Performance analysis of evaporation-freezing desalination system by humidity differences

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HIGHLIGHTS

• A new frozen desalination by humidity difference is proposed in this study.
• A mathematical model of the desalination method was proposed.
• An experiment system was built up to further verify the feasibility of the method.
• Effects of humidity difference and airflow rate on water production were analyzed.
• Humidity difference and airflow rate were the key factors for water production.

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ABSTRACT

Facing severer global shortage of fresh water and finite energy resource, it is of paramount importance to develop the new energy-efficient desalination methods to solve those problems. A new freezing seawater desalination is proposed in this study that sea water can be frozen driven by humidity difference (humidity difference denotes absolute humidity difference) between air and liquid surface in a 0 °C environment, which utilizes latent heat of vaporization to freeze seawater and thereafter produces fresh water. Based on heat and mass balance equations, the theoretical model of this desalination process was built and it was verified through experimental results obtained from our experimental unit. The effects of humidity difference and airflow rate on fresh water production were studied and they were confirmed to be the key factors for the water production of evaporation-freezing desalination. The theoretical data was consistent with experimental data, and the water production characteristic of this desalination approach was well illustrated by the theoretical model. The results in this research would be in favor of further studies and engineering applications for the evaporation-freezing desalination driven by humidity difference.

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1. Introduction

Shortage of fresh water has become a global concern, and several solutions have been developed to alleviate this issue including invoking water from other water enriched places, enhancing underground water exploitation and reinforcing administration of water source. Comparing with the former methods, seawater desalination would be the most promising approach and could ultimately solve the problem. Currently, there are many seawater desalination methods around the world, such as distillation and reverse osmosis. The latter methods have disadvantages of prohibitive processing cost. Freezing method is quite energy-efficient with the minimal theoretical energy requirement that energy consumption is 1/7 of distillation in the same conditions [1,2], and it has less corrosion to equipment and fewer requirements for seawater pretreatment in contrast with reverse osmosis. Hereby, a new freezing method is presented in this paper. Zero temperature of dry and cold air sweeps sea water surface. Under the humidity difference between air and liquid surface, part of liquid evaporates and absorbs large quantity of heat (latent heat of vaporization is 2501 kJ/kg), then the liquid left which is not evaporated loses heat and it is frozen (latent heat of solidification is 334 kJ/kg). The quantity of latent heat of solidification is about 1/7 of the latent heat of vaporization in the same condition. After that the ice is melted to obtain the fresh water.

Many researches about freezing desalination have been carried out, which included the heat transfer during freezing process, ice crystal formation, the freezing factors etc. in order to increase the water
was analyzed by Ding [7]. Makut [8,9] established a one-dimensional restraining frost of surface and fractal dimension of surface structure, the correlation between petition phenomenon of ice interface. For the frosting process of mined that the degree of super cooling was the driving factor for com- liquid freezing process, and subsequently analyzed as well as deter-
supercooled liquid. Yuan [6] observed the interface of ice crystals during by experiment. A membrane was used by Okawa [5] to freeze production. John et al. [3] employed magnetic resonance imaging (MRI) to visualize ice formation in water-saturated packed beds. William [4] analyzed the interfacial free energy of ice/water and obtained the interfacial free energy value of 31.7 ± 2.7 ergs/cm² at the ice–water interface by experiment. A membrane was used by Okawa [5] to freeze supercooled liquid. Yuan [6] observed the interface of ice crystals during liquid freezing process, and subsequently analyzed as well as determined that the degree of super cooling was the driving factor for com-
petition phenomenon of ice interface. For the frosting process of surface with nano hydrophobic structure, the correlation between restraining frost of surface and fractal dimension of surface structure was analyzed by Ding [7]. Maykut [8,9] established a one-dimensional thermodynamic model of sea ice variation, and analyzed the relationship between ice growth rate and salinity of solution, which provided a theoretical fundamental to forecast the disaster of sea ice. A description of micro-structural types of ice was given by David [10], and the relationship between the micro-structural of sea ice and fresh water was examined. In the report of Ahmed et al. [11], they proposed a new freezing desalination system utilizing heat pump and analyzed its thermal performance. It was shown that this system had lower cost than other desalination methods. Dickey [12] analyzed the relationship between pressure and evaporation rate for a freezing NaCl solution and found that the size of condenser could be estimated by the vapor pressure. An experiment has been conducted by Mandri [13] to study the effect of ice concentration, sweating temperature and sweating time on the ice formation. Rich [14] analyzed the formation of ice layer in a static crystallizer. Beier [15] studied the ice purification by sweating of ice layers in a cold circumstance and found that removal of salt from the ice layer was possible. Wijeysundera [16] analyzed an ice slurry generation system by direct contact, in which gas ejector was easy to be plugged. Thongwik [17] studied the heat transfer characteristic during ice formation, in which carbon dioxide temperature was from −15 °C to −60 °C and water temperature was 28 °C.

However, the constitutive relationship between frozen driving factors and ice development, especially the relationship between ice evolu-
humid difference, was not investigated in the previous studies. Moreover, the problem of how liquid relies on its own evaporation-
freezing power to freeze itself by the humidity difference has not been solved yet. Therefore, in this paper, based on the heat and mass balance, an evaporation-freezing desalination model driven by humidity difference was proposed. After that, the experimental system was built up to further verify the feasibility of the method. The consistency of theo-
retical model and experimental results was also examined in this study.

2. Physical model and experimental device

2.1. Physics process of liquid evaporation-freezing

In a 0 °C condition, zero temperature of dry and cold air sweeps the sea water surface. Driven by the humidity difference between air and
liquid surface, partial liquid evaporates and absorbs much larger amount of heat, and the un-evaporated part of liquid loses heat and is frozen. The physical model of this process is shown in Fig. 1. The bottom of the evaporation-freezing chamber is filled with liquid at 0 °C which is adiabatic with the surrounding environment, and the airflow channel locates on top of the evaporation-freezing chamber in which the dry and cold air (low absolute humidity) flows into the evaporation-freezing chamber from the right side and the air flows out from left side. The mass transfer takes place in the evaporation-freezing chamber since there is humidity difference between dry airflow and the liquid surface. The humidity of dry airflow increases so as to induce the evaporation of liquid. The evaporated liquid takes away large amount of heat during the evaporation process, and then leads to the freezing of the left un-evaporated liquid.

2.2. Experimental device and instrumentation

The experiment system of evaporation-freezing desalination is shown in Fig. 2. The system is mainly composed of a constant temperature tank (1), an evaporation-freezing chamber (2), two axial fans (3), a low temperature dehumidifier (4), a set of refrigerating system (5), a computer control system (6), one temperature transmitter (7) and one humidity transmitter (8). The evaporation-freezing chamber (2) is embedded in the constant temperature tank (1). The constant temperature tank (1) is filled with saline water to provide a low-temperature environment at 0 °C and its cooling load is provided by the refrigerating system (5) which can be adjusted by the computer control system (6) through the temperature transmitter (7). The low temperature dehumidifier (4) which is a rotary dehumidifier can dehumidify the airflow in the 0 °C. The axial fans (3) induce air flow in the closed airflow channel. Then the wet airflow is subsequently dehumidified. After that, the air passes through the constant temperature tank (1) from the bottom and is cooled down to 0 °C again. At this point, the airflow cycle is completed and the evaporation-freezing process of liquid is realized. The photo of experiment unit is shown in the Fig. 3.

The thermodynamic state evolution of airflow on the psychrometric chart is shown in Fig. 4. Point A denotes the inlet state of airflow which is 0 °C with low humidity, point B denotes the outlet state of airflow which is 0 °C with high humidity, and point C means the thermodynamic state of airflow disposed by low temperature dehumidifier. For process A → B, the airflow is undergoing a humidifying process in the evaporation-freezing chamber and it is an isothermal process under 0 °C. For process B → C, the wet airflow is dehumidified by the low temperature dehumidifier which is a dehumidifying and enthalpy rising process. For process C → A, the dehumidified airflow is cooled down to 0 °C by the refrigerating system with the constant humidity. Thereafter, the airflow cycle is completed and presented as an enclosed cycle shown in Fig. 4, which is composed of the A → B → C → A.

All the important variables were measured and recorded during the experiment, which included temperature, humidity and flow rate of airflow. The main parameters of instrumentations are shown in Table 1.
The airflow humidity and temperature at the inlet and outlet of the evaporation-freezing chamber were measured by humidity and temperature transmitters. The airflow rate in the airflow channel was determined by an ultrasonic flow meter. The air velocity in the evaporation-freezing chamber was measured by a hot-wire air velocity transmitter. All the instrumentations were calibrated in advance to determine their probing sensibilities, and they were connected to the computer with data acquisition system (Datataker 800).

### 3. Mathematical model and solution

#### 3.1. Mathematical model

#### 3.1.1. Airflow side state equation

When airflow sweeps liquid surface, its flow state equation is shown as follows: As flow is turbulent, the velocity of airflow in the evaporation-freezing chamber is

\[
\dot{u} = U \cdot \left(1 - \frac{r}{R}\right)^n
\]

where, \( R \) is equivalent radius and \( R = \frac{BL}{4(B-L)} \) in which \( B \) and \( L \) are the cross section width and height of evaporation-freezing chamber respectively; the relationship between \( n \) and \( R \) is

\[
\begin{align*}
4 \times 10^4 < \text{Re} < 1.1 \times 10^5 & \quad n = \frac{1}{5} \\
1.1 \times 10^5 < \text{Re} < 3.2 \times 10^6 & \quad n = \frac{1}{7} \\
\text{Re} > 3.2 \times 10^6 & \quad n = \frac{1}{10}
\end{align*}
\]

As the flow is laminar, the velocity of airflow in the evaporation-freezing chamber is

\[
\dot{u} = U \cdot \left[\frac{3r}{2\delta} - \frac{1}{2}\left(\frac{r}{\delta}\right)^3\right]
\]

where, \( \delta \) is the boundary layer thickness represented as \( \delta = 4.64 \sqrt{\frac{\nu}{\nu}} \), which is adopted from the literature [18].

In formula (1) and (2), \( r \) is distance from the air–liquid interface to the center of airflow channel.

#### 3.1.2. Mass transfer between air and liquid surface

For the evaporation-freezing physics model in Fig. 1, when the airflow sweeps the liquid surface, mass diffusion along the \( x \)-direction is ignored in the process. Therefore, the mass transfer equation between the air and liquid surface is

\[
\frac{\partial C}{\partial \tau} = D \left(\frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)
\]

(3)

In this formula, \( D \) is mass diffusion coefficient \((m^2/s)\).

The mass transfer process could be divided into \( N \) units along the \( z \)-direction of airflow. In each unit body, mass transfer meets the one-dimension unsteady diffusion, which is

\[
\frac{\partial C_N}{\partial \tau_N} = D \frac{\partial^2 C_N}{\partial y^2}
\]

(4)

The initial condition is

\[
\tau = 0, \quad 0 \leq y \leq \infty; \quad C = C_{Nf}
\]

(5)

The boundary condition is

\[
\begin{align*}
\tau > 0, \quad y = 0; & \quad C = C_w \quad (6a) \\
\tau > 0, \quad y \to \infty; & \quad C = C_{Nf} \quad (6b)
\end{align*}
\]

In formula (6), subscript \( Nf \) represents airflow mainstream concentration of the \( N \)th unit body; and subscript \( w \) represents concentration at the air–liquid interface of the \( N \)th unit body.

Along the airflow flow \( z \)-direction of airflow, the relationship between the \( i \)th unit body and the adjacent \( i-1 \)th unit is

\[
C_{Ni} = C_{(N-1)i}, \quad C_{Nf} = \left(\frac{C_w + C_{wi}}{2}\right)
\]

(7)

In formula (7), subscript \( Ni \) represents the input parameter of the \( N \)th unit body; and subscript \( No \) represents the output parameter of the \( N \)th unit body.

### Table 1

Technical specification of instrumentations & devices used in the experiment system.

<table>
<thead>
<tr>
<th>Instrumentation/Type</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-wire air velocity transmitter/CTV200</td>
<td>0–20 m/s</td>
<td>±3.0%</td>
</tr>
<tr>
<td>Humidity transmitter/TH200</td>
<td>0–100% RH</td>
<td>±1.5% RH</td>
</tr>
<tr>
<td>Temperature transmitter/TH200</td>
<td>−40 °C–180 °C</td>
<td>±0.2 °C (PT100)</td>
</tr>
<tr>
<td>Ultrasonic flowmeter/SIEMENS 7ME3510</td>
<td>0–10,000 m³/h</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Refrigerating system/Copeland 10HP</td>
<td>Temperature of −15 °C–0 °C refrigerating capacity of 7.5 kW</td>
<td></td>
</tr>
<tr>
<td>Low temperature dehumidifier/DH-500PE</td>
<td>Regeneration air volume of 0–150 m³/h temperature of −20 °C–70 °C</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2

Parameters of the air entering and exiting the evaporation-freezing chamber.

<table>
<thead>
<tr>
<th></th>
<th>Relative humidity of airflow (%)</th>
<th>Partial vapor pressure (Pa)</th>
<th>Absolute humidity of airflow (g/(kg dry air))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet of freezing chamber</td>
<td>A. 71.9</td>
<td>A. 443.9</td>
<td>A. 2.73</td>
</tr>
<tr>
<td></td>
<td>B. 45.7</td>
<td>B. 282.3</td>
<td>B. 1.73</td>
</tr>
<tr>
<td></td>
<td>C. 19.4</td>
<td>C. 120.0</td>
<td>C. 0.73</td>
</tr>
<tr>
<td>Outlet of freezing chamber</td>
<td>98.5</td>
<td>605.2</td>
<td>3.73</td>
</tr>
</tbody>
</table>

A, B, and C are three different inlet air states in this study.
In the analysis, $C_i$ is deemed as the humid air concentration. The concentration at the air–liquid interface $C_w$ is regarded as the concentration of the saturated moist air in a $0\ ^\circ\ C$ condition.

Humid air concentration $\rho$ can be derived by

$$\rho = 1 + 0.001d \quad \text{(8)}$$

where, $d$ is absolute humidity (g/(kg dry air)), and $v$ is humid air volume (m$^3$). $d$ and $v$ can be obtained by formula (9) and (10).

$$d = 622 \frac{\phi \cdot p_s}{p - \phi \cdot p_s} \quad \text{(9)}$$

where, $\phi$ is relative humidity, $p$ is ambient pressure (Pa) and $p_s$ is the pressure of saturated moist air.

$$v = \frac{R_g \cdot T}{p} (1 + 0.001606 \cdot d) \quad \text{(10)}$$

where, $R_g$ is gas constant with a value of 287 J/(kg·K), and $T$ is temperature (K).

In this study, the relative humidity, the partial vapor pressure and the absolute humidity of the air entering and exiting the evaporation-freezing chamber are shown in Table 2.

3.1.3. Thermal equilibrium at air–liquid interface

Without considering heat loss of the process, for the $N$th unit body, $M_{NA}$ is the evaporation quantity of the liquid (kg) driven by humidity difference, $H_A$ is the latent heat of vaporization (kJ·kg$^{-1}$), solidification heat of liquid is $L_N$ (kJ·kg$^{-1}$), and $I_N$ (kg) means amount of ice. Based on the principle of heat balance, energy equation can be shown as

$$q_N = I_N \cdot L_A = M_{NA} \cdot H_A \quad \text{(11)}$$

3.2. Solving method

According to one-dimension unsteady diffusion theory in the unit body and after integral transformation, mass transfer equation is

$$C_w - C(y, \tau) = \text{erf} \left( \frac{y}{2 \sqrt{D \tau}} \right) \quad \text{(12)}$$

In formula (12), erf is the Gaussian error function which is $\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du$.

Derivation from formula (12) is determined by the Fick law,

$$m_N|_{x=0} = -D \left( \frac{\partial C}{\partial x} \right)_{x=0} = \sqrt{\frac{D}{\pi \tau}} \cdot (C_w - C_N) \quad \text{(13)}$$
In the time period $\tau$, the amount of mass transfer in the unit body is

$$m_N = \frac{1}{\tau} \int_0^\tau \sqrt{\frac{D}{\pi \tau}} \cdot (C_w - C_{nf}) \, d\tau = 2 \sqrt{\frac{D}{\pi \tau}} \cdot (C_w - C_{nf})$$

In formula (14), mass transfer time for each unit body along the direction of air flow is $\tau = \frac{G}{u}$, $N$ is unit body number, and $G$ is length of the evaporation-freezing chamber.

Integrating formula (14) along the $z$-direction, the entire evaporation amount at the solution interface is

$$M = \int_0^G m_N \, dz = \int_0^G \frac{1}{\tau} \int_0^\tau \sqrt{\frac{D}{\pi \tau}} \cdot (C_w - C_{nf}) \, d\tau \cdot dz = \int_0^G 2 \sqrt{\frac{D}{\pi \tau}} \cdot (C_w - C_{nf}) \cdot dz$$

Based on formula (11) and (15), the amount of ice produced in the process of evaporation-freezing can be obtained, and then we can

(a) evaporation-freezing time $\tau = 3600s$  
(b) evaporation-freezing time $\tau = 6000s$

Fig. 9. Ice distribution at different experiment times.

(a) humidity difference 0.001 kg/(kg dry air) 
(b) humidity difference 0.002 kg/(kg dry air)

(c) humidity difference 0.003 kg/(kg dry air)

Fig. 10. Water production in airflow rate of 0.6 m$^3$/s.
derive the fresh water production rule of the evaporation-freezing desalination.

4. Analysis

4.1. Freezing velocity at different humidity differences and airflow rates

When the dry and cold airflow with the temperature of 0 °C swept the surface of sea water in the 0 °C environment, freezing of sea water was studied. Analysis of seawater freezing velocities at varied humidity differences and airflow rates was important for the research of water production in the evaporation-freezing desalination process.

Figs. 5 and 6 illustrated the variations of freezing velocity at the different humidity differences and airflow rates. When the humidity difference between the air and liquid surface increases from 0.001 kg/(kg dry air) to 0.003 kg/(kg dry air), the variation of freezing velocity at different airflow velocities is shown in Fig. 5. When airflow rate is changed from 0.6 m³/s to 1.2 m³/s, the profile of freezing velocity at increasing humidity difference is shown in Fig. 6. As can be seen from Figs. 5 and 6, seawater freezing velocity is ranged from $1.0 \times 10^{-6}$ kg/s to $5.0 \times 10^{-6}$ kg/s. The freezing velocity is not very fast, because the frozen process of seawater is mainly affected by airflow rate under the constant humidity difference. From Figs. 5 and 6, it is shown that when the airflow rate is small, the velocity of seawater freezing is quite slow. However, seawater freezing velocity can rapidly increase if the airflow velocity reaches the magnitude order of $10^2$.

4.2. Water production at different airflow rate and humidity difference

When the humidity difference between the airflow and the seawater surface is 0.003 kg/(kg dry air), water production at varied airflow rates 0.6 m³/s, 0.9 m³/s and 1.2 m³/s is shown in Fig. 7. The water production of evaporation-freezing desalination increases with the increasing airflow rate when the humidity difference between air and liquid surface is constant in Fig. 7. Under the certain humidity difference, higher airflow rate can strengthen the mass transfer effect between air and liquid surface. Hence, more seawater evaporation results in more ice formation so as to produce more fresh water.

When the airflow rate is 0.9 m³/s, water production at different humidity differences: 0.001 kg/(kg dry air), 0.002 kg/(kg dry air) and 0.003 kg/(kg dry air) is shown in Fig. 8 respectively. Under the certain airflow rate, production of fresh water rapidly increases with the increasing humidity difference. More fresh water can be obtained when the humidity difference is larger. That is because when the airflow rate is unchanged, freezing of seawater is mainly determined by the humidity difference, and larger humidity difference will be in favor of seawater freezing.

4.2.1. Comparison between theoretical results and experimental results

The photo of experiment system was shown in Fig. 2. The size of evaporation-freezing chamber is $0.45 \times 0.30$ m ($G \times B$). During the experiment, the dry and cold airflow velocity was $U = 0.5$ m/s, and
The humidity difference was \( d = 0.002 \text{ kg/(kg dry air)} \). The ice formation was shown in Fig. 9 at different time periods.

Comparisons between theoretical data and experimental data are shown in Figs. 10–12 under different humidity differences and airflow rates. At the same humidity difference and operation time, water production increases with the increasing airflow rate; meanwhile, at the same airflow rate and operation time, water production is larger when the humidity difference is larger. Larger humidity difference and higher airflow rate can produce more fresh water. In this case, more attention should be paid to the two factors, especially in engineering research fields.

It can be seen that theoretical results agree well with the experimental values (Figs. 10–12), which means that the theoretical model can simulate water production of the evaporation-freezing desalination well. In general, the experimental values are lower than the theoretical values due to the neglectation of heat loss in the theory analysis. In the real situation, heat loss inevitably exists even through the outside of the instrumentation is covered with the insulation layer; thereafter the loss of ice cannot be avoided.

![Graphs showing water production vs. operation time under different humidity differences](image)

(c) humidity difference 0.003kg/(kg dry air)

Fig. 12. Water production in airflow rate of 1.2 m\(^3\)/s.

The major conclusions are presented as follows:

1. In the process of evaporation-freezing, the humidity difference between the airflow and liquid surface as well as the airflow rate are the key factors affecting the freezing velocity of liquid. Larger humidity difference and airflow rate can be in favor of seawater freezing.

2. Water production of evaporation-freezing desalination increases with humidity difference and airflow rate increasing. A larger humidity difference provides a better mass transfer effect between the airflow and liquid surfaces so as to increase the water production of evaporation-freezing. For the certain humidity difference, higher airflow rate can be advantageous for the seawater freezing, and thereby, makes the fresh water production increase.

3. The theoretical model can simulate the water production of the desalination process well. It provides a theoretical basis for engineering applications of evaporation-freezing desalination driven by humidity difference.

5. Conclusion

Freezing desalination, with features of energy conservation, environmental friendly and easy operation, has been extensively studied. In this paper, the water production characteristic of evaporation-freezing desalination driven by the humidity difference was analyzed. The water production model of evaporation-freezing desalination process was proposed and examined. Theoretical analysis and experimental verification about water production were also studied.

Air, as a natural refrigerant, has been successfully applied in evaporation-freezing desalination process driven by humidity difference. It may avoid water and environment pollution. Moreover, it takes advantage of evaporation latent heat to freeze seawater, which could reduce energy consumption. Evaporation-freezing desalination driven by humidity difference, as a new desalination method, would have bright prospects for development in the near future.
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