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Gravity-induced sea ice desalination under low temperature

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ABSTRACT

The Bohai Rim is one of the water-scarce regions in China. But every winter, more than 1 billion m^3 of sea ice formed in the sea, about 40% of which distributes within 10 km offshore and is expected to be exploited and utilized as source of freshwater. The salinity of the Bohai sea ice ranges from 4 to 11‰, under suitable ambient temperatures, gravity driven brine drainage and flushing from the melted water can convert sea ice into freshwater ice. To study the influence of ambient conditions on the process, we conducted two experiments on the coast of the Bohai Sea from January to March in 2011. The results showed that ambient temperature was a decisive and controlling factor in gravity-induced sea ice desalination, and that insulation could affect the duration, volume and salinity of the drainage. If the ambient temperature was controlled between −4.0 and 3.0 °C, the drainage would have a low volume and high salinity. With a rise in the air temperature, the volume of the drainage increased and the salinity decreased. Sea ice desalination and freshwater production were negatively correlated: the higher the freshwater production, the lower the sea ice desalination and vice versa.

1. Introduction

Sea ice is frozen seawater floating on the sea that is present both in the Arctic and Antarctic. In the Northern Hemisphere, sea ice can be observed as far south as China's Bohai Bay (37°07′–41°0′N, 117°35′–121°10′E). Bohai is an inland sea in north China surrounded by land on three sides, and sea ice is formed on the surface every winter under the influence of the East Asian winter monsoon (EAWM) along with a cold wave and cold front. The ice forms around every December and melts around March the following year. The salinity of the Bohai seawater ranges from 29 to 31‰, whereas that for sea ice is only 4–11‰.

The Bohai-Rim region is an important economic zone in China. With an area of 518,000 km^2 and a population of 229 million, the per capita water resource is less than 350 m^3 per year, which is insufficient to meet the demands of sustainable development for the local society. However, due to its geographic position, obtaining freshwater from the sea is considered to be a new solution to this problem.

Recently, several companies around the Bohai Sea have launched seawater desalination projects, but the water productivity, energy costs and desalination prices were not ideal. To make up for the shortage of seawater desalination, Shi et al. (2002) proposed an idea to convert sea ice into freshwater, which was gravity-induced sea ice desalination.

Sea ice desalination is a type of seawater desalination with low energy consumption, which was recorded in the late 18th century (Nebbia and Menozzi, 1968). And depending on the mode of ice crystal formation (Manwell and McGowan, 1994; Nebbia and Menozzi, 1968), it can be subdivided into two types: the natural freezing method, which is the natural process of seawater freezing to form ice in a cold environment (Rice and Chau, 1997), and the artificial freezing method, which utilizes refrigerants or cooling media to indirectly freeze the seawater (Cheng, et al., 1987). Sea ice contains brine trapped in the ice during the process of freezing, which fundamentally differentiates it from freshwater (Cole and Shapiro, 1998; Medjani, 1996). Brines are liquid-phase substances whereas freshwater ice crystals are solids (Hoekstra, et al., 1965; Notz and Worster, 2009). To convert sea ice into freshwater, brine confined in the ice must be removed. The differences between the liquid and solid phases could be utilized to remove the brine in an energy-conserving fashion.

In recent years, researchers have desalinated sea ice with centrifuges and successfully separated the brine from pure ice crystals. Based on previous results, Xie et al. (2009) looked at the composition and concentration differences between sea ice crystals and brine and proposed using centrifugal force to remove brine from the sea ice. To do so, the sea ice must be finely crushed and placed in a centrifuge for separation, which is a highly energy-consuming method.

Since 1999, we have participated in various sea ice desalination studies funded by the Ministry of Science and Technology of PRC. In this paper, we present small-scale field experiments to explore an

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energy efficient method of sea ice desalination that is closely related to the structure of the sea ice, but the actual energy consumption needs to be calculated accurately.

2. Migration of brine due to gravity

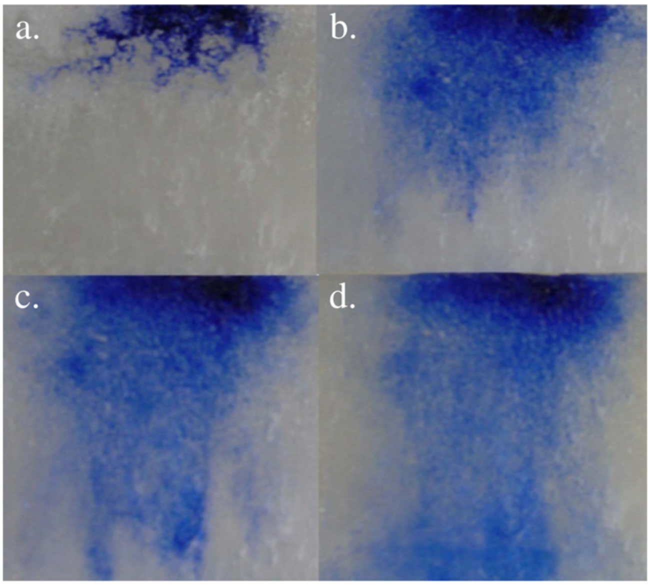
A photograph of sea ice shows that there are spaces among the ice crystals, composed of either brine or air pockets (Fig. 1). The volume of the space depends on the age and growth environment of the ice.

When the air temperature is below the melting point of the sea ice (about −1.4 °C for Bohai sea ice), the brine is firmly locked within the pockets in the sea ice. With a rising air temperature, some ice crystals will melt and the brine will expand (Cottier, et al., 1999). Moreover, the brine can form channels that transcend through the ice, creating a possible pathway for brine drainage when subjected to the force of gravity (Cox and Weeks, 1986). At this point, converting mildly saline ice into nearly freshwater ice becomes possible. To confirm the appearance of these channels through the ice, we used a tracer to study the path of the brine migration when subjected to gravity. Similar work was also conducted by Bennington (1967) and Kawano and Ohashi (2009).

A piece of sea ice (20 cm long, 20 cm wide and 18 cm thick) was obtained from Liaodong Bay of the Bohai Sea and stored at 0 °C in a top-down direction. A blue tracer was dropped onto the surface of the sea ice, and its dispersal process was recorded by a digital camera (Fig. 2). The photographs demonstrated that during the first 30 min, the tracer began to migrate dendritically among the pores on the upper part of the sample (Fig. 2a). Then, after 240 min, the tracer dispersed vertically from top to bottom (Fig. 2b), and 480 min later, a portion of the tracer migrated downwards along brine channels and approached the bottom of the sample (Fig. 2c). Finally, at 560 min, some of the tracer was expelled from the sample (Fig. 2d).

The tracer test shows that under a suitable temperature condition (generally above the melting point of sea ice), brine pockets in the sea ice can be connected and form brine channels and pathways. Liquid-phase brine inclusions confined in the pockets will migrate through the ice both vertically and laterally, although the majority disperses downward due to gravity. With time, the brine inclusions that entered vertical channels will be expelled, while those in lateral channels will remain in the ice. Theoretically, the rate of this transportation process is largely affected by temperature. If the ambient temperature is kept below the melting point of sea ice, brine pathways are difficult to form, and the brine expulsion may be restrained. Only when the ice temperature rises can the brine pockets be easily connected to form new vertical channels that will promote the expulsion of the brine inclusions. The expulsion of brine is also related to the melting of crystals on the surface of the sea ice. Melted solid sea ice in liquid water flushes the brine out of the ice, but the melting and drainage of ice crystals will inevitably reduce the yield of freshwater. That is, the process of brine expulsion occurs along with the loss of freshwater. However, sea ice with a certain salinity can be converted into freshwater ice as long as brine drainage is completed successfully, which is the fundamental theory behind gravity-induced sea ice desalination. By regulating the ambient temperature, maximum brine drainage can be achieved while minimizing the loss of freshwater.

Fig. 1. Photograph of the inner structure of the sea ice.



a. 30 min, b. 240 min, c. 480 min, d. 560 min.

Fig. 2. Dispersion of a blue tracer in sea ice collected from Liaodong Bay.

3. Experiments

To test the theory of sea ice gravity-induced desalination, we designed and conducted two field experiments from January to March, 2011.

3.1. Location and time

The experiment was arranged in the Sino-Czech Youyi Farm in Huanghua City, Hebei Province, located on the coast of China's Bohai Sea. This location was approximately 3 km away from the sea, with coordinates of 38°09′–38°39′N and 117°05′–117°49′E and an average elevation of 1.5 m. The local winter spans from the beginning of December to the end of March, and the sea ice forms from late December to early March the next year (Wang, 1991) (Table 1) at an average air temperature between −2 and −8 °C. The experiments in this paper were conducted from Jan. 2 to Mar. 13, 2011.

3.2. Experimental methods

Open cubic containers with a volume of 1 m^3 were made with stainless steel. The faces and bottoms of the containers were double

Table 1
Characteristics of sea ice formation in the experimental region (Wang, 1991).

	Initial date	Date of maximum ice volume	Date of initial melting	Final date
Earliest	Dec. 1	Dec. 30	Jan. 14	Jan. 16
Latest	Jan. 8	Feb. 22	Mar. 2	Mar. 12
Average	Dec. 25	Jan. 20	Feb. 9	Mar. 10