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Converting Ocean Water to Freshwater through Cryo-desalination using a Kitchen Freezer: A Novel Approach

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Abstract

Currently, 2.2 billion people lack access to drinking water. The 2024 UN Water Development Report predicts that climate change will further increase the frequency and severity of droughts. Our research assesses the feasibility of using a kitchen freezer for converting salt water to drinkable freshwater, and describes a novel approach to cryo-desalination. Ten containers with 200ml ocean water were placed in a kitchen freezer until completely frozen. Ice and brine were separated at 5 minute intervals. Salinity and volume of melted ice were recorded, identifying the sample with lowest salinity. The process was repeated serially for this sample until freshwater was attained. Ocean water salinity equals 32g/L, while freshwater salinity equals <= 1g/L. By 45 minutes of thawing, salinity of melted ice samples dropped 78.1% to 7g/L, with a yield of 143 ml (71.5% of 200 ml). The desalinated sample of ocean water was re-frozen and re-thawed. After a second cycle, salinity of melted ice dropped 86% to 1g/L, yielding 103 ml of melted ice (51.5% of the initial 200 ml). A third cycle of freezing and thawing yielded 56.6ml of melted ice (28.3% of the initial 200ml), with unmeasurable salinity and total dissolved solute level of 90ppm, comparable to tap water. Drinkable freshwater can be practically obtained at home with a kitchen freezer through 2-3 cycles of serial freezing and thawing. This process of cryo-desalination can help alleviate the world's water shortage crisis. As global water demands increase, it will be critical to further investigate automation and portability of this process.

Keywords: Novel, partial thaw, cryo-desalination, consumer kitchen freezer, drinkable freshwater from ocean water.

Introduction

Currently, 2.2 billion people lack access to drinking water, and roughly half of the world's population currently experiences severe water scarcity for at least part of the year[1]. The UN Water Development report predicts that in 30 years, global freshwater needs will increase 20-30% due to uneven water distribution caused by global warming and commercial influence[1,2]. 97% of the world's water is contained in the ocean, which cannot be consumed due to saline content. Desalination, or the purification of ocean water into usable freshwater, represents one potential solution to the earth's current water crisis[3,4]. Several common desalination methods such as distillation and reverse osmosis are energy intensive, requiring high heat or pressure. Cryo-desalination is an alternative desalination method based on exclusion of dissolved salt that occurs as ice crystals form[5]. Freezing requires seven times less energy than evaporation and does not require the use of membranes, which are expensive and difficult to manufacture[6]. Cryo-desalination represents an energy-efficient method of desalination[7].

Cryo-desalination involves three primary components: the formation of ice, separation of ice from brine, and thawing of the ice[8]. The separation of ice from brine can be conducted in two ways. The first method, partial thawing, involves completely freezing ocean water and progressively melting the ice to purify the water. The second method, progressive freezing, involves partially freezing ocean water to produce ice and brine.

The purpose of our study was to determine whether ocean water can be converted to drinkable freshwater through cryo-desalination using a kitchen freezer by means of both partial freezing and partial thawing.

Materials and Methods

Cryo-desalination was conducted using 5000 ml of ocean water (from Fort Baker, Sausalito, CA), a Kitchen Aid 42 inch built-in refrigerator, a Sungrow saltwater aquarium refractometer, a TDS meter digital water tester thermometer, Signature select 25 fluid ounce home entrée containers, a graduated cylinder and beaker set, plastic funnels and pipets, a metal strainer, and silicone tipped baking tongs.

First, cryo-desalination was tested through the process of partial freezing. 200 ml of ocean water was frozen to determine the time required for ice particles to begin forming, which was ascertained to be approximately 75 minutes. Then, 10 containers each filled with 200 ml of ocean water at 19℃ room temperature were labelled 1-10 with a sharpie marker.

The containers were stacked and evenly spaced on racks in an empty kitchen freezer with an internal temperature of -19℃ (Figure-1).

Every 5 minutes after the initial 75 minute mark, a container was removed, and its contents immediately transferred to a strainer for 25 seconds to separate the shards of ice from the brine (Figure-2).

Once the ice separated from the brine, it was melted in a microwave oven. The salinity and the volume of the melted ice, or product water, were then measured for each sample. Salinity was quantified using a saltwater aquarium refractometer (Figure-3).

A Spearman rank-order correlation was performed to assess the relationship between freezing times and salinity.

Figure-1: 10 Containers, each with 200cc ocean water, were placed in an empty kitchen freezer.

Figure-2: Contents of container were placed in a strainer to separate ice shards from brine every 5 minutes.

Figure-3: Salinity was measured with an aquarium saltwater refractometer.

Cryo-desalination was also tested through the method of partial thawing. For the method of partial thawing, 200ml of ocean water at 19℃ room temperature were again poured into 10 containers. The containers were evenly spaced on racks in a kitchen freezer and completely frozen at -19℃, which took 2.5 hours. After container contents were completely frozen, the containers were removed from the freezer simultaneously and then evenly spaced on a kitchen countertop. In order to ensure that the ice melted similarly and evenly, the ice blocks were immediately tilted to begin melting at a room temperature of 22.8℃ (Figure-4). After 5 minutes, the first piece of ice was lifted out of the container and gently shaken for 15 seconds using silicone tipped tongs (Figure-5). This process continued with each piece of ice being shaken in progressive 5 minute intervals. Analogous to the partial freezing experiment, each piece of ice was melted in a microwave oven, and salinity and volume measured for each sample. A Spearman rank-order correlation was performed to assess the relationship between thaw time and salinity. From those 10 samples, the sample with lowest product water salinity was identified. Then, that sample was completely re-frozen and thawed for the same time interval for 2 more successive cycles. For cycle 2 and cycle 3, both the salinity, total dissolved solids (TDS), and volume of the product water were measured. The TDS of kitchen tap water was also measured as a reference to compare with the salinity and purity of the product water generated from the third cycle (Figure-6).

Figure-4: Containers were removed from freezer and ice blocks were tilted and melted at 22.8 degrees Celsius.

Figure-5: After melting for 5 minutes, ice blocks were gently shaken for 15 seconds with silicone tongs.

Figure-6: Total dissolved solids (TDS), for product water as well as tap water were measured.

Results and Discussion

Both the partial freezing cryo-desalination experiment and the partial thawing experiment assessed the feasibility and efficiency of cryo-desalination by quantifying changes in salinity and volume of ocean water. The partial freezing experiment determined that there was no significant correlation between the time required to partially freeze ocean water and the product water's salinity. Spearman rank-order correlation, $\rho = -0.44$, $p = 0.21$. Throughout the 50 minute partial freezing experiment, the salinity of the product waters barely changed. At 75 minutes, the product water measured 28 g/L, a 21.9% drop from the ocean water's initial salinity of 32 g/L. From 80 to 90 minutes, the product water salinity dropped to 25g/L and remained at 25 g/L. At 95 minutes, the salinity of the product water rose back up to 28 g/L, and for the final 20 minutes of the partial freezing experiment, salinity of product water dropped back down to and remained at 25 g/L (Figure-7). Yield of the product water trended from 88-130 ml at 85 to 95 minutes, and thereafter, between 120 ml-109 ml to 120 minutes (Figure-8).

For the partial thawing cryo-desalination experiment, statistically significant negative correlation between partial thaw times and product water salinity was demonstrated. Spearman rank-order correlation, $\rho = -0.95$, $p < 0.001$, indicating that salinity decreased consistently with increasing thaw time. Product water salinity measured 26 g/L at 5 minutes, 17 g/L at 25 minutes, and 7 g/L at 45 minutes (Figure-9). The recorded 7 g/L salinity at 45 minutes represented a 78.1% drop in salinity from the initial salinity of 32 g/L for ocean water. From 5 through 45 minutes, volume of product water progressively decreased from 195 ml to 143 ml. 143 ml represented 71.5% of the initial ocean water volume of 200 ml (Figure-10). Product water salinity from successive cryo-desalination of the 45 minute sample measured 1 g/L for the 2nd cycle and was clearly below 1 g/L mark, but too low to accurately measure for the third cycle (Figure-11). The saltwater aquarium refractometer used in the experiment minimized at a salinity of 1 g/L. The TDS of the product water measured 624 ppm after the second cycle and 90 ppm (90 mg/L) after the third cycle. By comparison, the TDS of tap water was 75 ppm (Figure-12). 78.1% and 85.5% decreased salinity after the first and second cycles paralleled the 85.6% decreased TDS after the third cycle (Figure-13). Product water volumes yielded after the 1st, 2nd, and 3rd cycles were 143 ml, 103ml, and 56.5ml respectively. Product water volume yielded after the second and third cycles were 51.5% and 28.3% of the original 200ml of ocean water (Figure-14).

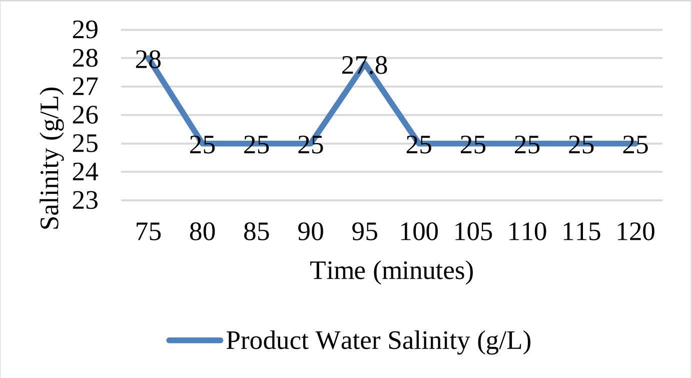

Figure-7: No significant correlation between the partial freeze times and product water salinity was demonstrated between 75 and 120 minutes.

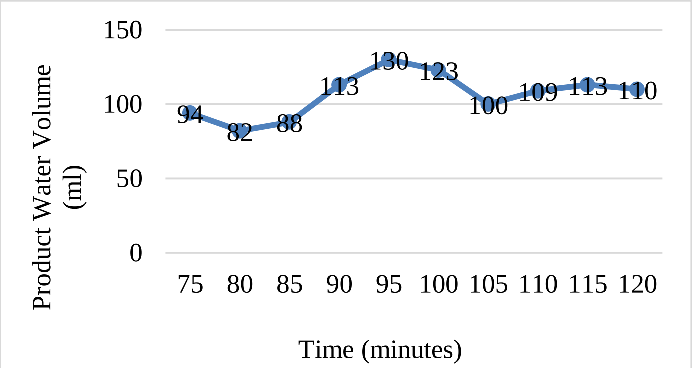

Figure-8: Product water yield in ml at partial freeze times between 75 and 120 minutes.

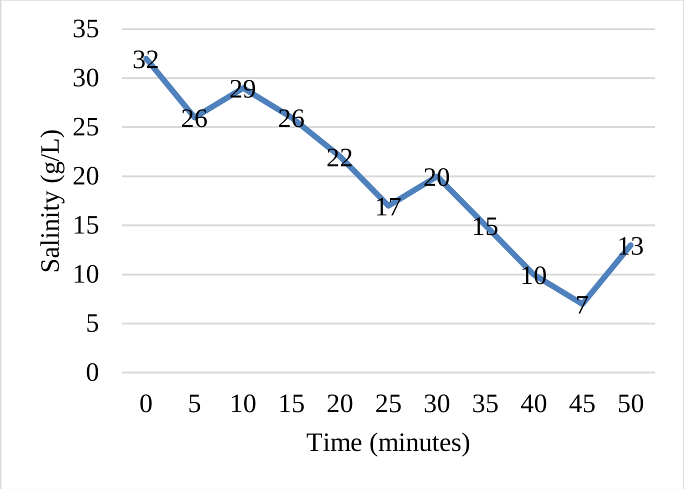

Figure-9: Statistically significant negative correlation between partial thaw times and product water salinity was demonstrated between 5 and 50 minutes.

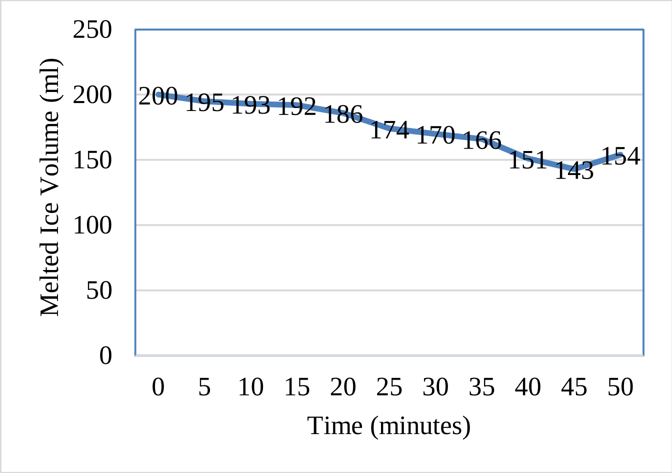

Figure-10: Product water yield with partial thawing between 5 and 50 minutes.

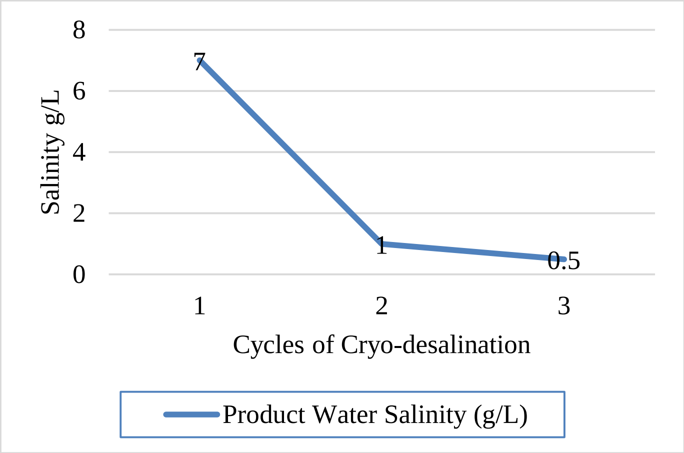

Figure-11: Product water salinity of 1g/L after the 2nd cycle and salinity below 1g/L and too low to accurately measure for the 3rd cycle (45 minutes partial thaw sample).

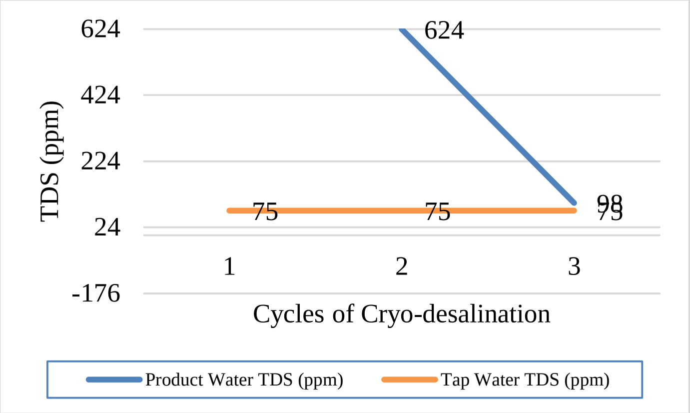

Figure-12: Total dissolved solutes (TDS) decreased from 624 ppm to 90 ppm between second and third cycles of cryo-desalination. For reference, tap water measured 75 ppm.

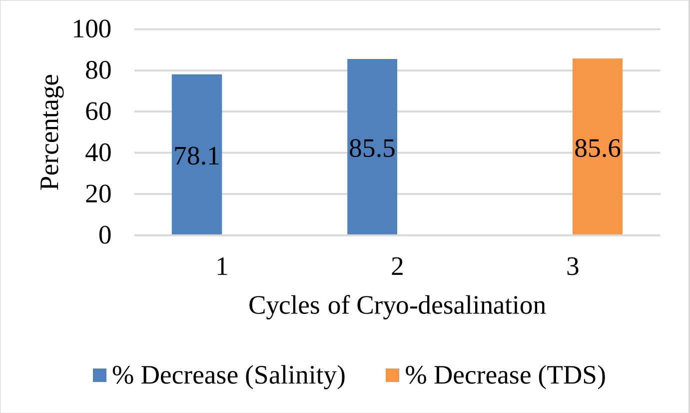

Figure-13: Percentage decrease in product water salinity between first and second cycles parallels percentage decrease in TDS between second and third cycles.

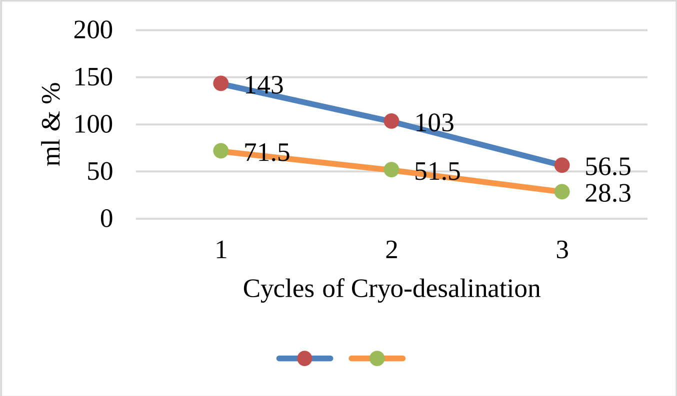

Figure-14: Product water yield in ml and as percentage of original volume after 3 cycles of partial freeze thawing cryo-desalination.

Conclusion

During the partial freezing cryo-desalination experiment, a slurry of brine and ice crystals formed. Ice crystals varied in size from small granules to ice sheets. Time dependent increase in ice crystal size was inconsistent, with some large ice sheets forming at earlier time points and some smaller ice crystals forming at later time points. Gravity separation of salt from ice within this slurry by a strainer was not very effective. Only a 21.9% decrease in ocean water salinity was achieved. This would require 14 successive cycles of partial freezing to produce freshwater, not a practical or efficient process. The variable sizes of ice with progressive freezing was due to one major variable: not all of the containers were in direct surface contact with the freezer racks; some containers were stacked on top of each other in order to fit all 10 containers. Different positions of the containers within the freezer likely accounted for the inconsistency in ice formation. While some containers' contents froze more quickly due to direct contact with the cold freezer racks, stacked containers did not freeze as quickly because stacked containers were being frozen purely by cold air, which was not as efficient. To summarize, partial freezing requires extreme attention to small details, making it not a practical or efficient method of cryo-desalination at home.

In contrast, the method of partial thawing of ocean ice achieved high separation of salt from ice. After 45 minutes of thawing, salinity of the ocean water decreased by 78.1%. With the partial thawing technique, all ocean water samples were completely frozen before thawing, thus eliminating variables encountered with partial freezing. Evenly spaced ice samples on a countertop in the center of the kitchen controlled for potential variations in room temperature. As ice thawed, water from thawing ice blocks washed away salt released from brine pockets within the ice as well as salt adherent to the ice surface[9,10,11]. With increased time, more salt was washed away, resulting in time dependent increase in brine volume and decrease in ice size and product water volume. In other words, time dependent separation of salt from ice was observed with partial thawing technique due to inherent time dependent washing that occurred with progressive thawing. After a second cycle of freezing and 45 minutes of partial thawing, 103 ml of freshwater (1g/L) was produced. After a third cycle, 53 ml of freshwater was produced with TDS values comparable to tap water, 90 vs 75 ppm. TDS values 50-150ppm are considered excellent for drinking water[12]. Although unmeasurable, salinity is estimated between 0.15-0.22 g/L based on trends in Figure-13. 53 ml represented 28.3% initial ocean water volume, an acceptable yield.

In conclusion, A kitchen freezer can be used to produce drinkable freshwater from ocean water. To our knowledge, this is the first research to describe effective cryo-desalination using a kitchen freezer. The partial thawing method of cryo-desalination proved to be effective and efficient compared to the partial freezing method. Using the partial thawing cryo-desalination approach, drinkable freshwater was obtained through 2-3 cycles of serial freezing and thawing. In conclusion, partial thawing cryo-desalination technique can help alleviate the world's water shortage crisis. As global water demands increase, it will be critical to further investigate automation and portability of this process.

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