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Study on sea ice desalination technology via centrifuge

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ABSTRACT

Sea ice desalination technology was studied through theoretical analysis, single factor experiments, and industrial tests. Influence factors, such as separation factor, separation time, viscosity, and ambient temperature, were analyzed. The experimental results indicate that desalination decreases exponentially with separation time and increase in separation factor, respectively. In addition, desalination increases with increase in viscosity, and the optimum particle size for sea ice centrifuge desalination is 6 mm. The sea ice desalination system was designed to satisfy the requirement of the process production. Industrial tests about the system were conducted, and the results indicate that the ice crushing, transportation, and desalination could be continuously operated, the sea ice salinity decreases below 1.0, the capacity could reach 5–6 m^3/h and above, and the energy consumption is 11.1–13.3 kJ/kg.

Keywords: Sea ice; Centrifuge; Desalination

1. Introduction

Seventy-one percent of the Earth's surface is covered with water, but freshwater only makes up 3% of all the Earth's water. Nearly 68.7% of the freshwater exists as frozen ice in the Antarctic and Greenland, and the remaining soil moisture or water deep underground is difficult to utilize [1]. Therefore, the shortage of freshwater has become a key limitation to the advancement of society. Many countries have been committed to the exploitation of new resources of freshwater.

To satisfy the demands of freshwater, many countries have been taking great efforts on developing desalination of seawater, especially in the Middle East, for example, Saudi Arabia, Kuwait, and the United Arab Emirates. Desalination of seawater has become an indispensable part of freshwater supply in these areas. Desalination of seawater has become an important approach to resolve global freshwater crisis. Recently, the global desalination production is about 66.4 million m^3/d, and it is expected to reach about 100 million m^3/d by 2015 [2]. In addition, as a branch of desalination, desalination of sea ice has attracted increasing attention in recent years.

Although China is rich of freshwater resource with total amount of 2.8 trillion m^3, China's per capita water resources are only 2,200 m^3, which is 1/4 of the world's average level [3]. Meanwhile, the uneven distribution of water resources is a serious problem in China. For example, in Bohai Rim, precipitation mainly occurs in summer and autumn, and rare in spring and winter, which results in severe lack of water. Every winter, large areas of ice come into being on the sea surface due to the low temperature in this area. The reserves of Bohai sea ice were estimated to

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yield a total freshwater volume of approximately 1.585–7.089 billion m^3 [4]. The salinity of frozen sea ice of Bohai Sea is only 3–8‰, which makes the desalination much easier than seawater. The sea ice after desalination can be used as industrial and agricultural water or used as drinking water after simple treatment.

2. Sea ice formation and desalination mechanism

Ice is monomineralic rocs and cannot coexist with salt. During the crystallization, water excludes impurities automatically to maintain its activity and purity. Because the freezing process of sea ice is very fast, the salt cannot be excluded completely. The formation of sea ice starts with a small part of freshwater, which will freeze into fine ice crystal, ice needle, and ice sheet, then form sea ice blocks after consolidation. During the freezing process, small amount of seawater and other impurities are encapsulated in the cavities to form the so-called "salt cell". Another part of seawater is separated out the space between ice crystals [5–7]. Therefore, instead of fresh ice, sea ice is the mixture of solid ice crystal, brine, air cell, and few solid impurities as shown in Fig. 1. The basic principle of desalination via solid–liquid separation is to remove brine out of sea ice through external force, such as, gravity or centrifuge force.

3. Sea ice desalination via centrifuge

3.1. Desalination via centrifuge

The core principle of desalination of sea ice via solid–liquid separation is to apply a centrifuge force to ice crystals and brine. Brine can resist both viscous force from ice surface and surface tension from salt cell tube, thus be separated from ice crystals eventually.

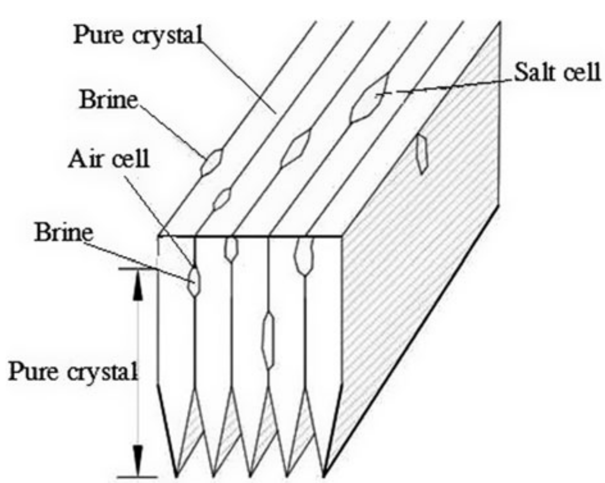

Fig. 1. Microstructure of sea ice.

According to research by the National Marine Environmental Monitoring Center on the desalination technology of Bohai sea ice [8], centrifugal speed is one of the control factors during Bohai gray–white ice desalination; the changes of centrifugal speed have different influences on the removal of main excessive salty materials. However, other factors for ice desalination, such as separation factor, ice particle size, and separation time, were not taken into consideration in the research, which is important to find out the right condition of desalination in the industrial process.

3.2. Theoretical analysis of sea ice

Because the sea ice itself is freshwater ice, and the salinity is mainly contributed by brine, the desalination of sea ice is actually dehydration of sea ice via centrifuge. The dehydration of sea ice is implemented by liquid film flow. In order to improve the quality of desalination, sea ice is diluted by seawater and the dehydration process actually consists of two stages: filtration and liquid film flow. The filtration of sea ice is a short process under centrifuge force due to the relatively large fraction of voids and small resistance. Therefore, the desalination is mainly dependent on the liquid film flow process. The flow process is influenced by separation factor, density, viscosity, surface tension, contact angle, resistance in flow channel, and separation time.

The theoretical equation of desalination of sea ice via centrifuge without phase transition was given in literature [9]. Assuming that the ice surface is flat and the thickness of particle layer is very small compared to the centrifuge radius, the acceleration of liquid film is considered as an constant; no phase transition occurs or phase transition can be neglected in the range of applied temperature; ice is pure and all the salt come from brine on the ice surface. The liquid film flow is shown in Fig. 2 and the thickness of liquid film can be calculated in Eq. (1).

$$\delta(z,t) = \sqrt{\frac{\mu}{\rho g'}\frac{z}{t}} \tag{1}$$

where μ is the liquid film viscosity, z is the thickness of liquid film, ρ is the liquid film density, g' is the acceleration of liquid film. The Eq. (1) was integrated to obtain the Eq. (2).

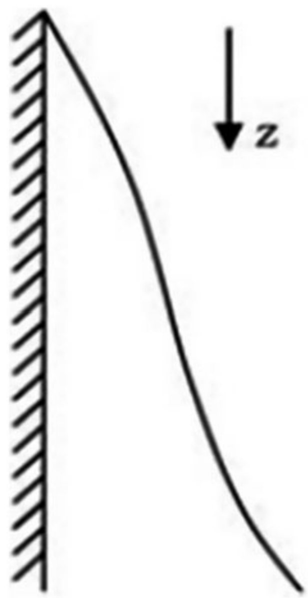

Fig. 2. Liquid film flow.

$$H = \int_0^z \delta(z,t)dZ = \frac{2}{3}\sqrt{\frac{\mu}{\rho g' t}} \cdot z^{\frac{3}{2}} = \frac{2z}{3}\delta(z,t) \quad (2)$$

where H is the mass of liquid film. Suggested the initial thickness of liquid film is δ_o and the initial mass of liquid film $H_o = \delta_o z$. Then, the residual rate of brine can be defined as follows.

$$\eta = \frac{H}{H_o} = k\sqrt{\frac{1}{t}} \quad (3)$$

$$k = \frac{2}{3\delta_o}\sqrt{\frac{\mu z}{\rho g'}} \quad (4)$$

where η is the residual rate of brine, k is the dehydration factor. For sea ice of initial salinity S_o and initial moisture content α, the salinity after dehydration can be defined as follows.

$$S(t) = \frac{H}{H_o}S_o = K\sqrt{\frac{1}{t}} \quad (5)$$

$$K = \frac{2S_o}{3\delta_o}\sqrt{\frac{\mu z}{\rho g'}} = \frac{2S_o}{3\delta_o}\sqrt{\frac{\mu z}{\mathrm{Fr} \cdot \rho g}} \quad (6)$$

where K is the desalination factor, S_o is the initial salinity of sea ice, δ_o is the initial thickness of liquid film, μ is the liquid film viscosity, z is the thickness of liquid film, ρ is the liquid film density, g' is the acceleration speed of liquid film, g is the acceleration of gravity, $\mathrm{Fr} = g'/g$ is the separation factor.

However, the actual operation is not same with the ideal situation. Due to the start-up and shutdown process of the centrifuge machine, the separation factor is below the normal operation value and the theoretical salinity is lower than the practical value. In addition, the liquid film flow is circuitous, the practical flow channel is longer than theoretical flow channel, and the theoretical salinity is lower than the practical value. So, the Eq. (5) can be corrected by a correction factor P as shown in Eq. (7). The Eq. (7) would be fitted in the Section 4.2.

$$S(t) = PK\sqrt{\frac{1}{t}} \quad (7)$$

4. Influence factors for sea ice desalination

According to the theoretical analysis, separation factor and separation time are the two key factors for desalination process. Therefore, experimental analyses are necessary to determine the applicable separation factor and separation time. Meanwhile, other factors, such as ice particle diameter and ambient temperature, are also analyzed to find out the right condition of desalination.

The experiments were conducted in Huanghua, Hebei province. The raw ice was collected from Bohai Bay. The thicknesses of sea ice were approximately 10–15 cm. LS200 centrifuge machine was used in the experiment. The FE 30 conductivity meter was used to measure salinity and the standard uncertainties of salinity were ±0.01‰. The ambient temperature was from −2 to 5℃.

4.1. The effect of separation factors

The definition of separation factor Fr is the ratio between the centrifugal force and gravity applied for the sea ice. Separation factor is the main factor to the effect of solid–liquid separation. About 100 g of sea ice was used each time for different separation factors. Separation factors Fr were set as 500, 700, 900, 1,100, 1,300, and 1,800, respectively, and the standard uncertainties were ±10. The experimental results are illustrated in Fig. 3. As separation factors increase, the salinity of sea ice after centrifuging decreases gradually. After 1 min centrifuging, the salinity can be decreased below 1 at the separation factor of 1,100.

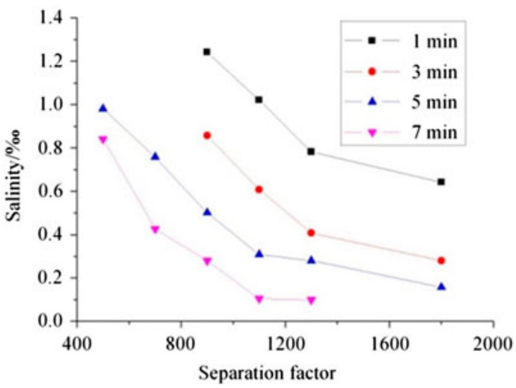

Fig. 3. The relationship of salinity and time for different separation factors.

4.2. The effect of separation time

For investigating the effect of separation time on desalination efficiency, 100 g sea ice was used to study each time with the separation factor of 1,100. Separation times were set as 1, 2, 3, 4, 5, 10, and 15 min, respectively. The experimental results are illustrated in Fig. 4. In addition, Eq. (7) was fitted as shown in Fig. 4 and $P = 82$. The correlation factor of the proposed model reaches 0.9827, which shows that Eq. (7) is suitable for calculating the salinity after centrifuging.

The salinity decreases below 0.3 when separation time reaches 1 min. The salinity of tap water in Tianjin is approximately 0.4, and the required salinity of irrigation water for saline-alkali soil is below 2. Therefore, for the site experiments, the separation time should be controlled within 1 min.

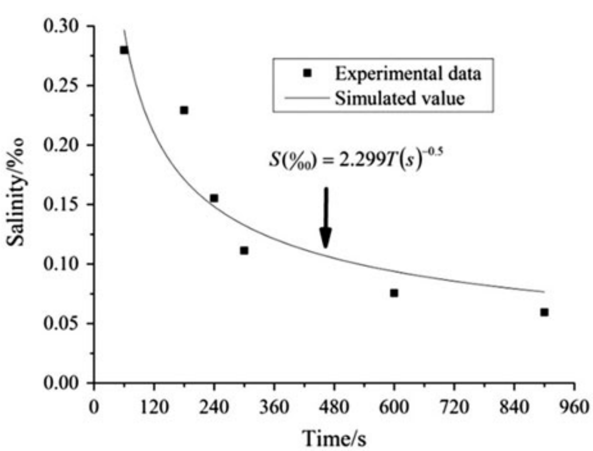

Fig. 4. The relationship between salinity out of ice and separation time.

4.3. The effect of ice particle size

The first step of sea ice desalination is to crush big block of sea ice so that the salt cell inside can be broken and exposed. Incomplete crushing would result in a part of salt cells remaining in the ice particles, which increases the difficulty of desalination via centrifuge.

Drum-type ice crusher was used in the experiments. The crushed ice was divided into 5 categories using a sample sieve: ≤ 3, 3–6, 6–9, 9–12, and 12–15 mm, and the standard uncertainties of particle sizes were ±1 mm. About 100 g of ice was picked from the five categories, respectively, and the salinity was measured before centrifuging; after 1 min centrifuging at separation factor of 1,100, salinity was measured again. The experimental results are shown in Table 1.

As shown in Table 1, the sea ice with particle diameter of less than 3 mm has the highest salinity, and the sea ice with particle diameter of 12–15 mm has the lowest salinity. Salinities decrease with the increase in particle diameters from 0 to 15 mm. It can be easily understood that the smaller ice particle has the larger specific surface area and more brine adhered on the particle surface.

The trends of salinity of ice particles after desalination decrease first and then increase with the increase in diameter. The minimum salinity is obtained on particles of 6–9 mm. The smaller particles possess a larger specific surface area, which result in more difficult separation; the larger particles contain salt cells that cannot be incompletely crushed, which results in a higher salinity after centrifuging. Based on above factors, the optimal diameters for desalination are 6–9 mm.

4.4. The effect of temperature

Site experiments indicated that ambient temperature also had a great effect on desalination. Therefore, the effects of ambient temperature for desalination were investigated. About 100 g of sea ice with particle diameters of 3–6 mm was used in desalination test at −4 and −2℃, respectively, and the standard uncertainties of temperature were ±0.1℃. The results are shown in Fig. 5.

As shown in Fig. 5, temperature has a great effect for desalination process; the salinity of sea ice at −4℃ is much higher than that at −2℃. It is assumed that the temperature of sea ice surface is consistent with air temperature. The low sea ice surface temperature results in a large surface tension and viscosity of brine, which makes the brine itself to be removed difficulty; on the contrary, when temperature of sea ice is high, the brine itself can be removed easily.

Table 1
The salinities before and after separation for different particle sizes

Particle size/mm	≤3	3–6	6–9	9–12	12–15
Salinity before separation/‰	5.892	5.715	5.473	5.407	5.089
Salinity after separation/‰	2.054	1.429	1.203	1.252	1.367

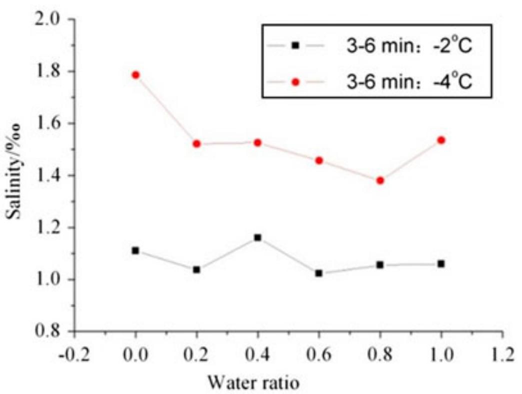

Fig. 5. The effect of temperature for small particles.

In addition, it can be shown in Fig. 5 that the experimental data have fluctuations, it can be explained that the temperature could not be controlled rigorously and the slight temperature fluctuations may result in the change of salinity.

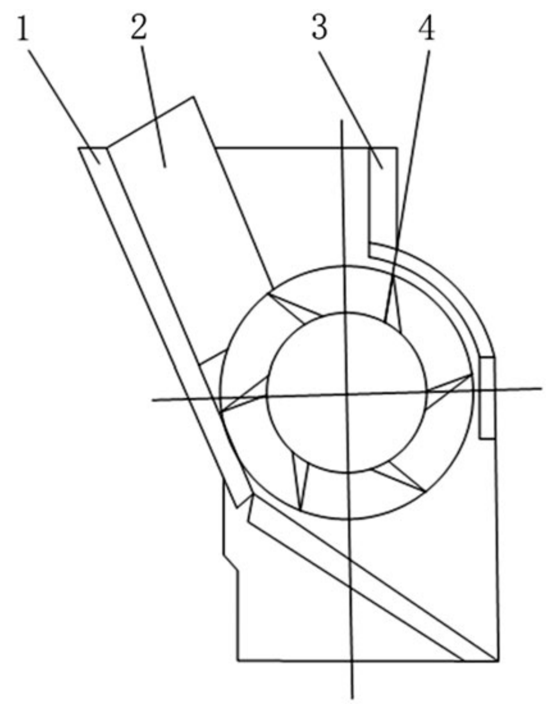

Fig. 6. Structure diagram of drum-type ice crusher (1) feed inlet; (2) ice block; (3) shell; (4) drum.

5. Industrial experiment

5.1. Experimental setup

The experiment was carried out in Wafangdian, Dalian, Liaoning Province. The raw ice was collected from Liaodong Gulf, and the thicknesses were 10–15 cm. The size of ice block was approximately 400 × 350 mm; the temperature was from −2 to −6℃.

In the industrial experiment, the primary goal was to ensure continuous production. In addition, the yield and energy cost were also be taken into consideration. IW-500 horizontal-type centrifuge machine was modified to be used as the core separation equipment. SY-BB-05 drum-type ice crusher and CY hammer crusher were co-used in the experiments to obtain both the quality and yield of ice crushing. The structure diagrams of SY-BB-05 drum-type ice crusher and CY hammer crusher are shown in Figs. 6 and 7, respectively.

Sea ice was collected first by ice collection equipment at the shore and then delivered into the ice crusher through conveyor belt. The raw sea ice was crushed into ice particles by drum-type ice crusher and

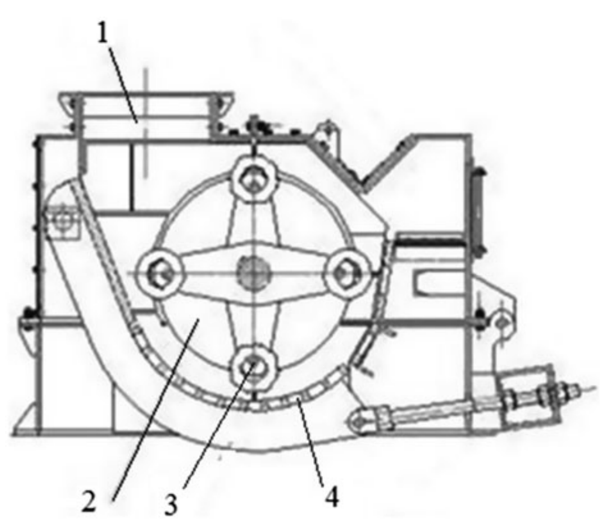

Fig. 7. Structure diagram of hammer crusher (1) feed inlet; (2) rotor; (3) hammer; (4) sieve.

then further crushed by hammer crusher. The obtained ice particles were of appropriate diameter for centrifuging, which would not block the centrifuge machine. After crushing, the ice particles were delivered by conveyor belt into the surge tank, which was connected to centrifuge machine. Then, the ice particles were delivered into the centrifuge machine by a spiral feeding device. Finally, the fresh ice was obtained through centrifuging. The equipment are shown in Fig. 8.

5.2. Morphology of sea ice after separation

The raw sea ice was in irregular shapes, the thicknesses about 10–20 cm. The sea ice after crushing was fine gray-white powders. The sea ice after centrifuging looked like white snow. The comparisons are demonstrated in Fig. 9. The sea ice after desalination can be used as industrial and agricultural water or used as drinking water after simple treatment.

Fig. 8. Continuous desalination equipment (1) production ice; (2) conveyor belt for production ice; (3) centrifuge machine; (4) conveyor belt for ice particles; (5) drum-type ice crusher; (6) hammer crusher; (7) conveyor belt for big block sea ice.

Fig. 9. Comparison of sea ice before and after separation.

Table 2
Salinity before and after centrifuging

No.	1	2	3	4	5	6	7	8
Salinity before centrifuging	2.9	2.5	2.9	2.5	3.5	3.9	3.3	3.9
Salinity after centrifuging	0.7	0.8	0.8	0.6	0.8	0.8	0.7	0.6

6. Results and discussion

The rotation speed of the centrifuge machine was 2000 r/min. The average resident time was 10–20 s. The ice after centrifuging was melted to measure the salinity. No block or freeze was observed during the experiments. The system was stabilized for 15 min; then, the ice was sampled to analyze as shown in Table 2.

According to the calculations, the salinity could decrease below 1.0 after continuous desalination via centrifuging, which could satisfy the requirement of industry water. The capacity of centrifuge machine could reach about 5–6 m^3/h of fresh ice; the total energy cost was 11.1–13.3 kJ/kg and was measured by an ammeter. Energy cost devices are composed of drum-type ice crusher, one CY hammer crusher, three conveyor belt, and one centrifuge machine. The energy cost of filtering and collecting of raw ice is very low and not taken into consideration.

7. Conclusions

In this research works, sea ice desalination was conducted using centrifugation to obtain freshwater. The sea ice desalination method and operation factors were investigated by the theoretical analysis and the experiments. The continuous industrial experiments were also carried out.

The experimental data indicate that the salinities after desalination increase firstly and then decrease with the increase in particle diameters. The optimal diameters for desalination are 6–9 mm. The co-use of drum-type ice crusher and hammer ice crusher could deal with large ice particles and offer a relatively uniform crushing so that blocking would not happen.

The industrial experiment results show that the sea ice desalination system can satisfy the requirement of the process production. In this system, ice crushing, transportation, and desalination can be continuously operated. The sea ice salinity decreases into below 1.0 after continuous desalination. Its capacity could reach 5–6 m^3/h and above, the total energy cost is 11.1–13.3 kJ/kg.

List of symbols

Fr – separation factor
H – mass of liquid film
H_o – initial mass of liquid film
K – desalination factor
P – correction factor
S_o – initial salinity of sea ice
δ_o – initial thickness of liquid film
μ – liquid film viscosity
z – thickness of liquid film
ρ – liquid film density
g' – acceleration speed of liquid film

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