector tubes with heat pipes used in this design as an example, the thermosyphon copper-water gravity heat pipe is used as a heat transfer component with a liquid filling rate of 25% and an operating temperature ranging from 30°C to 250°C. Materials used for the glass tube is borosilicate glass (\( \delta=2.0 \) mm); the selective absorbing coating is a molybdenum alumina selective absorbing coating, while glass metals are welded and clamped with a vacuum degree remaining less than \( 5 \times 10^{-3} \).

The glass tube is 1900 mm in length, 100 mm in outer diameter, 0.88 in emissivity, and 0.92 in transmittance. The finned absorbent plate is 1800 mm in length, and 95 mm in width; the coating is 0.07 in emissivity, and 0.93 in absorption rate.

For instance, the average temperature in Guangzhou is about 22°C. The average temperature and the ambient temperature of the absorbent plate are set as 100°C and 22°C respectively in the calculation, while the heat transfer coefficient of the glass tube and the environment is 10 W/m\(^2\)·°C. \( h_{ga} \) is 31.4 W/m\(^2\)·°C after conversion [5].

Substituted into the equations, \textit{错误!未找到引用源。}, \textit{错误!未找到引用源。}, and \textit{错误!未找到引用源。} with the Matlab software to simultaneously solve:
These above are substituted into the equation to obtain:

\[ Q_u = 149.93\text{W} \]
\[ Q_s = 169.93\text{W} \]

The heat collecting efficiency of the heat collecting system:

\[ \eta = \frac{Q_u}{Q_s} = 0.88 = 88\% \]

In that case, the energy absorbed by a collector tube per day and the useful energy output by a collector tube per day are:

\[ Q_{s-day} = Q_s \cdot h \] (11)
\[ Q_{u-day} = Q_u \cdot h \] (12)

Calculating by 12 hours a day, then \( h = 12 \times 60 \times 60 = 4320 \text{s} \), \( h \) and \( Q_u \) are substituted into the equations and and :

\[ Q_{s-day} = Q_s \cdot h = 169.93 \times 43200 = 7341\text{KJ} \] (13)
\[ Q_{u-day} = Q_u \cdot h = 149.93 \times 43200 = 6477\text{KJ} \] (14)

Specifically, the liquid working medium in each collector tube can obtain 6477 KJ per day. As the heat collecting system made by the laboratory is comprised of 6 collector tubes, the energy obtained from the liquid working medium in the heat collecting system per day is:

\[ Q_{total} = 6 \times Q_{u-day} = 6 \times 6477 = 38862\text{KJ} \] (15)

Assuming that the initial temperature of the liquid working medium is 25°C, the mass of working medium that can be vaporized theoretically by the heat collecting device per day is:

\[ m_{water} = \frac{Q_{total}}{C_{water}(T_{final} - T_{initial})} \] (16)

Where \( C_{water} \) - the specific heat capacity of water (J/ kg·°C); \( T_{final} \) - the temperature (°C) when water vaporizes.

Solve:

\[ m_{water} = 123.78\text{kg} \]
5. Conclusion
This paper designed and researched the heat collecting system of the seawater desalination device driven by solar energy and wave energy. Heat-pipe evacuated collector tubes are used as heat collectors in the heat collecting system with the liquid working medium being pure water. And the angle iron as a bracket is arranged in a row in parallel at a certain inclination angle and direction. Governing equations of the heat collecting system were obtained from the theoretical analysis. Based on the case study of Guangzhou, the ultimate daily heat absorption of the collecting system of the device was calculated as 38862 KJ, increasing the temperature of the working medium totaling 123.78 KG from 25°C to 100°C.

References
[1] Zhou X B, Jiang F L and Sun W 2001 Heat pipe vacuum solar collector and its application *Sol. Energy* 16 52-8
[2] Ding X, Lin W X and Xu J 2011 The research and applications of heat-pipe-type evacuated tubes and solar collectors *J. Yn Norm. Univ. (Nat. Sci. Ed.)* 4 41-9
[3] Huang X Y, Wang J, Wang J P, Wang J and Zhang Y M 2016 Research on thermal performance of a finned heat-pipe evacuated tube collector *Acta Energiae Solaris Sinica* 9 2298-305
[4] He Z N, Jiang F L, Ge H C and Li W 1994 Study on thermal performances of heat pipe evacuated tubular collectors *Acta Energiae Solaris Sinica* 1 73-82
[5] He Q B, Wang S F, Xu Y S and Cao J 2013 Characteristic analysis and modeling of solar radiation in Guangzhou *J.Sd Polytech.* 1 5-8