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Effects of watering parameters in a combined seawater desalination process

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ABSTRACT

Seawater desalination experiments using patented experimental platform that could recycle cold energy released from LNG (liquefied natural gas) re-gasification process were conducted in laboratory. Combined freezing, watering and centrifugal desalination (FWCD) process was employed. The effects of the key watering parameters, including proportion, temperature and pure water or seawater, on removal efficiencies of salt and measured ions and on ice yield rate were investigated. Results showed that watering process benefits the brine-ice separation through centrifugation and therefore the ice purity can be enhanced. To ameliorate ice product purity, increasing the mass proportion of watering raw seawater is a more feasible method than watering pure water. The desalination effect of adding raw seawater would be better in summer than in winter when other parameters constant. Comparing with combined freezing, gravity-induced and centrifugal desalination (FGCD) method, FWCD is a continuous process that can accelerate the desalination duration, and more ice with the same purity can be yielded within the salt removal efficiency range of FWCD method. Whereas more energy has to be consumed using FWCD process because higher centrifugation rotation rate is also necessary to achieve the same salt removal efficiency. Whereas the total energy consumption for unit ice product is acceptable.

1. Introduction

With the rapid growth of global economy, the fresh water crisis is becoming a very serious problem. Seawater desalination seems to be one of the methods to alleviate the situation, especially in the countries with per capita water resources much less than the world average amount like China.

Seawater desalination technologies can be divided into two types which are separation methods and thermal methods. Separation methods, such as reverse osmosis (RO) and electro dialysis (ED) method, remove salt from water using electrical or mechanical forces. Thermal methods separate salt through phase-change process such as distillation and freezing method [1–2].

Some previous research described the advantages of freezing method, e.g. high energy efficiency, corrosive resistance, easy operation and lowering cost etc. [3]. Some authors presented their research work on improving the energy efficiency of freezing desalination equipment or system. Ahmed A.A. Attia [4] proposed a heat pump system with high energy efficiency that can be used in seawater desalination. In the suggested system, ice formation, washing and melting processes can take place in sequence at the same heat exchanger through changing the refrigerant flow direction in the vapor compression cycle. Therefore, ice handing mechanical systems or special compressor types which usually involved in traditional freezing desalination system needn't be considered.

M.V. Rane [5] presented a freeze desalination system equipped with a heat pump and vented-double-wall tube–tube heat exchanger, which avoids the need of ice scraper/separation mechanisms and enables heat exchange between the refrigerant and the seawater/potable water without intermediate medium. It was also demonstrated that compared with conventional freeze desalination systems, the system has both initial and operating cost advantages.

Whereas, other than the desalination methods that have been widely used around the world such as RO method, multiple effect distillation (MED) method and multi-stage flash (MSF) method, freezing method have not yet been employed in large industrial production [6]. Theoretically, seawater freezing process can separate water from mother liquid because of higher crystallization temperature of pure water than that of brine. However, the following two cases would decrease the purity of ice greatly during freezing process. The first is that some brine pockets form within the big ice block when the freezing rate is higher than the mass transfer rate of salt ions and the second is that more brine is adhered to small crystal surfaces because of their large specific surface areas.

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Nomenclature

C_0	salinity of raw seawater (ppt, parts per thousand or ‰)
C_{0ion}	initial concentration of the measured ions or TDS in raw seawater (mg/L)
T_{lni}	liquid nitrogen temperature of cryogenic heat exchanger inlet (°C)
T_{iti}	intermedium temperature of ice-making machine inlet (°C)
T_{ito}	intermedium temperature of ice-making machine outlet (°C)
C_{pw}	salinity of pure water used in watering process (ppt, parts per thousand or ‰)
T_{swi}	temperature of seawater that sprayed to ice-making machine (°C)
M_i	mass of sample ice (g)
M_{pw}	mass of added pure water (g)
M_{sw}	mass of added raw seawater (g)
R_{pw}	mass proportion of added pure water (%)
R_{sw}	mass proportion of added raw seawater (%)
R	salt removal efficiency (%)
C_i	salinity of the ice product (ppt or parts per thousand ‰)
R_{ion}	removal efficiencies of measured ions or TDS (%)
C_{ion}	concentration of the measured ions or TDS in ice product (mg/L)
R_{iy}	ice yield rate (%)
M_{ip}	mass of ice product (g)

Therefore, some research work were conducted on the factors affecting the salt removal efficiency in freezing desalination process, such as cooling medium temperature, freezing time etc. Ryosuke Fujioka et al. [7] presented their laboratory equipment for progressive freeze-desalination, which could control the ice front in one-dimension. Their study showed that the desalination efficiency can be increased with either lower advance speed of the ice front (U) and initial concentration (C_0) or higher circumferential velocity of the stirrer (U_r). Although it has been demonstrated widely that the ice purity can be ameliorated by decreasing the freezing rate [8], low freezing rate also means the decrease of production efficiency in real seawater desalination plant.

To increase ice purity, some previous research stressed on methods such as washing, partial melting with gravity-induced brine drainage, centrifugation, soaking, watering etc. after freezing process. Nicholas Beier et al. [9] proved experimentally that the desalination effect in the ice melting process is more obvious than freezing process. Mokhtar Mahdavi et al. [1] carried out three rounds of frozen-melting (FM) experiments to yield pure water. T. Mtombeni et al. [10] used Venturi effect to suck and drain out the brine attaching to the ice crystals and then melted the dried ice crystals to produce the portable water. Youssef Mandri et al. [11–12] improved the purities of seawater ice and NaCl solution ice using partial melting method to drain out the trapped brine pockets. Cong-shuang Luo et al. [13] employed unidirectional-freezing method to make layered ice and then improved the quality of ice through crushing and centrifugation method. Gravity-induced desalination method can use free natural heat resources to deal with ice, such as Gu Wei et al. [14] studied the effect of gravity-induced desalination in winter on natural sea ice taken from Bohai Bay and got pure water with the salinity range from 0.8‰ to 1.4‰. However, if the free air heat resources were used in real industrial desalination production based on artificial freezing process, some instability problems should be concerned. For example, desalination process will be much longer in winter than in summer if the natural air environment changes in a relative large range in the whole year. Centrifugal desalination could enhance salt removal efficiency and shorten process time by consuming certain of energy. X. C. Gao et al. [15] added a certain proportion of seawater into crushed natural seawater ice taken from Bohai Bay before it was centrifuged. Their experiments showed that is an easy and economical way that can reduce the salinity of the remaining ice.

Some research was also carried out on seawater desalination using LNG cold energy. W.S. Cao et al. [16] introduced the freeze desalination (FD) system equipped with flake ice maker utilizing LNG cold energy and simulated the thermal process using HYSYS software. M.B. Huang et al. [17–19] designed both direct-contact and indirect-contact freezing seawater desalination schemes that can use LNG cold energy and discussed the choice of refrigerant as well as the determination of the main process parameters. They carried out some experiments using the indirect-contact freezing method to deal with seawater and the results showed that salt removal efficiency was not high. It was concluded that the freezing desalination can be the middle treatment process for seawater desalination. P. Wang and T. S. Chung [20] developed a hybrid desalination system comprising freezing desalination (FD) and membrane distillation (MD) processes, which is energy-saving through utilization of LNG cold energy. It was proved experimentally that the total water recovery rate achieves at 71.5% and the quality of the water product meets the standard for drinkable water using this hybrid FD-MD system. This hybrid FD-MD process is suitable for the practical situation that has waste heat energy and LNG cold energy to be used for MD process and FD process respectively. Above works paid more attentions on improving energy efficiency of the seawater freezing process than ameliorating the salt removal efficiency of the ice.

Although it was demonstrated that higher freezing rate results in lower salt removal efficiency because more brine can't be expelled in time and therefore is trapped to form brine pockets in ice, lower freezing rate also means lower production efficiency. What is more, it was proved that pure ice can't be produced through artificial freezing process even with very low freezing rate [8,13]. In laboratory, the authors of this paper utilized the experimental platform, which can use LNG cold energy, to freeze Bohai Bay seawater, and then combined freezing, gravity-driven and centrifugal desalination (FGCD) technologies to increase ice purity. The effect of gravity-induced brine drainage proportion in FGCD process was investigated. The research showed that the FGCD method is feasible in improving salt removal efficiency and acceptable in energy consumption [21]. Whereas, if gravity-induced desalination process took place in ambience in order to use free air heat resources, the duration time of FGCD process would be long and dependant on the natural climate environment that can't be controlled artificially. For shortening the desalination process, other method worthies to be studied as substitute of gravity-induced process. Washing and watering methods have been proved effective to enhance ice purity since water can decrease the viscosity of brine adhering to the ice and accelerate the melting process of some ice [15]. In this paper, freezing, watering and centrifugal desalination (FWCD) processes were combined to desalinate seawater and the effects of the key watering parameters including mass proportion, temperature and pure water or seawater on salt removal efficiency were investigated.

2. Materials and methods

The patented experimental platform (shown in Fig. 1) same as that used in [21] (with the authorized number ZL 2016208330324 in China) was employed to freeze seawater taken from Bohai Bay near an under-construction LNG receiving terminal. The flow diagram of FWCD process that can use LNG cold energy is shown in Fig. 2.

In the sea water freezing process, indirect cooling-crystallization method was employed to avoid necessity of intermedium separation faced by direct cooling-crystallization method. Ice flake machine was used to accelerate seawater freezing process, which benefit a