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Simplified Freeze Desalination through Enhanced Recovery Rate and Desalination Efficiency

Mohammad Hendijanifard *, Habibullah Sharifi

Faculty of Mechanical Engineering, Shiraz University, Shiraz, Iran

ABSTRACT: Freeze desalination is an emerging technique since it uses much less energy than most other thermal technologies. As a portion of zero/minimum liquid discharge technologies, crystallization is being commercially used, however, it is probably the most expensive section of the desalination plant. Several freeze desalination techniques are being developed including progressive layer, falling film, suspension freeze, and gas hydrate desalination. The emphasis of most of these methods is to improve the desalination efficiency. Developing a complete freeze desalination plant requires recognizing the critical importance of both recovery rate and desalination efficiency. In a study, a comprehensive freeze desalination plant was designed with a 50% recovery rate and 50% desalination efficiency. To achieve proper salt rejection from 78% of incoming seawater, the plant needs to undergo 46 stages of desalination. The plant is then redesigned with a recovery rate of 90% and a desalination efficiency of 90%. It is shown that in only 6 stages of desalination, 89% of the whole seawater can be desalinated which is a cost reduction of at least 87%.

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1- Introduction

Freeze desalination is gaining more attention due to much lower energy usage compared to other thermal desalination techniques. The latent heat of the solidification of water is 334 kJ/kg [1] which is almost one-seventh of the latent heat of the vaporization of water, 2260 kJ/kg [2]. From the perspective of energy usage, the freeze techniques potentially use much less energy than distillation [3, 4]. Since the temperature during freeze desalination is low, it is much more resistant to corrosion and scaling compared to most other thermal techniques [5]. Freeze desalination is insensitive to fouling and does not require pretreatment. It can also be employed to reduce the concentrated brine of the reverse osmosis technique to close to zero liquid discharge [6, 7].

Freeze desalination consists of three major portions, precooling, crystallization, and separation/melting [8, 9]. Precooling helps with energy usage by precooling the incoming seawater to a low temperature before crystallization. Crystallization is the mechanism that changes the phase of the incoming seawater to ice crystals. As the ice crystals emerge, a portion of the salt content gets rejected by the rest of the solute. Some of the salt content gets trapped between the ice crystals. Some of the salt content of the ice can be further removed. Different techniques are suggested for separating, melting, and washing the ice crystals [10-13].

The crystallization or freeze portion of the freeze desalination is obtained either through direct contact of the solute with the refrigerant or indirect contact [14]. The indirect contact methods are mainly comprised of suspension freeze [6], progressive film [15-19], and falling film [20]. In suspension freeze, the ice crystals are grown and separated from the coolant walls. Initial ice seeds are required for this type of freezing. In progressive freeze, a layer of the ice is in contact with the coolant wall and the ice layer gradually thickens. Using a seed layer is optional, however, it improves the quality of the grown ice [17]. A large ice crystal is grown during progressive freezing. As the layer grows, the salt content of the solute increases. The salt content is expected to be the highest near the contact interface of the crystal and the solute since the salt is being rejected from the ice into the solute [4]. One way to reduce the salt content near the crystal interface is to use a convectional mechanism such as a stirrer. Progressive layer freeze may be from the bottom of the container towards the top or from the top of the container towards the bottom. The progressive layer might also be on a vertical coolant plate [19]. In the progressive layer freeze from bottom to top, implementing a stirrer is more convenient. A stirrer is used to reduce the highly concentrated salt near the ice/solute interface by convection mechanism. Progressive layer freeze from top to bottom may use the natural convection mechanism since the solute with high salt content is heavier than the ice and also the solute with lower

*Corresponding author's email: Mohammad.Hendijani@shirazu.ac.ir

salt content. Therefore, without any forced convectional mechanisms, an ice crystal that grows from top to bottom is expected to have a better quality [16] than the ice which grows from bottom to top.

Falling film crystallization or dynamic layer freeze is another type of indirect freeze method in which a thin layer of the solute falls on a coolant wall and freezes as it falls. An ice layer grows on the coolant wall and the concentrated liquid drops into a bottom container [20].

During crystallization, a certain amount of salt is rejected from the ice crystal and a portion of the salt stays between the crystal boundaries. Therefore, the desalination efficiency is defined as the ratio of the salt concentration of the ice to the incoming solute. Other terms such as desalination rate [21, 22], removal efficiency [16], and salt removal efficiency [13, 23] are also used on behalf of the desalination efficiency. Most of the articles on freeze desalination are correctly focused on improving desalination efficiency. However, there is one more equally important criterion for making freeze desalination viable for commercial use, the recovery rate. The recovery rate is defined as the ratio of the mass of the ice produced to the total mass of the incoming solute. Other similar terms such as solid fraction [21], ice ratio [10], a fraction of solid phase [15], ice yield rate [24], ice mass fraction [25], and recovery ratio [26] are also used on behalf of the recovery rate. Not only the efficiency but also the recovery rate has to be high enough for a commercial freeze desalination plant to be economical.

Lu et al [26] show that in a hybrid freeze-membrane-crystallization desalination unit, as the recovery rate of the ice increases to almost 25%, the energy consumption of the unit decreases, which means that the plant is more economical for higher recovery rates.

In this research endeavor, a comprehensive desalination plant design is presented, employing the progressive freeze technique. A series of experiments were conducted to establish the baseline recovery rate and desalination efficiency for a progressive freeze desalination process from top to bottom, without the involvement of any stirring mechanisms. The study then shifted its focus to investigate the impact of the recovery rate and desalination efficiency on the overall design of the freeze desalination plant. Furthermore, the relationship between a favorable recovery rate and efficient desalination in reducing desalination efficiency costs was demonstrated.

Although the paper commences with baseline experimental data, its overarching objective is to underscore the significance of the single-stage recovery rate in the process flow for industrial freeze desalination in a quantitative way.

2- Experimental setup

A comprehensive desalination plant design is presented, based on the progressive freeze desalination technique. The single-stage desalination efficiency, referred to as desalination efficiency, is distinguished from the total desalination efficiency. Throughout the text, the term “recovery rate” is consistently employed to denote the single-stage recovery rate, differentiating it from the total recovery rate.

The design emphasizes single-stage desalination efficiencies ranging from 50% to 90% and single-stage recovery rates varying between 50% and 90%. Notably, the total recovery rate can surpass 95%. To ensure a fair comparison, the total recovery rate has been set at approximately 78%. Even though the desalination efficiency of most freeze methods is reported to be around 50%, the recovery rate is not clearly stated in many articles. Tests are conducted independently, measuring both the desalination efficiency and the recovery rate for progressive freeze desalination.

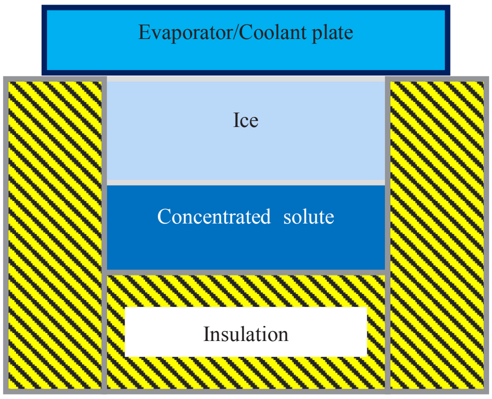
Although most freeze desalination methods freeze from the bottom to the top, the choice is made to freeze from the top to the bottom in this case. For progressive freeze without the intervention of any mixing, freezing from the top is preferred and is expected to give better ice quality since the salted water is heavier and the gravity pulls the extra concentration down. Most freeze desalination methods freeze from the bottom and use mixing techniques to remove the salt component from the ice front as much as possible. Freezing from the top requires mixing the solute in the bottom side of the container. Mixing from the bottom of the container presents challenges due to potential leakage around the mixer shaft. Therefore, the decision is made to focus solely on establishing the best baseline for a progressive freeze by freezing from the top without attempting further technique enhancements at present. It is conceivable that utilizing a stirrer, a more effective ice/solute separation mechanism, a seed layer, and post-treatment techniques like sweating could potentially enhance the baseline.

Figure 1 shows the schematic of the progressive freeze desalination from the top. The icing container is a cylindrical vessel measuring 9.5 cm in diameter and 6.5 cm in height. The temperature at the top of the container is set to -9ºC. The container is well insulated all around except for the top side to enforce top-to-bottom freezing. Therefore, the freezing layer starts from the top and gradually grows down. Given the importance placed on both the recovery rate and desalination efficiency, multiple tests are carried out where the ice content is extracted following freezing at various recovery rates. The incoming solute mass as well as the ice mass are measured before and after the experiments and the differences are recorded.

The ice formed during the process is subsequently melted and brought to a lab-controlled temperature of 24°C, at which point the salt content is measured using a METROHM 660 conductometer. Additionally, the salt content of the ice and the concentrated solute is determined through a drying technique. The original salt content for all samples was prepared by mixing 4 grams of NaCl salt with 100 ml of twice-distilled water.

Following the icing process, the concentrated solute is extracted from the ice, and both the ice and concentrated solute are individually analyzed for salt content. To achieve varying recovery rates, the icing duration is adjusted, resulting in different amounts of ice content obtained.

As depicted in Figure 1, an Arduino Uno is utilized in



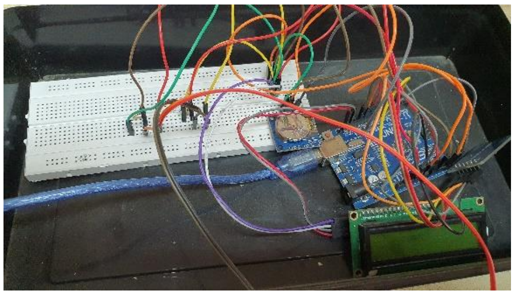


Fig. 1. Left: schematic of the progressive freeze setup from top to bottom. The container is fully insulated to facilitate top-to-bottom freezing. After the ice forms, it is removed from the container, melted down to a lab-controlled temperature, and then measured. The diameter of the container is 9.5 cm and the height is 6.5 cm. Right: An Arduino Uno module as well as a data card module and display.

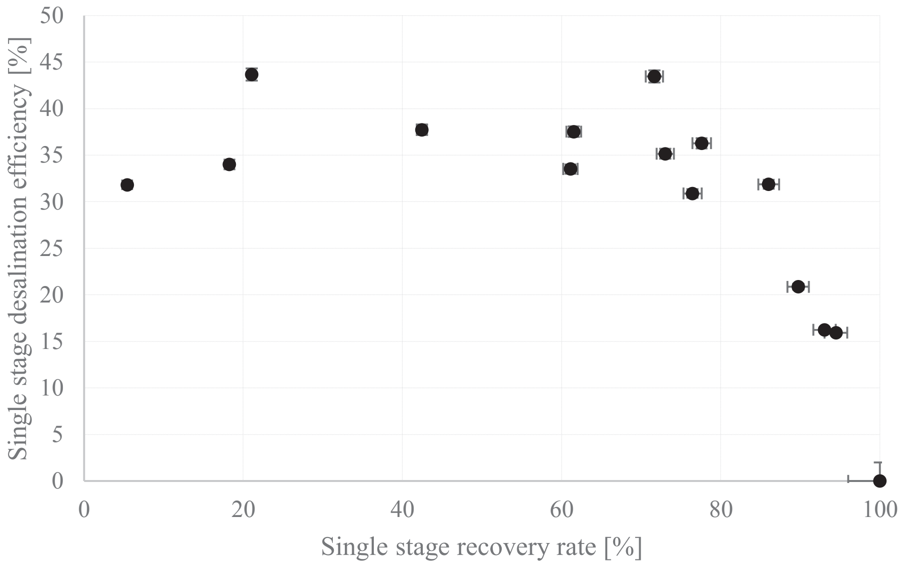


Fig. 2. The baseline desalination efficiency versus the recovery rate for progressive layer freeze from top. No stirring or post-treatments are performed on the ice content.

conjunction with temperature sensors and a data card module 3231 for data logging purposes. Additionally, a monitor is employed for displaying the recorded data.

Figure 2 shows the desalination efficiency versus the recovery rate. The recovery rate is defined as the mass of the frozen material divided by the total mass of the seawater or solute in the vessel. For instance, if half of the vessel mass gets frozen and the ice is removed, the recovery rate is 50%.

The presence of error bars on the graph is attributed to measurement errors, including those stemming from the 2-digit scale and estimated human error measurements. Notably, the data point corresponding to the 99.9% recovery rate is anticipated to exhibit significantly higher measurement errors. This is primarily due to the concentrated nature of the brine at this point, which leads to rapid melting and an expectation of oversaturation in the concentrated salt.

Moreover, the contact point of the brine with the surrounding ice is projected to be highly concentrated as well. The definition of desalination efficiency at this specific point is also somewhat unreliable. For the remainder of this article, the data point for the recovery rate of 99.9% will be referred to as 100%.

Regarding the repeatability of the experiments, achieving an exact amount of ice and, consequently, an exact recovery rate is likely close to impossible. However, efforts have been made to increase the number of data points for the experiments as much as possible. For instance, the data point close to a 61% recovery rate shows that the desalination efficiency ranges between 34% and 38%. Therefore, it is expected that the graph may be reproduced with an approximate deviation of less than 5%.

As observed in Figure 2, the baseline desalination efficiency peaks at approximately 40% with a recovery rate of around 72%. The desalination efficiency then drastically reduces to 0% for a recovery rate of 100% since the whole content of the salt gets trapped within the ice crystals near the bottom of the container. While some salt may be rejected from the ice crystals, it gets re-trapped in the melted ice during removal from the container. Recovery rates between 70% and 100% are expected to increase the salt content in the ice, leading to lower desalination efficiency due to high solute concentration.

As the article transitions to modeling a more industrial process flow in the subsequent section, the more significant portion of Figure 2 lies in the higher recovery rate region, as intuitively expected. For instance, while a desalination efficiency of 40% is observed at both 20% and 72% recovery rates, the more significant result is the 40% desalination efficiency achieved at the 72% recovery rate. Intuitively, it is anticipated that the number of desalination stages required will be lower for higher recovery rates, rendering them more favorable for industrial applications.

Even though the desalination efficiency versus the recovery rate is probably as expected for the recovery rates of more than around 60%, the desalination efficiency seems quite low for lower desalination efficiencies. It might be assumed that a thin layer of ice has lower salt content per unit mass and is cleaner than a thicker layer; however, Figure 2 indicates otherwise. Further tests demonstrate that the baseline can be enhanced through more rigorous methods of removing ice from the concentrated solute. The removing method is expected to be critical due to the higher surface tension of the concentrated solute. As the current study solely necessitates baseline data, further discussion on this subject is deferred for now.

As depicted in Figure 2, desalination efficiencies of approximately 45% are achieved at recovery rates of about 72%. Using proper mixing techniques, a better ice removal from the concentrated solute, sweating [17], and other methods [27], the desalination efficiency and the recovery rate can be further improved. Even though higher single-stage desalination efficiencies are reported, studies seldom report single-stage recovery rates. In the pursuit of additional validation, comparable results were sought in other literature where both single-stage desalination efficiency and recovery rates were reported. However, the search did not produce definitive findings. Subsequently, repeated tests were conducted at different intervals throughout the year for specific data points, resulting in consistent outcomes.

Based on the above experiments, the question comes up on if the recovery rate matters or not. For further emphasis, within the rest of this work, a full freeze desalination plant is designed using several different recovery rates and desalination efficiencies.

3- Method and results

It is an intuitive notion that higher desalination efficiencies and higher recovery rates are favorable, but the quantitative significance of each of these two factors may not be fully understood. Based on the baseline experimental data, it is observed that even without employing any washing techniques, desalination efficiencies of 40+% could be achieved at recovery rates of 50+%. The implementation of post-processing techniques, such as washing, could potentially aid in attaining much higher desalination efficiencies. However, since washing necessitates the utilization of the desalinated water itself and may render the problem excessively complex to be addressed within the scope of this text, only baseline data is utilized, and no post-washing techniques are employed.

Nonetheless, it is comprehensible that, as a starting point for process modeling, a recovery rate of 50% and a desalination efficiency of 50% could be considered reasonable.

Figure 3 illustrates the process flow model designed for a freezing plant with a 50% desalination efficiency and 50% recovery rate. The incoming seawater salt content is assumed to be 40000 ppm and is shown on the left side of the process. Due to the inability to reject all salt content in a single stage, multiple desalination stages are necessary to produce potable water. In each desalination stage, the vessel freezes the incoming solute. The ice is then removed, and melted in a second vessel, and energy is recycled efficiently. The melted ice has less salt content. The melted ice undergoes a second freezing stage for further purification. This process has to continue until the ice is considered acceptable for potable water. For further simplicity, the criterion for accepting the purified ice is considered to be 900 ppm which is somewhat higher than the standards. Within each stage and during the freezing stage, the extra salt content of the ice gets rejected by the rest of the solute, thus creating a highly concentrated solute. The highly concentrated solute may or may not be further desalinated based on the designer's goals. To facilitate a more effective comparison among various design scenarios, a rejection criterion of 120,000 ppm for the concentrated solute has been taken into account. One more rejection criterion in this study is when the solute volume is less than 2% of the original incoming water. This small amount of water is rejected regardless of the salt content.

Both of these criteria are subjective and highly depend

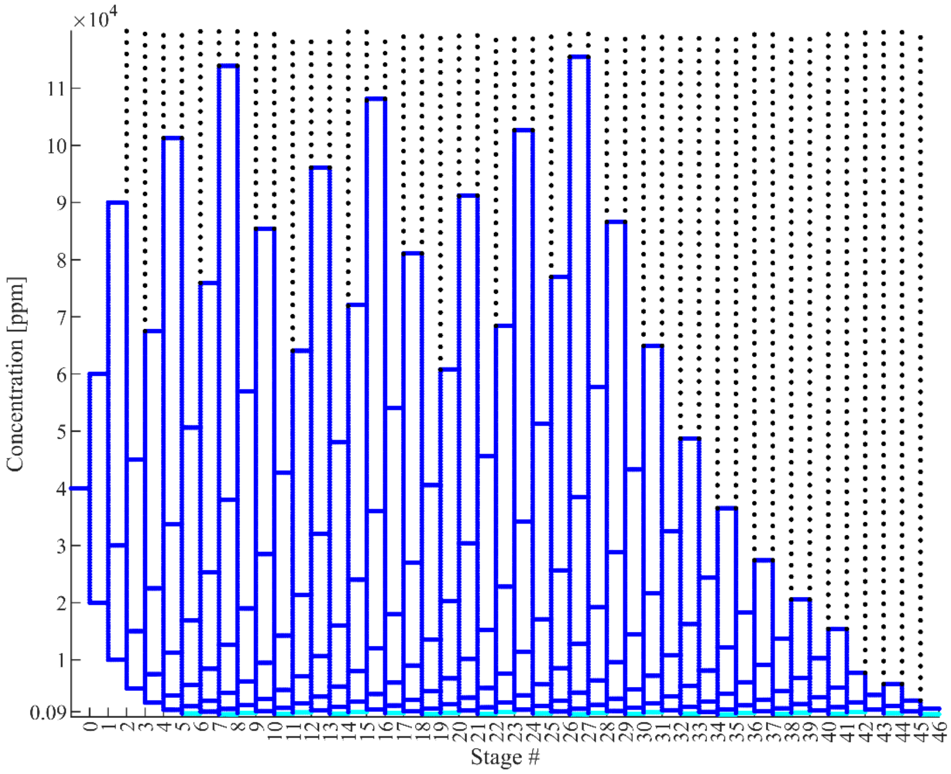


Fig. 3. Process flow with 50% recovery rate and 50% desalination efficiency for each stage. 46 stages of freeze desalination are required to achieve 78% total desalination rate.

on the designer and the economies of scale. In Figure 3, as the incoming 40000-ppm seawater enters the plant, it is distributed into multiple similar freezing/melting vessels. The total number of vessels is arbitrary and depends on the scale of the plant. The plant can be regarded as designed for 1 m^3 of the incoming feed. The brine flows are shown in blue. The potable water extract from the plant is shown in Cyan. The rejected water is shown in dotted black.

The blue feed line with 40000 ppm concentration, after the first stages gets separated into two streams. The ice gets melted and goes to the next stage for further desalination. The concentrated brine depending on the reject criteria and the total recovery rate required, goes to the next stage and in separate vessels for further desalination. The same process repeats enough times until the total recovery rate is met.

Some authors use the term recovery yield instead of the total desalination rate [28]. In the transition from the incoming 1 m^3 feed to the first stage, half of the solute mass freezes due to the 50% recovery rate. The other half of the vessel, which contains the concentrated solute, is expected to have a higher salt content. For example, in the first freezing stage with a 50% desalination efficiency, the ice should have a salt content of 20000 ppm. As a result, the rejected salt content transfers to the concentrated solute, potentially increasing its salt content to 60000 ppm. The ice content has to be desalinated again. Since the ice content volume is only half of the incoming vessel (the recovery rate is 50%), half of the volume is sent to the next stage for further desalination. Therefore, the ice moves to the second stage and the molten ice gets desalinated one more time. This process continues further until the ice contains less than 900 ppm and does not require any further desalination. Following 6 stages of ice desalination, 1.5% of the initial solute becomes potable water. In order to get more potable water, the solute should also be desalinated multiple times. The same process repeats on the solute side as well, until the incoming water is desalinated to the desired total percentage. For further comparison, approximately 78% of the total incoming seawater is desalinated.

As the solute gets more and more concentrated, it reaches a point that might get rejected depending on one of the rejection criteria as discussed earlier. The number of stages required to complete this task highly depends on both the recovery rate and the desalination efficiency. For instance, with a recovery rate of 50% and a desalination efficiency of 50%, it takes 46 stages of desalination to desalinate 78% of the whole incoming water.

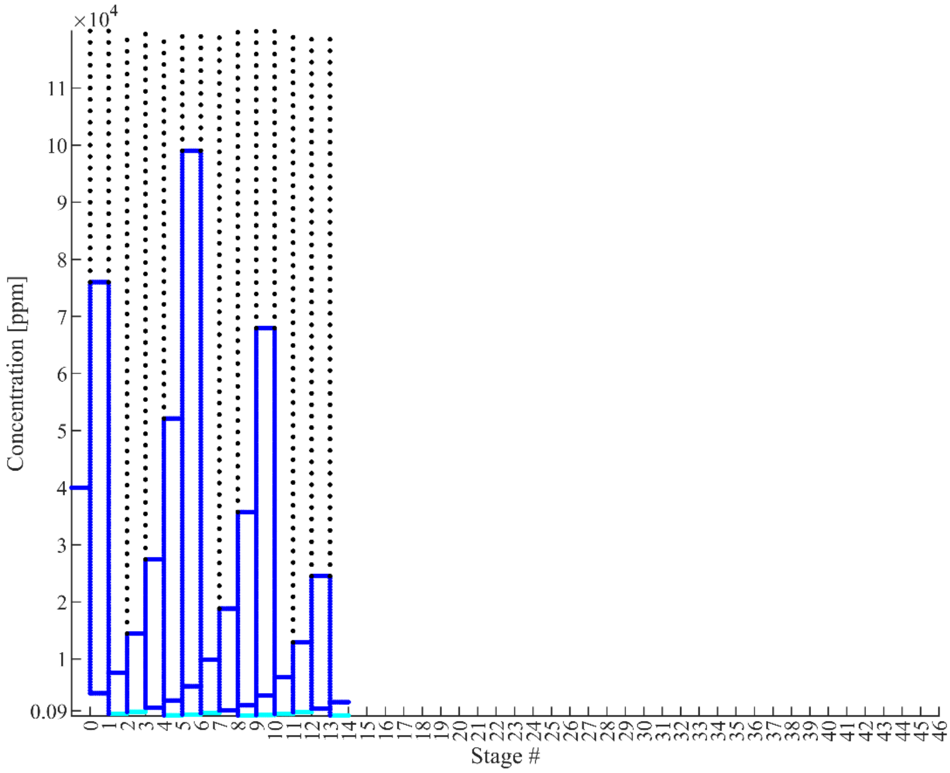


Fig. 4. Process flow with 50% recovery rate and 90% desalination efficiency for each stage. With 14 stages of freeze desalination, 84% total desalination rate can be achieved. 50% of the freeze vessels become available for reuse after 4 stages of desalination.

In this case, since both the recovery rate and the desalination efficiency are 50%, it is straightforward to perform the calculations. However, in other cases, this could be quite complex. Therefore, the salt concertation within the ice and the brine are formulated after each stage of the desalination. The salt concentration within the ice for each stage can be calculated as

$$C_{ice} = C_{incoming\,mixture\,from\,previous\,stage} \times (1-\eta) \tag{1}$$

in which C_{ice} is the average concentration of the salt in the frozen portion of the mixture (ppm), $C_{incoming\ mixture\ from\ previous\ stage}$ is the average concentration of the salt in the incoming water to the desalination vessel (ppm), and η is the desalination efficiency in each stage of the freeze desalination (0 to 1). For instance, if the incoming salt content of the solute to the first stage is 40000 ppm, the salt content within the ice after the first stage can be calculated to be 20000 ppm with a desalination efficiency of 50% (η = 0.5). The extra salt content of the ice has to be rejected into the brine. The salt content of the concentrated solute can be calculated as

$$C_{concentrated\ solute} = C_{incoming\ mixture\ from\ previous\ stage} \times \left(1+\frac{R\times\eta}{(1-R)}\right) \tag{2}$$

in which R is the recovery rate (0 to 1) equivalent to the mass percentage of the ice divided by the total incoming mixture. The salt content of the concentrated solute after the first stage is therefore calculated to be 60000 ppm for a recovery rate of 50% (R = 0.5). Noteworthy to mention, Moharramzadeh [18] has defined a recovery rate based on volume, but defining the recovery rate on a mass basis is deemed more practical.

Figure 4 displays the same process flow as in Figure 3 except that the desalination efficiency is increased from 50% to 90% while the recovery rate is maintained at 50%. While there exist numerous practical approaches to attain higher desalination efficiencies, including the utilization of post-washing techniques, the aim of this article is not to enhance efficiency per se. Instead, the objective is to quantitatively demonstrate, through modeling, the significance of achieving such higher desalination efficiency values in the context of the overall process. The desalination content is calculated in

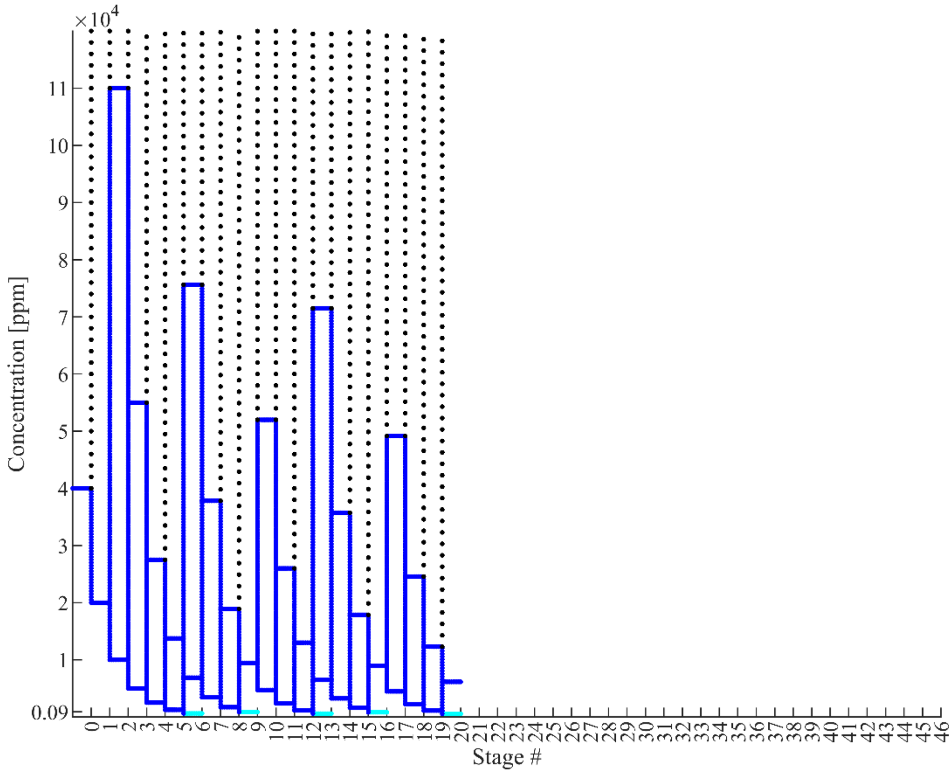


Fig. 5. Process flow with 90% recovery rate and 50% desalination efficiency for each stage. With 20 stages of freeze desalination, 84% total desalination rate can be achieved. 53% of the freeze vessels become available for reuse after 7 stages of desalination.

each stage employing equations 1 and 2 and according to the procedure described in Figure 3. Similar criteria are used for both the accepted desalinated concentration and the rejected concentrated solute. The process flow is designed such that the total desalination rate is kept as close as possible to the 78% target. The total desalination rate in the process flow of Figure 4 is 84%.

This type of modeling does not exert significant control over the total recovery rate, as it somewhat depends on the designer's approach. Although the upper limit for brine concentration may be dictated by potential scaling concerns, the number of stages for repeating the desalination process is left to the designer's discretion. For instance, a designer may choose to desalinate even the smallest amount of reject on the cleaner side (towards the ice side), or they may decide that the amount of desalinated ice is too insignificant to warrant further desalination.

In the current article, for the sake of reproducibility and comparison, it is decided that if the desalinated amount falls below 2%, no further desalination is performed, and the brine is rejected. This rejected brine may be relatively clean but not potable, yet within this design, it is considered rejected due to its small quantity. This free designer parameter is associated with a real industrial case in which, even if a small amount of water exists and is close to being clean, it may not be feasible from a cost standpoint to desalinate it.

This free designer parameter causes the total amount of the desalinated recovery rate to vary slightly between the cases presented within this article. Within the model of Figure 3, 78% of the total amount is recovered, while in the model of Figure 4, 84% of the total amount is recovered. It is evident that a higher total recovery rate is more favorable. Nevertheless, to compare the models within this work, an approximate target comparison of a 78% total recovery rate is considered.

As observed in Figure 4, the total number of stages required for desalination is drastically reduced to 14 stages. Therefore, most freeze desalination studies correctly emphasize the importance of improving desalination efficiency. By improving the desalination efficiency from 50% to 90%, the number of desalination stages is reduced to one-third. The capital cost of the equipment and operational costs are also expected to reduce by at least one-third. Furthermore, with 50% of the desalinated water extracted after 4 stages, half of the vessels become available for reuse. Therefore, the capital cost of the equipment is expected to decrease even further.

The schematic is repeated once more, and this time, the recovery rate is increased without increasing the desalination efficiency. Figure 5 displays the same process flow as in Figure 3, except that the recovery rate is increased from 50%

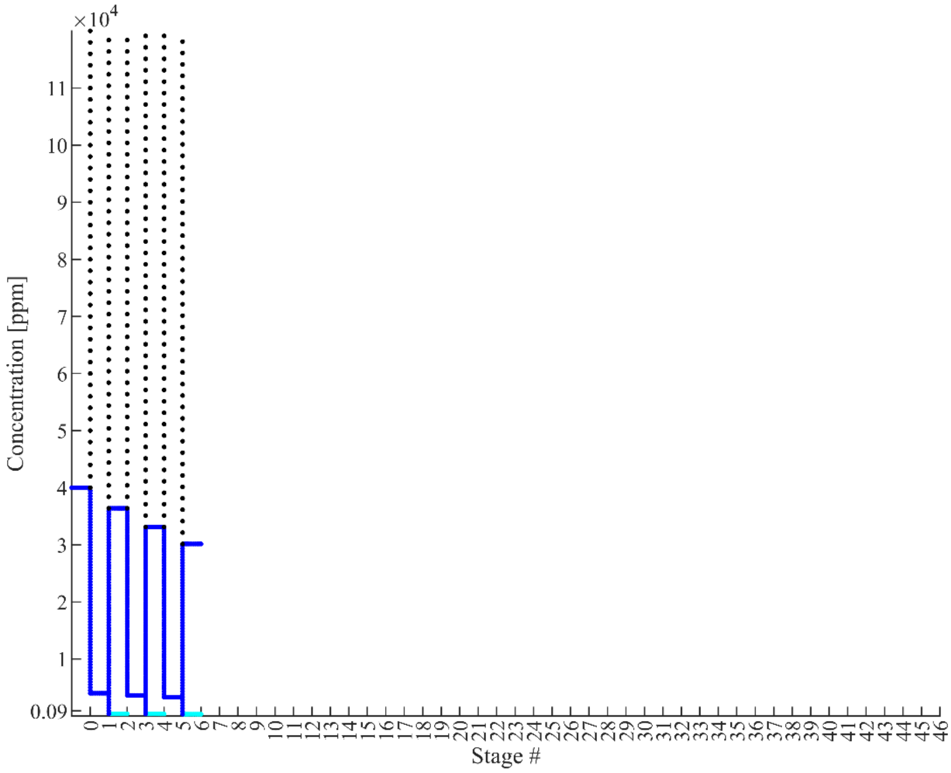


Fig. 6. Process flow with 90% recovery rate and 90% desalination efficiency for each stage. With only 6 stages of freeze desalination, 89% total desalination rate can be achieved. 81% of the freeze vessels become available for reuse after 3 stages of desalination.

to 90%, while the desalination efficiency remains at 50%.

The primary objective of this article is not to present practical methods for improving the recovery rate. Instead, it aims to quantitatively demonstrate, through modeling, the extent to which enhancing the recovery rate may influence the overall cost benefits of the entire process. Unlike desalination efficiency, the importance of the recovery rate has not been extensively explored, and consequently, few studies have focused on improving this parameter.

While practical approaches for enhancing the recovery rate can be envisioned, such as employing a secondary assisting liquid for salt dissociation from water, this article does not delve into such implementation details. Rather, it concentrates on quantifying the potential impact of recovery rate improvements on process economics through modeling and analysis. Therefore, the 90% recovery rate is merely a numerical value used for comparison with the 50% recovery rate, and this article does not specifically introduce the means to achieve higher recovery rates.

The total desalination rate is again designated as 84%, making the results comparable to Figures 3 and 4. The number of stages required to complete the task compared to Figure 3 is reduced to less than half. In only 20 stages of desalination, 75% of the incoming water is desalinated, which is less than half of both the capital cost and operational costs. Additionally, 53% of the vessels become available for reuse after 7 stages of desalination. The results of Figure 5 are almost comparable to those of Figure 4. Therefore, the recovery rate is almost as critical as the desalination efficiency. Researchers are expected to work simultaneously on improving both the desalination efficiency and the recovery rate.

Since the effect of the recovery rate appears to be as critical as the desalination efficiency, a new process flow schematic is designed for the case with a desalination efficiency of 90% and a recovery rate of 90%, as shown in Figure 6. The 90% values for both the recovery rate and desalination efficiency seem practical and likely close to the highest achievable limits. In this new setup, 89% of the total incoming water (compared to 78% in Figure 3) could be desalinated in just 6 stages of desalination. This reduction would significantly cut capital and operational costs to only 13% of the process flow in Figure 3. Furthermore, 81% of the freezing vessels become available after 3 stages of desalination, further reducing costs. Therefore, the process flow schematic in Figure 6 likely represents the closest approach to the lower cost limit for freeze desalination. Additionally, the efficient reuse of melting energy for precooling the freezing vessels could bring operational costs close to the minimum practical limits.

Figures 3, 4, 5, and 6 are plotted using a consistent range of process stages to demonstrate how improvements in desalination efficiency or recovery rate affect the required reduction in stages. The decrease in the number of stages directly impacts the capital cost of the freeze desalination plant, as each stage necessitates a specific number of equipment components such as vessels and control systems.

Assuming a direct correlation between the number of stages and capital/operational cost, the reduction from 46 stages in Figure 3 to 6 stages in Figure 6 signifies an 87% decrease in capital/operational costs.

This article delves into a range of desalination efficiencies and recovery rates from 50% to 90%. Actual efficiencies may vary based on post-processing methods such as ice washing and different icing techniques like brine mixing during icing. Adjusting the timing of ice content can also lead to varying recovery rates.

Energy recovery plays a vital role in freeze desalination, although it is not addressed in this article. Several scenarios exist for energy reuse. For example, melted ice could potentially lower the feed temperature for subsequent stages. However, as brine concentration increases, icing temperature decreases, necessitating matching brine mass flow rates. Another option involves using melted ice to reduce condenser temperature, thereby improving the Coefficient of Performance (COP) of the refrigeration cycle. These scenarios require detailed design considerations beyond this article's scope.

4- Conclusion

In this paper, both the desalination efficiency and the recovery rate have been measured for a baseline progressive layer freezing technique. The desalination efficiency is observed to range from 30-45% at a recovery rate of approximately 5-85%. Various methods can enhance desalination efficiency to higher levels, including washing, sweating, centrifugation, [21, 28, 29], and microwave technology [30], among others. Throughout the article, processes with varying desalination efficiencies and recovery rates have been illustrated. The findings emphasize that enhancing the recovery rate is equally crucial to improving desalination efficiency. For instance, elevating both desalination efficiency and recovery rate from 50% to 90% could lead to a substantial 87% reduction in both capital and operational expenses.

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