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Evaluation of the energy consumption of industrial hybrid seawater desalination process combining freezing system and reverse osmosis

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ABSTRACT

Desalination of seawater can provide an almost inexhaustible source of freshwater if it can be made affordable. This work is part of an innovative approach aimed at improving the seawater desalination cost through the development of a new method which is more efficient than the existing processes in use. A benchmarking study and a literature analysis were realized, and the results helped us in orientating research study toward the development of an industrial hybrid system coupling freezing and reverse osmosis (RO). The freezing process is proposed as a method of seawater pre-treatment for the RO membranes. It is coupled with a heat pump system which freezes the seawater inside a crystallizer and melts the ice in a melting chamber. By combining freezing and membrane desalination processes, the hybrid system has been successfully improved. The evaluation of the proposed systems' energy consumption shows energy savings of approximately 25%, and an improvement of the quality of osmotic water for about 71% when compared to the conventional-RO desalination. This evaluation was conducted on the basis of mass and energy balances of the freezing process and simulation of the RO desalination process using a non-commercial software.

Keywords: Hybrid desalination; Seawater; Freezing; Reverses osmosis; Ice crystallization; Energy consumption

1. Introduction

Despite important progress in the management of water resources, the drinking water scarcity increases and represents a major technical and economical issue in many countries. To overcome this problem, the main solutions are the wastewater reuse and seawater desalination. The latter is used principally because the ocean constitutes 97% of the water on our planet. Indeed, it is considered an almost inexhaustible resource.

Two major types of technologies are used for desalination and can be classified as either thermal or membrane process. For thermal processes, distillation is widely used where the energy source (oil or solar energy) is abundant. This method is quite expensive

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despite the improvements made in the energy recovery systems [1].

For membrane processes, reverse osmosis (RO) represents more than 50% of the global capacities of the water produced by desalination. This is due to its simplicity of implementation and its low energy cost when compared with other industrial desalination processes [2]. One of the most significant factors in successful operating of RO desalination plant is a good quality pre-treatment process. Pre-treatment technologies serve to reduce the fouling potential, increase the RO membrane life, and minimize scaling on the membrane surface. These technologies are commonly grouped into two categories, namely conventional process and membrane process.

Conventional RO pre-treatment system has been widely applied for seawater RO plants to achieve the expected quality of feed water to the RO membrane. However, the system was very difficult to control [3]. With the deterioration of feed waters and the consideration of the less efficient conventional system, an increasing number of plant owners are nowadays considering the use of membrane pre-treatment [4].

The membrane pre-treatment increases permeate flux, supplies better quality feed water to the RO stage, and often makes the use of cartridge filters unnecessary. However, the microfiltration/ultrafiltration element cannot be operated at high flux rates while treating highly fouling surface water due to the severe membrane fouling and plugging of fibers [5].

Other techniques for desalination of seawater are currently under development, such as freezing, electrodialysis, humidification and dehumidification. Although, freeze desalination is not widely used commercially, this process has some advantages. The most important one is the very low energy requirement compared to that of distillation processes [6,7]. Reduction in energy costs results as the latent heat of ice fusion is only one-seventh the latent heat of water vaporization. Effectively, desalination by freezing could achieve 75–90% reduction in the energy which is required for the conventional thermal process [8]. It also has the advantage of a low operating temperature, which minimizes scaling and corrosion problems [9]. Thus, inexpensive plastics or low-cost materials can be used at low temperature [10]. Desalination by freezing process does not need pre-treatment step; thus chemical products required for this pre-treatment could be avoided. In addition, it is not subject to fouling, similar to membrane desalination [11], and has a low ecological impact [12].

It is almost impossible to obtain pure ice crystals by freezing method aone. Ice quality is influenced by some factors during the freezing desalination process [13–15].

Thus, during the formation and growth of ice crystals, the contamination induced by impurities is not avoided, which results in poor water quality, loss of mother liquid, and difficulty in purifying ice crystals [16].

Therefore, freezing process could be used as a pre-treatment for seawater desalination with further treatment followed by another method. This hybrid approach could provide a synergy to the desalination process [17]. Various researches indicate that there is a high potential in combining the freezing process with other desalination techniques, such as RO, since fouling is always the major limitation of the process.

In this work, we propose and explore a new concept for desalination process based on hybrid technology. This process uses both freezing and membrane processes in the aim of reducing the energy consumption for seawater desalination. The proposed industrial hybrid process presents several advantages, such as fewer foulants and lower operating pressure in RO module compared to typical RO processes since relatively pure solution is fed into the RO module. Therefore, the costs of the pump and membrane can be reduced, and a high-quality water can be obtained as a product.

In this paper, we have used database of the industrial desalination plant, for energy consumption evaluation study of the proposed industrial hybrid process, to determine the potential of freezing process for seawater pre-treatment of the membrane modules. The obtained results are promising.

2. Description of industrial hybrid desalination process

Hybrid seawater desalination process that we proposed in this study involves both thermal and membrane processes. This process involves three main steps: filtration for removing the suspended solids of feed seawater, pre-treatment by freezing process that represents the subject of this work, and RO modules desalination. Fig. 1 represents the basic diagram of the hybrid process proposed.

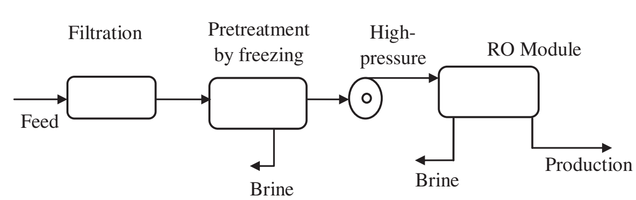

Fig. 1. Basic diagram of the proposed hybrid seawater desalination.

To our knowledge up till now, freezing seawater desalination plant is not commercialized. We have conducted many researches for analyzing industrial suspension crystallization plants [18,19]. Thus, we have adapted for freezing pre-treatment of seawater; the flow sheet is presented in Fig. 2.

In order to recover the process energy, the freezing unit is coupled with a heat pump system, and the feed seawater is pre-cooled by heat exchange with brine rejected and water pre-treated.

The pre-cooled seawater is then pumped into the crystallizer scraped surface heat exchanger (SSHE) where ice crystallization is conducted at a temperature, T_c, equal to −4˚C. Pure ice particles crystallized are scraped and entrained by concentrated seawater flow. The suspension obtained is sent to a separation column. Then, obtained ice crystals are melted in the melting chamber.

3. Methods of evaluating the hybrid process energy consumption

In this section, we presented the method of calculating the developed industrial hybrid process energy consumption. First, we have evaluated the heat pump energy consumption on the basis of mass and energy balances of the freezing plant. Then, we have determined the RO modules' energy consumption using a non-commercial simulation software.

3.1. Heat pump system's energy consumption

The ice crystallization in the SSHE is allowed by refrigerant evaporation in the heat pump, while ice melting in the melting chamber is due to the refrigerant condensation in the heat pump

Coefficient of performance (COP) can evaluate the performance of heat pump using the ideal value of COP_C calculated by:

$$COP_C = T_{EVAP}/(T_{COND} - T_{EVAP}) \quad (1)$$

where T_{EVAP} and T_{COND} are the evaporator and the condenser temperatures, respectively.

Isentropic compressor efficiency is assumed as the average value of 80%. Thus, the heat pump energy consumption is given by:

$$E = Q_{EVAP}/0.8 \times COP_C \quad (2)$$

where Q_{EVAP} is the heat that the primary refrigeration cycle removes from the crystallizer and is evaluated by:

$$Q_{EVAP} = Q_C + Q_{ADD} \quad (3)$$

where Q_C is the ice crystallizer's net cooling capacity and Q_{ADD} is the additional power required for preventing ice scaling.

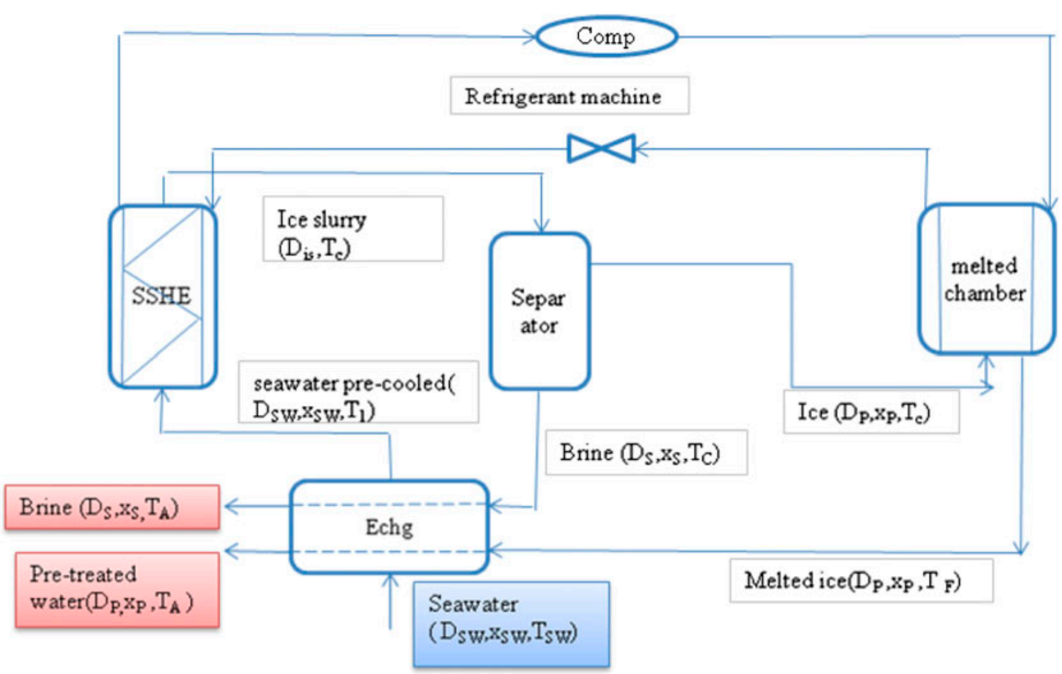

Fig. 2. Flow sheet of the freezing pre-treatment plant.

Furthermore, the additional power consumed by the motor driving the scraper blades in ice slurry generators is estimated at about 8% of net cooling capacity for ice slurry temperatures below −2˚C [19]:

$$Q_{ADD} = 0.08 \times Q_C \tag{4}$$

While the heat amount, Q_C, to be removed during the freezing step is given by:

$$Q_C = D_{SW} \times C_{PSW} \times (T_{SW} - T_C) + D_{CRY} \times (-\Delta H_F) \tag{5}$$

In order to estimate the ice crystallizer's net cooling capacity, Q_C, the mass and energy balances of the different freezing process units were developed and analyzed in Appendix 1.

Analysis of the degree of freedom realized for freezing plant showed that to solve the mass balance and energy balance equations, two specifications must be fixed:

(1) The ice crystal mass fraction in the crystallizer, k.
(2) The pre-treated water salinity in the output of the freezing plant, x_P.

3.2. RO modules energy consumption

The RO simulation software is a design program that estimates the performances of elements and/or membrane systems. Its permit is to determine the specific energy consumption and to evaluate the system energy requirements cost.

There is much non-commercial simulation software to determine the RO modules' specific energy consumption. In this study we have used IMS Design (Hydranautics, USA).

4. Results

4.1. Database

Before illustrating and discussing results, we should present the database used in this study.

A conventional RO desalination plant in the region of South Morocco designed by the "Office National de l'Eau Potable et de l'Electricité (ONEE)" is considered as a reference for this study [20]. The conventional pre-treatment used in this reference plant (RP) consists of acid addition, coagulant/flocculent addition, disinfection, media filtration, and cartridge filtration. The characteristics used are presented in Table 1.

The ice quality, x_P, in the output of the freezing process in this study is estimated to be equal to 14 g/l. This value represents a reduction of 60% (mean rate generally obtained) of the salinity after freezing desalination [21,22].

In this work, the average ice crystals mass fraction, k, in the crystallizer with a temperature T_c equal to −4˚C is estimated to be 35% [21]. Many studies indicate that higher solid fraction in the crystallizer resulted in lower ice quality [23], while lower solid fraction could give higher purity of ice [24].

A study of the effect of these parameters on the freezing process energy consumption will be presented thereafter.

4.2. Calculation of the freezing plant energy consumption

The resolution of mass balance and energy balance equations of different freezing process units gives results summarized in Table 2. This table represents flows, salinity, temperatures, and heat amount to be removed and to be provided for the freezing and melting of ice.

Thus, the heat, Q_{EVAP}, which, the primary refrigeration cycle removes from the crystallizer, is evaluated to be equal to 1.52 kW.

The ideal COP_C is evaluated to be 44.52. This value is high due to the low temperature difference between the condenser (0˚C) and the evaporator (−6˚C). The actual COP of the heat pump is estimated to be 35.62.

Therefore, the heat pump energy consumption is evaluated to be about 2.14 kWh/m^3.

4.3. Calculation of RO high-pressure pump energy consumption

The RO section having the same characteristics as the RP is constitutes of two trains; each train is composed of two stages. These latter involve six pressure vessels, each containing six RO modules (SW5+, spiral).

The feed flow rate per train is 10 l/s (average conversion rate is 50%). Therefore, the average flux is 13.5 L/m^{2}h.

Table 3 summarizes the obtained simulation results of RO modules. These results show a high-pressure pump energy consumption of about 1.36 kWh/m^3 and a very low salinity of osmosis water pre-treated by freezing of about 0.111 g/l. This value satisfies the drinking water standards.

4.4. Total hybrid process energy consumption

The total hybrid desalination process' energy consumption is the sum of the energy consumptions of the pre-treatment plant, RO modules, pumping

Table 1
Characteristics of this RP [20]

Characteristics	Value
Capacity (m^3/d)	864
Seawater salinity (g/l)	35
Seawater temperature (°C)	22
Conversion rate (%)	50
Energy consumption (kW/m^3)	6.95
High-pressure pump energy consumption (kWh/m^3)	3.73
Salinity of osmosis water (g/l)	0.387

Table 2
Results of mass and energy balances calculation related to the freezing plant

Rate of flow (m^3/d)		Salinity (g/l)		Temperature (°C)		Quantity of heat (kW)	
D_{SW}	3,653.48	X_{SW}	35	T_0	22	Q_C	5,086.44
D_P	1,728	X_P	14	T_1	−0.7		
$D_{SW,c}$	2,374.76	$X_{SW,c}$	53.84	T_C	−4		
D_S	1,925.48	X_{Cry}	0	T_F	−0.8	Q_F	5,264.96
D_{Imb}	449.28			T_A	20		
D_{Cry}	1,278.72						

Table 3
Data and results of the simulation of the operation of membranes

Simulation data base		Simulation results	
Type of membranes	SW5+	Average flow (l/m^2h)	13.5
Nature of membrane	Spiral	Feed pressure (bar)	32.9
Number of trains	2	RO water salinity (g/l)	0.111
Number of tubes per train	6	Pressure brine (bar)	29.2
Element number per tube	6	Salinity of brine (g/l)	30
Feed flow per train (l/s)	10	High-pressure pump power (kW)	47
Design temperature (°C)	20	High-pressure pump consumption (kWh/m^3)	1.36
Salinity of the seawater (g/l)	14		
Conversion rate (%)	50		
Age membranes (an)	5		
Fouling rate (%)	7		

stations, and the station of osmosis water demineralization. Table 4 shows that it is evaluated to be about 5.171 kWh/m^3.

5. Discussion

In this part, we presented a comparison of the proposed hybrid process with the conventional RO RP used. We also discussed the influence of the specification variation on the freezing process energy consumption.

5.1. Comparison of hybrid process and conventional-RO (RP) energy consumption

The theoretical evaluation of the energy consumption first showed that the high-pressure pump energy consumption of the industrial hybrid process (freeze RO) was lower than that of conventional RO process. The high-pressure pump energy consumption for hybrid process was about 1.36 against 3.73 kWh/m^3 for conventional RO process, which allows 63% of gain.

Also this study shows an improvement in the quality of osmosis water of about 71% compared to conventional-RO desalination. Freeze RO process reduced the salinity of seawater from 35 g/l to approximately 0.111 g/l, whereas the conventional RO water quality was about 0.387 g/l.

In addition, the total industrial hybrid process energy consumption was estimated to be 5.171 kWh/m^3 which is less than that of the conventional RO process (6.95 kWh/m^3), which allows 25% of gain.

Table 4
Total energy consumption of the hybrid process

Post	Consumption (kWh/m^3)
Pumping station of the drilling	0.394
Pumping station of pre-treatment unit	0.157
Pre-treatment plant by freezing	2.141
High-pressure pumping station of the RO	1.36
Remineralization of osmosis water [24]	0.483
Pumping station of treated water [24]	0.636
Total	5.171

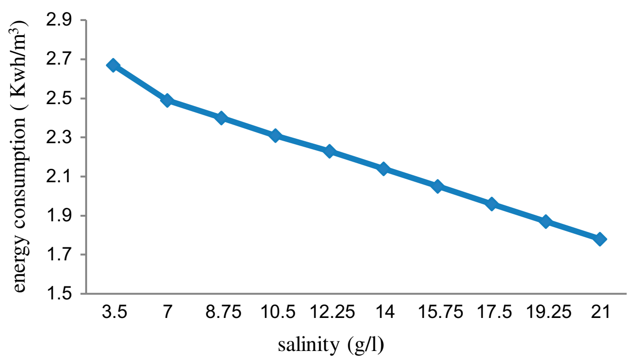

Fig. 3. Energy consumption depending on pre-treated water salinity.

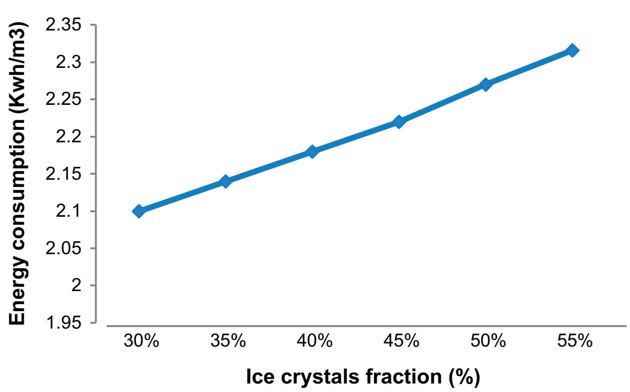

Fig. 4. Variation of energy consumption with the ice fraction in the crystalliser.

5.2. The effect of specifications variation on the freezing plant energy consumption

5.2.1. The effect of pre-treated water purity

Generally, the salinity of water obtained after desalination by freezing is reduced from 40% (21 g/l) to 75% (3.5 g/l) [21,22]. Fig. 3 illustrates the effect of pre-treated water purity on the freezing plant energy consumption.

This figure shows that the energy consumption increased with the salt quantity eliminated. Thus, better pre-treated water quality improves higher energy consumption. This explains the lack of industrial plants for seawater desalination by freezing.

5.2.2. The effect of ice crystals fraction in the crystallizer

Assuming that the ice crystals fraction in the SSHE, operating at −4˚C, varies between 30 and 55% [21,23,24]. Fig. 4 shows the freezing energy consumption variation with the ice crystals fraction in the crystallizer.

This figure shows that energy consumption is significantly influenced by the ice crystals fraction. The increase in the ice fraction implies higher energy consumption due to the higher removal heat, $Q_{EVAP,}$ from the crystallizer.

6. Conclusion

Seawater desalination as a source of potable water is likely to continue in the future, as available pure water sources are reducing. Conventional desalination technologies, such as RO and distillation, have equipment scaling-related issues that increase the operational and maintenance costs. Although the freeze desalination technique is not widely used commercially, this process has several advantages.

In this work, we proposed an industrial hybrid desalination process using freezing for pre-treating seawater of the RO membranes. Using industrial desalination plant characteristics as database, we have evaluated the hybrid process energy consumption to prove the potential of the freezing process for RO seawater pre-treatment.

The preliminary study results show that the combined system (freeze RO) reduces the energy consumption by about 25%, improves the osmosis water quality of about 71%, and decreases the brine-rejected salinity by approximately 26% compared to RO process using conventional pre-treatment. Moreover, as it is expected, the effective study of specifications variation shows that the energy consumption of the freezing process increased with the salt quantity eliminated and also by the ice crystals fraction in the crystallizer. These results are promising for the future development of such processes.

As future work, scientific knowledge of ice crystallization kinetics from seawater will be explored. This work will be based on an experimental study with the proposed freezing process test stand, and also a study of seawater freezing effect on the RO feed water quality in order to optimize the RO process and the energy required.

Nomenclature

D_{SW}	—	seawater rate at the input of the freezing plant, m^3/d
D_{IS}	—	ice slurry flow rate at the outlet of SSHE, m^3/d
D_{Cr}	—	ice crystals flow effectively crystallized in SSHE, m^3/d
$D_{SW,c}$	—	concentrated seawater flow non crystallized in the output of SSHE, m^3/d
D_S	—	brine flow in the outlet of the separation column, m^3/d
D_P	—	ice flow at the inlet of the melting chamber, m^3/d
D_{Imb}	—	imbibitions flow, m^3/d
T_0	—	average temperature of feed seawater, ℃
T_1	—	temperature of the seawater pre-cooled, ℃
T_C	—	freezing temperature, ℃
T_A	—	average temperature of pre-treated water and brine rejected, ℃
T_F	—	temperature of ice fusion, ℃
T_{EVAP}	—	evaporator temperature of the heat pump, ℃
T_{COND}	—	condenser temperature of the heat pump, ℃
x_{SW}	—	feed seawater salinity, g/l
$x_{SW,c}$	—	no crystallized seawater salinity, g/l
x_P	—	pre-treated seawater salinity, g/l
x_{Cry}	—	ice crystals salinity, g/l
x_S	—	rejected brine salinity, g/l
k	—	the average ice crystals mass fraction in the crystallizer (SSHE), %
Q_C	—	heat quantity for cooling, kW
Q_{EVAP}	—	heat quantity removed from the crystallizer, kW
Q_{ADD}	—	the additional power required preventing ice scaling in SSHE, kW
Q_F	—	heat quantity for melting, kW
E	—	the energy consumption of the heat pump, kWh

Abbreviations

RO	—	reverse osmosis
COP	—	coefficient of performance
SSHE	—	scraped surface heat exchanger
ONEE	—	office National de l'Eau Potable et de l'Electricité of Morocco
RP	—	reference plant

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Appendix 1. Analysis of the freedom degree of freezing plant

Mathematical modeling of the proposed pre-treatment process includes the analysis of each freezing system component. Mass and solute conservation equations along with energy balance equations are formulated.

The mass and energy balance equations related to the freezing plant

(1) Crystallizer (SSHE)

The mass balance equations are given by:

$$D_{SW} = D_{CRY} + D_{SW,C} \tag{A.1}$$

$$D_{CRY} = K \times D_{SW} \tag{A.2}$$

$$X_{SW} \times D_{SW} = X_{CRY} \times D_{CRY} + X_{SW,C} \times D_{SW,C} \tag{A.3}$$

The amount of heat removed during the freezing step is given by:

$$Q_C = Q_{SENS} + Q_{LAT} \tag{A.4}$$

$$Q_C = D_{SW} \times C_{PSW} \times (T_C - T_1) + D_{CRY} \times (-\Delta H_C(T_C))$$

(2) Separation column

The mass balance equations are given by:

$$D_{IS} = D_{CRY} + D_{SW,C} = D_P + D_S \tag{A.5}$$

$$X_{CRY} \times D_{CRY} + X_{SW,C} \times D_{SW,C} = X_P \times D_P + X_{SW,C} \times D_S \tag{A.6}$$

(3) Melting chamber

The mass balance equations are given by:

$$D_P = D_{CRY} + D_{IMP} \tag{A.7}$$

$$X_P \times D_P = X_{CRY} \times D_{CRY} + X_{IMB} \times D_{IMB} \tag{A.8}$$

The amount of heat required for melting is given by:

$$Q_F = D_{CRY} \times \Delta H_F(T_F) + D_{IMB} \times (T_A - T_C) \tag{A.9}$$

(4) Pre-cooling heat exchanger

The heat balance equation is given by:

$$D_{SW} \times C_{PSW} \times (T_1 - T_0) + D_P \times C_{PP} \times (T_A - T_F) + D_S \times C_{PS}(T_A - T_C) = 0 \tag{A.10}$$

Before solving the balance equations, we must ensure that the corresponding system of equations admits a solution. This involves looking for the number of degrees of freedom (DDL) of the system utilizing:

(1) Number of independent variables (NV);
(2) Number of independent balance equations (NE);
(3) Number of specifications (NS);

Where

$$DLL = NV - NE - NS \tag{A.11}$$

Calculation of DLL of the system

(5) Number of variables: $NV = 18$

Flow rates: D_{SW}, D_{Cry}, $D_{SW,c}$, D_S, D_{Imb}, D_P
Salinity: x_{SW}, x_{Cry}, x_{Imb}, x_P
Mass fraction of ice: k
Temperatures T_0, T_1, T_C, T_F, T_A
Amount of heat: Q_C, Q_F

(6) Number of specifications: 6

Flow rates: D_P
Salinity: x_{SW},
Temperatures T_0, T_C, T_F, T_A

(a) Number of equations: 10.
(b) DDL: 2.

It is therefore noted that the process is under-specified (DDL = 2 > 0); it is therefore necessary to add the following specifications to reduce the degrees of freedom at the unit level:

(a) The ice crystal mass fraction in the crystallizer (k).
(b) The pre-treated water salinity in the output of the freezing plant (x_P).