

Two strategies for freeze desalination of seawater by progressive and block techniques

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ABSTRACT

This work is focused on the study of desalination of salt solutions (as a simulation of seawater fluid) through progressive stirred freeze concentration (PSFC) and block freeze concentration (BFC). The first strategy studies the effect of the initial concentration (C_0), agitation speed (ω) and refrigerant temperature (T) on the parameters of the PSFC process: ice concentration (C_i), impurity ratio (\bar{K}), and removal efficiency (RE). The results show that all the studied factors affect the final result of the solids concentration on ice, being the concentration of solids in the initial fluid the most relevant. Considering that the concentration 3.5% w/w is the same as seawater in Mediterranean Sea, based on the regression equation for C_i and taking the parameters ω (rpm) and T (°C) at its optimum value, there could be a scheme of progressive freezing in three stages. At the end of the three stages, ice with an electrical conductivity below the limits set by Directive 98/83/EC (2.5 mS/cm), to be considered safe water for human consumption can be obtained. Likewise, the use of vacuum-assisted BFC is analysed by combining different pressures and vacuum times on samples of salt solutions to simulate seawater. The absolute pressure of 10 kPa and an extraction time of 45 min allows obtaining ice with conductivity <2.5 mS/cm in three stages. Finally, the results obtained suggest that it is possible to combine the two techniques (PSFC + vacuum assisted BFC) in the same equipment.

Keywords: Seawater; Progressive freezing; Block freezing; Electrical conductivity; Ice

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1. Introduction

Freeze concentration is a unit operation to concentrate liquids through freezing and the subsequent separation of the purest frozen water fraction. The process involves a controlled decrease of temperature of the solution below the freezing point, with the purpose of avoiding the eutectic temperature where all the components of the product solidify [1]. Freeze desalination causes minimum problems of corrosion comparing with thermal desalination process. Relative to energy requirement, evaporation of water requires 2,500 kJ/kg while ice fusion is 333 kJ/kg. For desalination, the initial solution to be frozen does not need a pre-treatment step, thus chemicals required for pre-treatment could be avoided. In addition, it is not subject to fouling. The major advantage over membranes is that membrane processes can only concentrate to the osmotic limit. The freeze concentration can continue to be concentrated beyond this limit. In general, it can be seen that the membrane processes have the lowest energy consumption for desalination purposes, although it must be considered that freeze concentration is an emerging technology with wide possibilities for improvement. For example, a study by He et al. [2] reported how using liquefied natural gas, by replacing the external refrigeration cycle used in classical hydrate desalination plants, could reduce energy consumption to 0.84 kWh/m³, which is 75% of the energy saved that is required for the reverse osmosis process.

Diverse studies [3,4] suggest the following classification for the desalination by freezing process, according to the contact between the refrigerant and the solution: direct method and indirect method. On direct contact systems, a close mixture between the refrigerant and the product to be frozen takes place. The refrigerant, in a liquid state and under pressure, expands on the solution, where it vaporises at a lower pressure. The vaporisation process provides a refrigerating effect, and the formation of ice and/or solute crystals on the product. Recent studies focus on the use of the indirect method in order to avoid the contamination of the product and to maintain the stability of the refrigerant, although this method has high levels of ice productivity. The clathrate hydrate process can be considered as a variation of the direct freezing method, as most of the refrigerants used during the freezing process form hydrates under specific temperature and pressure conditions. Clathrate hydrate crystals are non-stoichiometric compounds and contain water and the hydrate-forming substance only. They can be formed at temperatures above the freezing point of water, being very interesting from the energetic viewpoint [5].

In the indirect method, there is a wall that separates the solution and the refrigerant. That is, there exists a physical barrier that hinders the heat transfer process between the refrigerant and the saline solution. Generally, indirect type processes can be classified in suspension crystallisation (SFC) [6–8] and layer crystallisation. The difference between the suspension and layer crystallisation involves the development of a single ice crystal in the case of layer crystallisation, which forms an ice sheet on the heat exchange surface (instead of several ice crystals as occurs in the suspension system) so that separation between the ice crystal and the solution will be easier and can be done

on the same equipment. In turn, the layer crystallisation method can be classified into three types: progressive freezing (PFC) [9,10], static crystallisation [11] and dynamic crystallisation [12,13]. Recently, the study of a PFC system entitled progressive stirred freeze concentration (PSFC) [14,15] has been reported. It consists of a stirred cylindrical reactor where the crystallisation occurs on the bottom and walls of the vessel. Ethanol–water and sucrose model solutions were used to study this technique.

In addition to the previously mentioned techniques, on the freeze concentration of liquid foods the block system (BFC) can as well be included, also known as freeze concentration by freezing–thawing. During BFC, the solution freezes completely and the temperature at the centre of the product is under the freezing point. The freezing process takes place in forced air freezers (air blast freezers). Subsequently, the formed block is thawed and the concentrated fraction detaches from the ice fraction by gravity [16]. One of the main advantages of this technique is the absence of moving parts, such as agitators or pumps, which is very interesting in relation to production costs. There exist several studies focused on improving the efficiency in solute recovery of the solution through the application of vacuum, centrifugal force, microwaves, annealing, ice nucleation protein, among others [15], with very promising results. Among them, we can emphasize by its simplicity the application of vacuum [17]. Its application in water desalination is not known, although in some cases vacuum filtration has been used as part of the ice-washing system [18].

On the other hand, several researchers [19–21] consider that the future of the freeze concentration applications will guide the development of new PFC and BFC equipment to replace the SFC system due to the simplicity of the separation process. The comparison or the combination of the two techniques for application in desalination has not been reported.

Taking into account all the above, the objective of this work is to study two strategies for water desalination: the first one by optimizing the PSFC process variables of salt solutions (initial concentration, refrigerant temperature and agitation velocity), using the response surface method (RSM); the second one by analysing the vacuum-assisted block technique (BFC) through several pressure–time combinations to obtain ice of comparable quality of water suitable for consumption. The possibility of combining the two techniques is also raised.

2. Materials and methods

2.1. Relationship between salt concentration and electrical conductivity

To establish the salt concentration–electrical conductivity curve, the following common salt solutions were prepared at different salt mass concentrations: 0.01, 0.025, 0.05, 0.1, 0.5, 1, 1.8, 2, 3.5, 5 and 7% w/w. The electrical conductivity was measured in triplicate by a CM35 portable conductivity meter (Crison, Spain) with an accuracy of $\pm 0.5\%$, at ambient temperature, previous calibration with patterns of 147 $\mu\text{S/cm}$; 1,413 $\mu\text{S/cm}$ and 12.88 mS/cm.

Eq. (1) allows to obtain the salt concentration from the measurement of electrical conductivity:

$$C = \frac{CE - 0.716}{16.71} (R^2 = 0.998) \quad (1)$$

where C is the concentration of salt in the solution (% w/w), and CE is the electrical conductivity (mS/cm).

2.2. Experimental procedure

2.2.1. Progressive stirred freeze concentration tests

To simulate seawater, commercial common salt (Unión Salinera de España) solutions of 1,200 mL were prepared in PSFC tests at different concentration levels, namely 0.025, 1.76 and 3.5% w/w (equivalent to 2,500; 17,600 and 35,000 mg/L). Before tests, the solutions were maintained at 1°C for 24 h. The experimental setup used is described in Moussaoui et al. [15]. The freeze concentration tests were performed with experimental equipment shown in Fig. 1. The solutions previously prepared were poured into a jacketed container (1) with an inside diameter of 115 mm, 230 mm of high (Trallero y Schlee, Barcelona, Spain) and 2,400 mL capacity. To control the heat exchange, the recipient was isolated using polyurethane foam (2). A blend of ethylene glycol–water 50% w/w was used as refrigerant fluid (5). The refrigerant that circulated the recipient comes from a thermostatic bath (3) (Polyscience 9505, USA), which allows for maintaining the temperature between -30°C and $150^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ and also have a temperature control system (4). The solution to be concentrated (6) was stirred in the jacketed tank by means of a mechanical stirrer (7). RGL-100 (Heidolph Instruments, Germany) provide with a speed control system (8). PCE-DT62 (PCE Deutschland GmbH, Germany) with 0.05% of precision and 0.1 rpm of resolution.

Before starting the tests, a pure ice layer was formed on the walls and bottom of the jacketed tank, according to the methodology described in previous works [15]. The freeze concentration tests were performed with 75 min duration, according to previous studies [15,22]. At the beginning and at the end of each test, as well as in the ice obtained, the electrical conductivity was measured at ambient temperature. The solution temperature was registered using a digital data logger Testo 925 (TESTO, Germany) provided with a K thermopar with precision of $\pm 0.1^{\circ}\text{C}$. At the end of the process, the concentrated salt solution was collected in a container to separate it from ice.

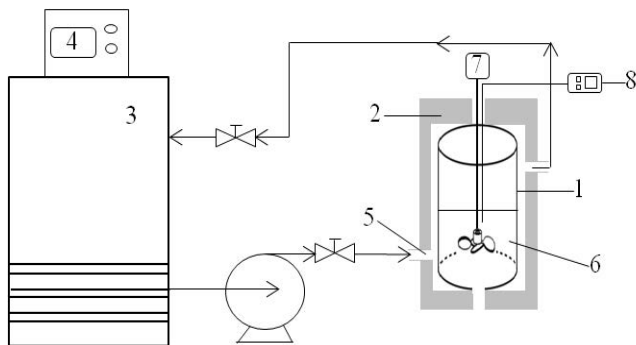


Fig. 1. Schematic experimental equipment for progressive stirred freeze concentration.

The concentrated salt solution and the ice obtained were weighed using a precision scale KB 1200-2N (KERN, Germany). The ice obtained was not washed.

2.2.2. Block freeze concentration tests

Saline solutions of 3.5% w/w (corresponding to an electrical conductivity of 59.2 mS/cm according to Eq. (1)) were prepared in 50 mL plastic tubes and frozen at -20°C for 48 h in a static freezer (THC 520 N1, Frigocon S.A., Portugal), according to the method described in Orellana-Palma et al. [23]. The tubes were covered with 9 mm thermal insulation of elastomeric foam ($K = 0.036 \text{ W/m } ^{\circ}\text{K}$) to maintain unidirectional heat transfer. The samples were removed from the freezer and then the extraction was completed under vacuum at room temperature. For the extraction, a vacuum pump (Comecta S.A., Barcelona, Spain) was used. Two pressures (10 and 40 kPa absolute) and two extraction times (30 and 45 min) were tested. Through a series of previous tests, the following vacuum pressure–time combinations were established: condition (1) 10 kPa and 30 min; condition (2) 40 kPa and 45 min; condition (3) 10 kPa and 45 min. To observe the improvement with respect to gravitational thawing, tests were carried out at 30 and 45 min without applying vacuum.

In Fig. 2, the general scheme of the tests is indicated. According to previous tests, a minimum initial quantity of 450 mL was established, that is, $N1 = 9$. The liquid phase extracted in each stage is discarded. The ice in each tube is thawed, mixed, its electrical conductivity was measured and used to prepare the samples of the next freezing and extraction stage. This process is repeated until ice of electric conductivity $< 2.5 \text{ mS/cm}$ is obtained.

2.3. Experimental design and statistical analysis

The results obtained were analysed statistically using Minitab 17 for Windows (Minitab Inc., State Collage, PA, USA) and expressed as the mean \pm standard deviation. A statistical significance level of $\alpha = 0.05$ was used in all tests.

The data of PSFC test were modelled and analysed by RSM. In order to determine the optimum conditions for the parameters, assays were performed using low and high levels for the independent variables, initial concentration (% w/w), temperature ($^{\circ}\text{C}$) and agitation (rpm). Coded levels for independent variables are presented in Table 1.

A 2^3 central composite design (CCD) with eight factorial points, six axial (star) points and three central points was used to obtain a second-order prediction model with 17 treatments in total (three replicates), as described in Table 2. The response surface results are shown in the results section.

2.4. Data analysis

2.4.1. Impurity ratio \bar{K}

Impurity of the ice refers to the salt from the solution retained in the ice and that, therefore, diminishes its purity [10,15,20]. Consequently, lower impurity ratio indicates better desalination efficiency. This parameter is defined as the relation between the concentration of solutes in the ice (C_i)

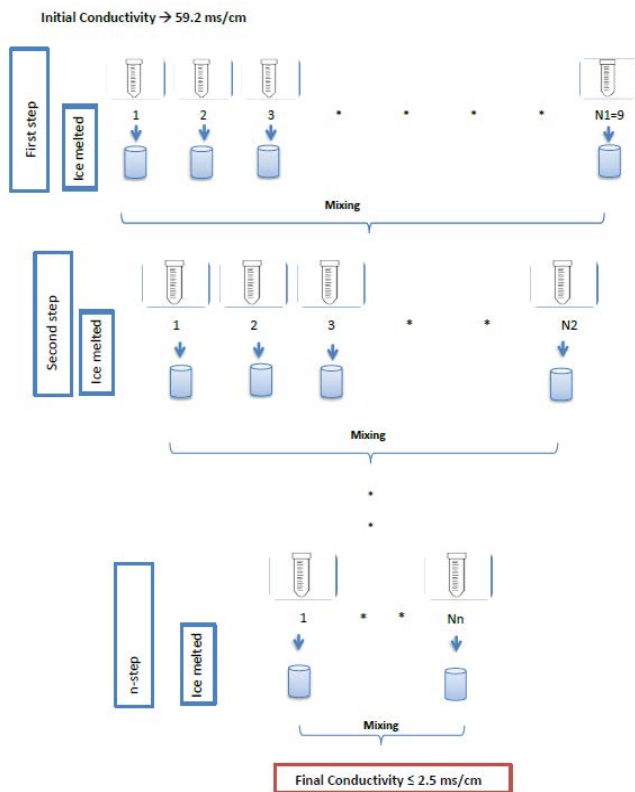


Fig. 2. General scheme of the tests in block freeze concentration. For each stage, the liquid fraction is discarded and the ice obtained is thawed and mixed.

Table 2

Central composite design and the experimental values from the response variables according to the levels of the factors in progressive stirred freeze concentration

	Test	C_0 (% w/w)	T (°C)	ω (rpm)	Response		
					K	RE	C_i (% w/w)
Factorial	1	0.025	-14	500	0.028 ± 0.005	89.3 ± 2.2	0.0027 ± 0.0005
	2	3.5	-14	500	0.34 ± 0.04	31.6 ± 7.1	2.40 ± 0.25
	3	0.025	-6	500	0.021 ± 0.003	95.6 ± 0.69	0.0011 ± 0.0002
	4	3.5	-6	500	0.31 ± 0.02	61.2 ± 1.1	1.36 ± 0.04
	5	0.025	-14	1,500	0.025 ± 0.004	85.9 ± 2.95	0.0035 ± 0.0007
	6	3.5	-14	1,500	0.28 ± 0.03	37.3 ± 4.4	2.20 ± 0.15
	7	0.025	-6	1,500	0.033 ± 0.007	93.2 ± 1.39	0.0016 ± 0.0004
	8	3.5	-6	1,500	0.22 ± 0.01	69.7 ± 1.7	1.06 ± 0.06
	9	0.025	-10	1,000	0.018 ± 0.001	95.1 ± 0.23	0.0012 ± 0.0000
Star	10	3.5	-10	1,000	0.29 ± 0.03	54.2 ± 5.2	1.60 ± 0.18
	11	1.76	-14	1,000	0.23 ± 0.02	40.9 ± 2.3	1.04 ± 0.04
	12	1.76	-6	1,000	0.28 ± 0.02	58.3 ± 4.1	0.73 ± 0.07
	13	1.76	-10	500	0.30 ± 0.04	45.8 ± 2.2	0.95 ± 0.04
	14	1.76	-10	1,500	0.24 ± 0.04	51.1 ± 6.9	0.86 ± 0.12
Center	15	1.76	-10	1,000	0.22 ± 0.02	55.5 ± 8.8	0.78 ± 0.16
	16	1.76	-10	1,000	0.21 ± 0.01	59.3 ± 10.4	0.72 ± 0.18
	17	1.76	-10	1,000	0.22 ± 0.00	61.2 ± 6.9	0.68 ± 0.01

Table 1

Factor values at the low (-1), center (0) and high (+1) levels studied in progressive stirred freeze concentration tests

Factors	Levels		
	-1	0	1
Concentration (% w/w)	0.025	1.76	3.5
Temperature (°C)	-14	-10	-6
Agitation (rpm)	500	1,000	1,500

and the concentrated solution (C_s) at the end of each experiment, as described in Eq. (2).

$$\bar{K} = \frac{C_i}{C_s} \quad (2)$$

2.4.2. Freeze salt removal efficiency (RE)

The freeze salt removal efficiency is defined as the percentage of salt removed during freeze desalination. It was calculated by Eq. (3). The removal efficiency is equivalent to the salt rejection or the desalination rate [24,25]. The desalination rate can also be an indicator to the efficiency of the system. A higher value of RE indicates a better performance for the system.

$$RE = \left(1 - \frac{C_i}{C_0}\right) \times 100 \quad (3)$$

where C_i is the salt concentration in the ice fraction and C_0 is the salt concentration in the initial solution.

3. Results and discussion

3.1. Progressive stirred freeze concentration tests

The experimental data corresponding to the impurity ratio (\bar{K}), removal efficiency (RE) and ice concentration (C_i) in PSFC tests are presented in Table 2.

The p -values of the reduced model are shown in Table 3 for \bar{K} , RE and C_i . Although the initial model for each response variable studied was significant ($p < 0.05$) and also with a high coefficient of determination (R^2), the reduced model was used in order to eliminate the redundant information by means of the forward selection of terms method (α to enter 0.25).

3.2. Impurity ratio (\bar{K}) and removal efficiency (RE)

In general terms, the less solute retained in the ice, the more salt concentrated in the solution, and therefore the lower \bar{K} becomes. For the desalination purpose, it is important to obtain high purity ice, that is, a low \bar{K} and high RE values. In the reduced final model (Table 3), it is observed that only the individual factors (C_0 and ω), the quadratic factor of C_0 and the double interaction have a significant effect on the response variable ($p < 0.05$). The factors that most affect \bar{K} are in this order: C_0 , the quadratic factor C_0^2 , ω and the interaction $C_0-\omega$. For the parameter RE, the individual factors C_0 and T , the quadratic factors C_0 and ω , and the interactions of C_0 with T and ω are significant.

At a low initial salt concentration, few solutes accumulate at the ice–liquid interface and they can easily escape the ice front that is forming. The higher the initial salt concentration, the higher the concentration of solutes near the interface, the higher the viscosity and the lower the solute mobility. The mass transfer of the solute near the interface ice–liquid would be retarded, so there would be a greater tendency of the solute to be trapped by the ice [26–28]. On the other hand, some studies [29] suggest a change in

ice structure from the columnar (planar front) to the dendritic form in the progressive freezing of NaCl solutions (the main component of simulated seawater solutions) at concentrations $\leq 0.05\%$ w/w. The higher the concentration of NaCl, the finer and smaller the dendritic structure is [30], which could favour the retention of solutes. This indicates that the desalting effect by the agitated progressive freeze concentration system is better at low initial concentrations of solutes. A similar trend has been observed in desalination works [10].

3.3. Multi-stage PSFC process for obtaining water suitable for human consumption

As shown in Table 3, in the final reduced model, both the individual factors and the double interactions have a significant effect on the concentration of solids in ice (C_i). The factors that most affect C_i are in this order: C_0 , T and interaction C_0-T . The regression equation of the reduced model for C_i is presented in Eq. (4), with an R^2 value of 0.974:

$$C_i = 0.331 + 0.177C_0 + 6.67 \cdot 10^{-3}T - 6.91 \cdot 10^{-4}\omega - 3.9 \cdot 10^{-2}C_0 \cdot T - 7.2 \cdot 10^{-5}C_0 \cdot \omega \quad (4)$$

With the adjusted coefficient of determination (R^2), it can be said that the reduced final model explains 97.4% of the response variable, indicating an optimal adjustment. The conditions that minimize the retention of solids on ice are $C_0 = 0.025\%$ w/w; $T = -14^\circ\text{C}$; $\omega = 995$ rpm.

From the regression equation for C_i (Eq. (4)) and taking the parameters of ω (rpm) and T ($^\circ\text{C}$) at their optimum value, a freeze concentration scheme could be proposed in several stages. Fig. 3 shows a possible scheme that would allow obtaining drinking water through PSFC in several stages. Within the tables, there are the initial concentrations in % w/w and the corresponding conductivity in mS/cm, according to Eq. (1). Taking into account that the legal limit for drinking water is a conductivity of 2.5 mS/cm (Directive 98/83/CE and Royal Decree 140/2003) in three stages ice assimilable to water suitable for human consumption could be obtained.

3.3.1. Block freeze concentration tests

For BFC tests, the methodology provided in Fig. 2 was followed. During the initial extraction phase (first step), ice conductivity results manifest that defrosting by vacuum (conditions 1, 2 and 3) surpasses gravitational defrosting (pattern 1 and 2), which oscillates between 46 and 48 mS/cm. As it can be observed in Fig. 4, the best result is obtained in condition 3, applying an absolute pressure of 10 kPa during 45 min, reaching a mean conductivity value of 15.22 mS/cm. This represents an approximate reduction of 74% from the original.

The analysis of variance (ANOVA) was applied in first step to compare the means of conductivity for the different conditions (obtained from the combination of time and pressure), followed by the corresponding separation of means. The distribution of the variable conductivity could be assumed to approach the normal

Table 3
 p -values of ANOVA test from the regression of the reduced model in progressive stirred freeze concentration

Term	p -value			
	Response			
	K	RE	C_i	
Reduced model	Constant	0*	0*	0*
	C_0	0*	0*	0*
	T	0.438	0*	0*
	ω	0.001*	0.153	0.009*
	$C_0 \times C_0$	0*	0*	–
	$T \times T$	–	–	–
	$\omega \times \omega$	0.053	0.003*	0.013*
	$C_0 \times T$	0.034*	0*	0*
	$C_0 \times \omega$	0.002*	0.021*	0.014*
	$T \times \omega$	–	–	–

–: term no applied in the model;
*Significant term (p -value < 0.05).

distribution. The assumption of equal variances was also met. Since it was concluded that the conditions had a significant effect on the conductivity (p -value < 0.001), then the Tukey test was used to compare differences between all pairs of groups. Table 4 provides a numerical summary of the variable conductivity according to the three conditions studied. The means for conditions 1 and 2 showed no significant differences between them. That is to say, conductivity behaved similarly in both conditions. The lowest mean was achieved in condition 3.

As results on conditions 1 and 2 did not display statistically relevant differences, it was decided to continue the extraction in further stages with conditions 1 and 3 only. In Fig. 5, the results of the different extraction by vacuum stages in condition 1 (10 kPa during 30 min) and condition 3 (10 kPa during 45 min), respectively, are collected.

In condition 1, water suitable for human consumption (<2.5 mS/cm) can be obtained on a five-stage process (150 min). In condition 3, the process is reduced to three stages (135 min). The longer the defreezing time at each stage, the purer ice is obtained, with less conductivity. The longer the duration of each stage, the solutes

have more time to leave the ice matrix. A possible strategy would be to extend the timings on each stage in order to reduce the final time. Under the conditions in which these tests have been performed, it has not been possible to establish stages with timings greater than 45 min due to the loss of vacuum on the samples.

3.3.2. Comparison between PSFC and vacuum-assisted BFC

From all the above, it is concluded that the two freeze desalination strategies presented allow the desalination of seawater until reaching a conductivity of less than 2.5 mS/cm, which is the legal limit for drinking water. Based on the experiments carried out and the proposed desalination schemes (Figs. 3 and 5), the total amounts of ice suitable for human consumption are similar in the two proposed strategies and are in the range of 145–175 mL. In the PSFC process, it takes a time of 225 min (three stages of 75 min) to obtain ice less than 2.5 mS/cm, while in the vacuum-assisted block system (BFC), the best condition (10 kPa, 45 min) allows obtaining this ice in only 135 min of extraction (three stages), to which the freezing time must be added in each

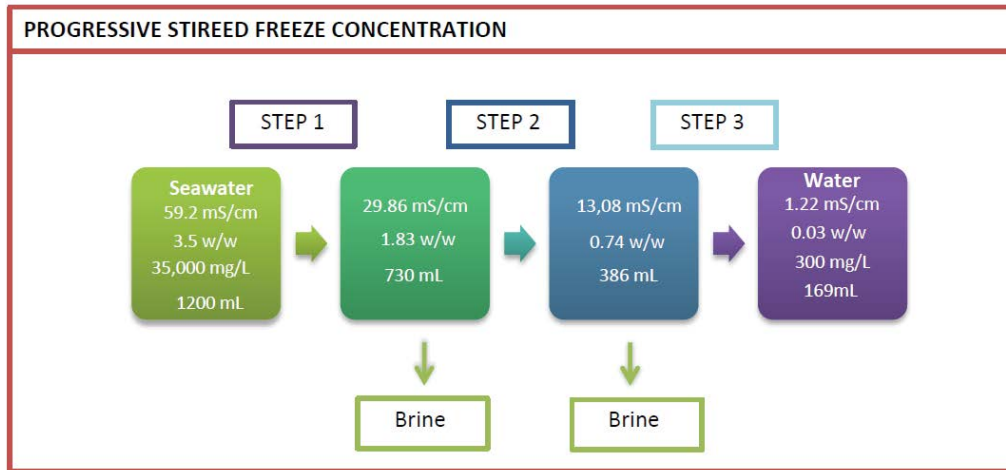


Fig. 3. Progressive stirred freeze concentration system scheme for a three-stage desalination.

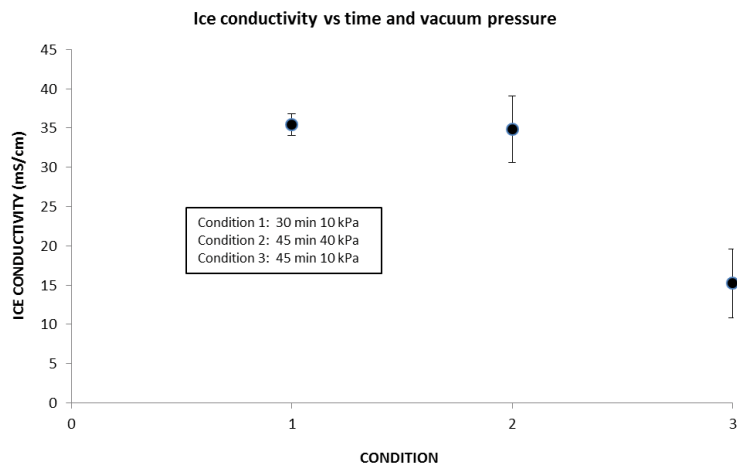


Fig. 4. Ice conductivity vs. vacuum condition (time and pressure) during first stage of block freeze concentration.

stage. The freezing time of the 50 mL samples used in the block system has been estimated applying the model proposed by Pham [31], resulting in a value of 240 min at each stage. So in the block system, the total time (freezing + vacuum) in the three stages is 855 min. The PSFC system requires less processing time than the BFC system, although it has the advantage of its simplicity, it may be of interest due to its lower initial investment cost. In addition, according to Figs. 2 and 4b, it can be seen that the productivity of water suitable for human consumption is higher in BFC-assisted vacuum, 39 mL water/100 mL seawater, compared with the 14 mL water/100 mL seawater provided by the

PSFC system. This may be because the salt removal efficiency (RE) is higher in the vacuum-assisted BFC than in PSFC system. The results seem to suggest that it would be possible to combine the two techniques (PSFC + vacuum assisted BFC) on the same device. A stirred reactor could be designed where rapid ice production (PSFC) is achieved. Subsequently, by applying a vacuum, efficient recovery of the solutes retained in the ice occurs.

Table 5 is attached where information on the main indicators of the PSFC and BFC process tested on a laboratory scale is collected.

Although it was not among the objectives of the work to evaluate the energy efficiency of the process, it is a laboratory-scale equipment, it has been possible to make an estimate of energy consumption. Energy costs are around 40%–60% of the total costs through desalination [32]. In both processes, the source of energy used is electricity. For the purposes of calculating the specific energy consumption (SEC), the data reported previously [33] have been taken into account for PSFC, while for BFC a coefficient of performance in the refrigeration system of 2 has been adopted. As can be seen, the SEC for each process, expressed as kWh/kg of seawater (SW) is 1.7 higher in the case of BFC compared with PSFC, which suggests more operating costs

Table 4
Grouping information using the Tukey Method (95% confidence) in block freeze concentration

Conditions	N	Mean	Grouping
Condition 1	9	34.01 ± 4.54	A
Condition 2	9	34.86 ± 4.23	A
Condition 3	9	15.25 ± 4.41	B

Means that do not share a letter are significantly different.

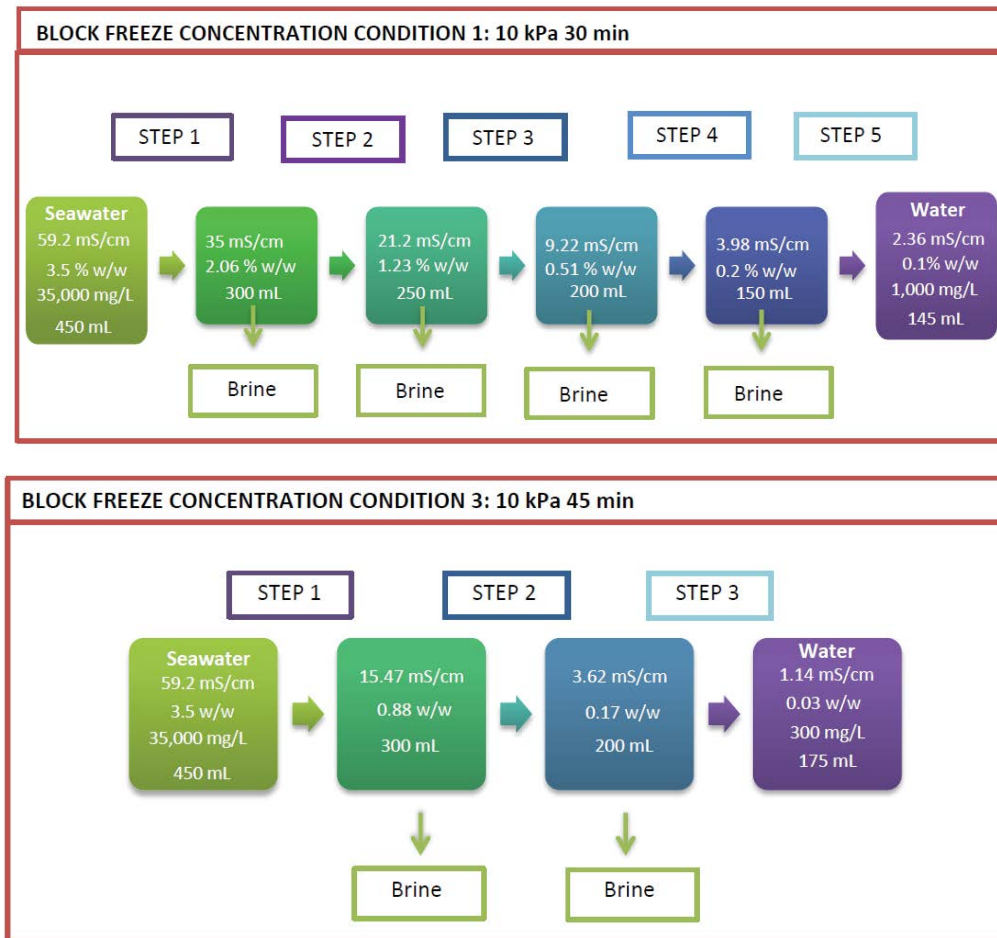


Fig. 5. Block freeze concentration system scheme for desalination: (a) condition 1 and (b) condition 3.

Table 5
A comparison of main parameters, between PSFC and BFC

	PSFC	BFC
Process time (h)	3.75	14.25
SEC (kWh/kg SW)	0.42	0.72
Productivity (kg DW/kg SW)	0.14	0.39

SW: seawater; DW: drinkable water; PSFC: progressive stirred freeze concentration; BFC: block freeze concentration; SEC: specific energy consumption.

reduced for PSFC. On the other hand, research carried out on the economic evaluation of the progressive freezing desalination process indicates that the energy consumption of a small installation could be very low. Indeed, the study has shown that freezing is positioned between reverse osmosis, less greedy (between 3 and 5 kWh/m³) and distillation 24–27 kWh/m³ [34]. Calculations show that the energy consumption of desalination by freezing is approximately 10 kWh/m³ [35,36]. Recent work [37] indicates that the coupling between reverse osmosis and freezing can reduce energy consumption to values close to 5 kWh/m³.

On the other hand, as the productivity of BFC is higher than PSFC, for the same production capacity of drinkable water, less consumption of seawater (SW) is required, therefore smaller equipment and probably lower investment costs initial. All of the above reinforces the idea that combining both techniques can be of interest for the desalination process and to adjust investment and operating costs.

4. Conclusions

It has been possible to perform water desalination of simulated seawater using two freeze concentration techniques (PSFC and BFC), and obtain water suitable for human consumption (electrical conductivity ≤ 2.5 mS/cm) in accordance with the European and Spanish regulations (Directive 98/83/CE and Royal Decree 140/2003). In the case of PSFC, both the individual factors were analysed: initial concentration (C_0), refrigerant temperature (T) and agitation velocity (ω), as some double interactions, have significant influence on the process. The conditions that minimize the retention of solids on ice are $C_0 = 0.025\%$ w/w; $T = -14^\circ\text{C}$; $\omega = 995$ rpm. Through a three-stage process, water suitable for human consumption could be obtained. Likewise, as regards the BFC technique, water suitable for human consumption has been obtained in a three-stage process, working at an absolute pressure of 10 kPa for a total time of 135 min. Although the PSFC system requires less processing time than the BFC system, the latter has the advantage of its simplicity, which may be of interest due to its lower investment cost. The results suggest the possibility of combining the two techniques (PSFC + vacuum-assisted BFC) in the same device, to produce and purify ice efficiently.

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