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Determination of the concentration polarization in a reverse osmosis plant to desalinate sea water

Determinación de polarización de la concentración en una planta de ósmosis inversa para desalinizar agua de mar

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Abstract
Water scarcity in the world is a real and latent problem. Reverse osmosis (RO) desalination processes are a widely used technology to reduce this problem. However, one limitation is the concentration polarization (CP), which represents the accumulation of salts on the active surface of the membrane. The physical measurement of this variable is complicated and expensive, due to the accessories and calculation implements for its determination. To determine the CP, in this study experimental tests were carried out in a reverse osmosis plant in a range of pressures from 1 to 6 MPa and permeate flux from 0.75 to 3.5 L min^{-1}, using brackish water (13,335 mg L^{-1}) and seawater (35,522 mg L^{-1}). A mathematical model was obtained for each established concentration, resulting in a fourth and second order polynomial model for brackish and seawater, respectively. A descriptive statistical analysis was applied to the results of these models to compare the similarity of the theoretical-experimental data and the reliability of the model. The models obtained will be of great help in decision making involving CP and its inherent variables.
Keywords: desalination, scaling, sea water, concentration polarization, water scarcity.

Resumen
La escasez de agua en el mundo, es un problema real y latente. Los procesos de desalinización por ósmosis inversa (OI), son una tecnología bastamente utilizada para disminuir éste problema. Sin embargo, una limitante es la polarización de la concentración (PC), que representa la acumulación de sales en la superficie activa de la membrana. La medición física de esta variable es complicada y de alto costo, por los accesorios e implementos de cálculo para su determinación. Para determinar el PC, en este estudio se realizaron ensayos experimentales en una planta de ósmosis inversa en un rango de presiones de 1 a 6 MPa y flux de permeados de 0.75 a 3.5 L min^{-1}, se utilizó agua salobre (13,335 mg L^{-1}) y agua de mar (35,522 mg L^{-1}). Se obtuvo un modelo matemático para cada concentración establecida, dando como resultado un modelo polinomial de cuarto y segundo orden para agua salobre y de mar respectivamente. A los resultados de estos modelos se les aplicó un análisis estadístico descriptivo, para comparar la similitud de los datos teóricos-experimentales y la confiabilidad del modelo. Los modelos obtenidos serán de gran ayuda en la toma de decisiones que involucren al PC y las variables inherentes.
Palabras clave: desalinización, escalamiento, agua de mar, polarización de la concentración, escasez de agua.

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1 Introduction

A major constraint to the world's growth and socioeconomic development is water scarcity, which also poses a threat to sustaining life on the planet (Liu *et al*., 2017). Today about 70% of the population experiences water scarcity at least once a year (Ghosh, 2022). This serious situation is due to population growth, increasing industrial demand worldwide and to the high pollution of river waters around the world, which makes seawater desalination processes increasingly attractive and necessary (Huang *et al*.,2021; Morin-Crini *et al*., 2022; Jrad *et al*., 2023).

Desalination is an effective technology that mitigates water scarcity in arid zones and coastal regions (Galicia *et al*., 2020; Saleem *et al*., 2020). It is a non-conventional technique that increases the availability of consumable water, and consists of treating brackish water from the sea or saline aquifers, removing salts and transforming it into water suitable for supplying populations or irrigation (Alsayed & Ashraf, 2021).

Seawater desalination using membranes is a process that separates saline water into two streams: a potable water stream with low concentration of dissolved salts - *called permeate water* - and a concentrated brine stream - *called reject water* - (Alsayed *et al*.,2021; Dévora-Isiordia *et al*., 2023).The most widely used system for seawater desalination is reverse osmosis because of its high flux production rate and salt removal (Dévora-Isiordia *et al*., 2013; Farahat *et al*., 2023). Reverse osmosis is the most widely membrane technology used in the world and in Mexico with 70 and 88.5% respectively in 2022, that provides the largest amount of water and has come to solve a percentage of water shortages in industrial, agro-industrial and human consumption systems due to its easy scalability in membranes, high-pressure pump systems and spare parts (Ríos-Arriola *et al*., 2022). The cost of desalinating seawater by reverse osmosis is cheaper than other technologies that use thermal energy. The amount of energy depends on the type of water to be desalinated, according to Devora-Isiordia (2023) the energy consumption by the RO is from 2 to 2.8 kWh m^{-3} and the cost is 0.6 USD m^{-3}, this in current pesos would be 10.15 mexican pesos m^{-3} instead the energy consumption by thermal technologies (MED: Multi-effect distillation and MSF: multistage flash distillation) is from 3.4 to 4 and 5 to 8 kWh m^{-3}, its cost respectively is 1.5 and 1.1 USD m^{-3}. The worldwide desalination capacity used by RO was 88,000,000 m^3 d^{-1} in 2015 (García, 2016). The desalination capacity per RO installed in Mexico in 2022 was 560,000 m^3 d^{-1} (Ríos-Arriola *et al*., 2022). Garcia (2016) published that desalination plants on an industrial scale in Spain fluctuate a conversion from 40% to 50% for the most part, although there are desalination plants (there are two) with conversions greater than 55% conversion, worldwide the range fluctuates from 40% to 50%, but desalination plants installed before 1990 have a conversion of 30 to 40%. In the case of Mexico, the desalination plant in the city of Ensenada has a conversion of 50%, in the city of Los Cabos the desalination plant has a conversion of 49% (Garcia, 2016) and in the desalination plant Guaymas-Empalme its conversion is 45% recently put into operation in 2021 (Gobierno del estado de Sonora, 2023).

However, there are problems associated with this process such as high energy consumption (Mi *et al*., 2023), environmental impact (Jalili *et al*., 2023), biofouling (Armendáriz-Ontiveros *et al*., 2022) and concentration polarization in membrane modules. Concentration polarization (CP) is defined as the deposition of salts on the membrane surface Dévora-Isiordia *et al*. (2023), presents an illustration about the CP that goes according to the previous definition (see Figure 1), due to an increase in permeate flux with respect to the filtration area, reducing the observed salt rejection which decreases the efficiency of the system (Fan, 2018; Armendáriz-Ontiveros *et al*., 2022).The PC phenomenon occurs naturally since the function of the membrane is to retain salts from brackish or marine water bodies, however when this exceeds the value of 1.2 the desalination process yields are affected this according to Kucera (2015). The CP is an important factor that determines the operating cost and the useful life of the membrane in reverse osmosis plants. Membrane modules that operate with very good pretreatment and good CP control using brackish water can last up to 12 years (Ruutenhuch, 1992) and in the case of seawater up to 5 years. If the membranes have to be replaced in a short time, it causes costs due to process stoppage and the cost of acquiring the membranes, hence the importance of having a good control of the CP and being able to predict it in reverse osmosis processes.

During a real process, the physical and numerical quantification of the polarization factor becomes difficult and in some cases, almost impossible (Bai *et al*., 2023). Therefore, the present research aims to obtain a mathematical model that determines by theoretical and experimental methods the CP factor in a reverse osmosis pilot plant as a function of operating pressure (MPa) and permeate flux (L m^{-2} h^{-1}). The model will allow the scientific and industrial community to have a quick and concrete tool for CP measurement that will allow making decisions to avoid further damage to the membranes, reduce production and energy costs.

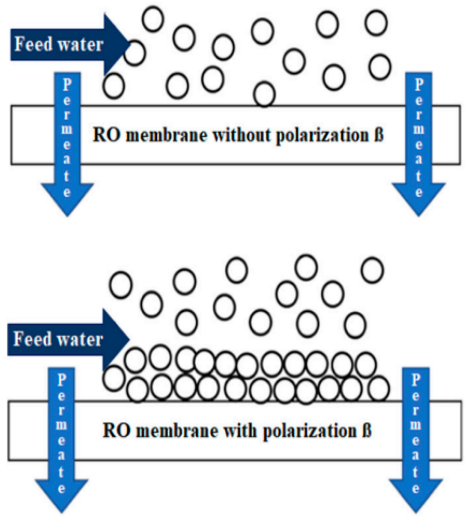

Figure 1. Concentration polarization in reverse osmosis membrane (Dévora-Isiordia *et al*., 2023).

2 Materials and methods

2.1 Description of the reverse osmosis plant

A reverse osmosis pilot plant with a capacity of 1 L min^{-1} (Figure 2 and 3) was used, consisting of the following parts: low pressure pump Webtrol PC100RMT 1HP, CDS3 pre-chlorination system, multimedia filter of 1" 263A910MM, activated carbon filter 263A910AC, CDS3 anti-scalant system, H-1034-BL ¾", cartridge filters with two compartment, pre and post filter pressure gauges 316SS, Danfoss APP 0.8 3HP -*stainless steel duplex motor*-, Nason low and high pressure sensors CU-15psi and CD^{-1}000 psi respectively, volumetric flow meters from 0.5 to 5 G min^{-1} and 0.1 to 1 G min^{-1} in the reject and permeate flow rates respectively, Cds3 post-chlorination system, 316SS pre-membrane pressure gauge, 2.5" x 40" FRP membrane module and Filmtec SW30-2540 reverse osmosis membrane, 2.5" x 40" with 2.8 m^2 active area.

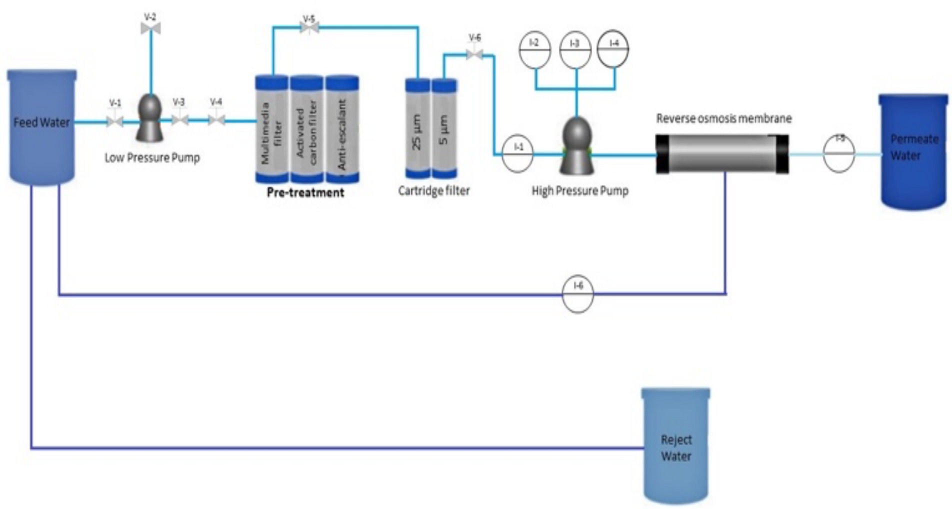

Figure 2. Diagram of reverse osmosis pilot plant.

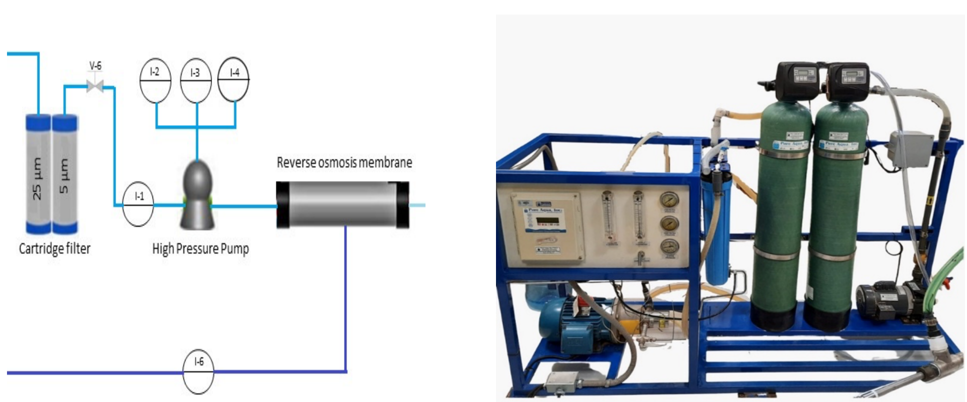

Figure 3. Reverse Osmosis Plant of 1 L min^{-1}

2.2 Calibration curve

A calibration curve was performed as a function of electrical conductivity to determine the concentration of the solutions to be used in mg L^{-1}. Instant ocean sea salt and a conductivity meter (YSI 30) were used.

The equation used to find the equilibrium between the conductivity of synthetic seawater and seawater is the following (see equation 1)

$$\omega = \beta\left[\frac{CT}{1+(\alpha_0+\alpha_1\omega)(T-25C)} - C\omega^{25}\right]^{\gamma} \quad (1)$$

Where:
CT: Electrical conductivity of water at the measured temperature (μS cm^{-1})
β: Experimental constant with a value of 4.10×10^{-7} for instant ocean sea salt.
α_0: Constant for instant ocean sea salt of 0.0209026.
α_1: Constant for instant ocean sea salt of 0.0347997.
ω: It is the result of the iteration of the previous equation.
T: Temperature (K) at which seawater conductivity was measured.

In order to prepare the synthetic seawater for the reverse osmosis plant, saltwater stock solution was created by adding 3.5 kg of Instant ocean sea salt, the stock solution was a total of 60 L at concentration of 58,300 mg L^{-1}, and thus be dissolved in total of 100 L. In this way, concentration of 35,522 mg L^{-1} of synthetic seawater was achieved.

In the case of the brackish water feed water, stock solution of salt water was created by adding 1.3 kg of instant ocean sea salt, the stock solution was a total of 60 L at concentration of 22,800 mg L^{-1}, and thus be dissolved in total of 100 L. In this way, concentration of 13,535 mg L^{-1} of brackish water was obtained.

2.3 Equations used in the reverse osmosis process

Two stock solutions were prepared at 100 L, and brought to 2 concentrations of 1) 13,535 mg L^{-1} and 2) 35,522 mg L^{-1}, for brackish water and seawater, respectively. With the data taken by the reverse osmosis pilot plant, different results were obtained such as membrane resistance (R_m), distilled water viscosity (μ_w), permeance (L_p), permeate flux (J_v), nominal operating pressure (P) and flow rate (Q_p), polarization (Γ), percentage of observed rejection ($\%R_{obs}$) and percentage of intrinsic rejection ($\%R_{int}$). For the experiments, 6 replicates were performed. The equations were taken from the report of NIST (2018), Jiang *et al*. (2003) and Armendáriz-Ontiveros *et al*. (2020).

To find the viscosity, the formula used was as follows:

$$\mu_w = \exp\left(5.495921 \times 10^5 T^{-2} - 1.66779 \times 10^3 T^{-1} - 7.612821\right) \quad (2)$$

Where:
μ_w: Distilled water viscosity (Pa s).
T: Temperature (K).

The following equation was used to obtain the flux (J_v) where the permeate flow rate (Q_p) is divided by the area of the reverse osmosis membrane.

$$J_v = \frac{Q_p}{A_m} \quad (3)$$

Where:
Q_p: Permeate flow rate (m^3 s^{-1}).
A_m: Membrane area (m^2).
J_v: Flux (m s^{-1}).

The following equation was used to find the actual viscosity of the salt water

$$\mu = \mu_w\left[1 + \sqrt{\omega}(b_1 + b_2T^3) + \omega(b_3 + b_4T^3) + b_5\omega^2T^3\right] \quad (4)$$

Where:
μ_w: Distilled water viscosity (Pa s).
ω: Mass fraction of salt water in process.
T: Salt water temperature (K).
b_1, b_2, b_3, b_4 and b_5: Constants for solution viscosity calculation. The values of the constants are: −1.07266, 1.2722×10^{-7}, −56.2241, 1.3332×10^{-6}, 1.2053×10^{-5} respectively and were obtained experimentally with instant ocean sea salt.

In order to determine the observed salt rejection, the following was necessary:

$$\%R_{obs} = \frac{C_a - C_p}{C_a} \times 100\% \quad (5)$$

Where:
$\%R_{obs}$: Observed sales rejection (%).
C_a: Feed water concentration (mg L^{-1}).
C_p: Permeate water concentration (mg L^{-1}).

In order to obtain the polarization factor, the following equation was required:

$$\Gamma = \frac{\Delta P - J_v\mu R_m}{(C_a - C_p)} \quad (6)$$

Where:
Γ: Polarization factor
ΔP: It is the pressure difference in the system (Pa).
J_v: Flux (m s^{-1}).
μ: Salt water viscosity (Pa s).
R_m: Membrane resistance (1 m^{-1}).
γ: Osmotic pressure for synthetic sea salt water (MPa).
C_a: Feed water concentration (mg L^{-1}).
C_p: Permeate water concentration (mg L^{-1}).

To obtain the intrinsic rejection of salts, the following equation was necessary:

$$\%R_{int} = \frac{1}{\Gamma(1/R_{obs} - 1) + 1} \times 100\% \tag{7}$$

Where:
$\%R_{int}$: Percentage of intrinsic rejection of salts (%).
R_{obs}: Observed rejection of salts without their percentage value.
Γ: Reverse osmosis membrane polarization.

2.4 Mathematical modeling

Microsoft Excel software version 16.66.1 was used to record the experiment. Each treatment was performed 6 times (13,535 mg L^{-1} and 35,522 mg L^{-1}). Equations 1 to 7 were applied with the CP calculation software. Subsequently, a regression adjustment was performed, and the best model was sought, with the highest R^2 value preferably close to 1. When the best model was obtained, a comparison of operating pressure-CP was performed experimentally versus theoretical values (model). At the end, a descriptive statistical analysis was performed to observe its reliability.

3 Results and discussion

3.1 Polarization effect of concentration at different salinities

The experiment started with a feed flow of 8 L min^{-1} at a concentration of 13,535 mg L^{-1} -*brackish water*-. The results are shown in Table 1. It is observed that at a pressure of 6.07 MPa (880 psi), there is a recovery capacity of 43.75%, similar to that reported by Villarino (2010) who found an intrinsic salt rejection of 99.46% at the same conditions. Considering an average seawater value of 35,000 mg L^{-1}, it is considered that there is no impact on marine flora and fauna if discharged into the sea. A salt rejection of more than 99.5% was achieved, which shows an excellent rejection of salts by the membrane (see Table 1).

The intrinsic rejection of salts shown in Table 1, is in accordance with the data reported by the technical sheet of the SW30-2540 membrane module, in approximate conditions the rejection was 99.4% (conditions: 5.5 MPa, 2600 L d^{-1}, 2.8 m^2 and 32,000 mg L^{-1} of NaCl), all the salt rejections were higher than that proposed by the manufacturer's Lenntech (2023) technical sheet, this is because sea salt contains larger ions than NaCl such as sulfates, carbonates, (contains 80-85% NaCl ions) and also because a lower concentration solution was used. Therefore, there is a greater rejection of salts using sea salt. Comparing the salt rejection results obtained by Dévora-Isiordia *et al.* (2023), with a plant with a capacity of 10 L min^{-1}, four modules of Hydranautics SWC4 RO membranes, using a pressure of 1.92 MPa, feed water of 10,000 mg L^{-1} with sea salt from Cortes, 40% conversion and a temperature of 28 °C, at these conditions, a salt rejection of 93.2% was obtained, at similar pressure conditions (Table 1), an intrinsic rejection of salts was obtained of 99.63%, which indicates that the RO pilot plant of this research was more efficient regarding the rejection of salts, but not in the conversion, since a value of 8.6% was obtained. The maximum value operated in the RO plant of this investigation was 43.7%, but later it will be seen in the following discussions that it is not recommended at least for a SW30-2540 membrane module of 2.8 m^2 and a capacity of 1 L min^{-1}. If you have a larger membrane area, for example 10 equal modules, you can easily work at 40% conversion without risk of damaging the membranes.

Comparing the CP results with the results obtained from Dévora-Isiordia *et al.* (2023), it was confirmed that the higher the operating pressure, the higher the CP will be (Table 1). For the aforementioned conditions (1.92 MPa, 10,000 mg L^{-1} feed water with Cortes Sea salt, 40% conversion and temperature of 28 °C), the CP was 1.09, very similar to the result obtained in this investigation (1.05). This indicates that the equations used in this research and the elaborated mathematical models can be used by researchers who have RO plants with similar capacity.

On the other hand, CP is not only a very important parameter in the operation of reverse osmosis plants, but also in ion exchange plants since, as mentioned, concentration polarization in both cases limits performance by generating a narrow diffusion boundary layer along the membranes (Al-Amshawee *et al.*, 2023). Table 1 shows that the CP increases directly with increasing pressure, at a pressure of 2.76 MPa it has a polarization factor of 1.14 which is recommended as expressed by Sandin *et al.* (2012) and Kucera (2015). Having a PC value higher than 1.2 leads to unfavorable conditions, which increases membrane fouling (Bai *et al.*, 2023), increased energy consumption (Saeed *et al.*, 2023), reduced permeate water quality and flux (Matthiasson *et al.*, 1980). Values of permeate flow rate (Q_v), permeate flux (J_v) are shown in the table. It is observed that the intrinsic and observed rejections are very similar, and normal values of CP (Γ) are highlighted in green color, in transition of CP problems in yellow color, and in red color values not allowed in risk of CP operation.

Table 1. Salt rejection and polarization with brackish water at 13,535 mg L^{-1}.

P (MPa)	T_{Perm} (°C)	Q_v (L min^{-1})	J_v (Lm^{-2} h^{-1})	R_{obs} (%)	R_{int} (%)	Γ
1.90	26.10	0.75	16.07	99.65	99.63	1.05 ■
2.27	26.53	1.00	21.42	99.70	99.67	1.10 ■
2.76	29.41	1.50	32.14	99.73	99.69	1.14 ■
3.65	29.23	2.00	42.85	99.75	99.69	1.22 ■
4.69	30.23	2.50	53.57	99.75	99.58	1.69 ■
5.17	29.75	3.00	64.28	99.76	99.63	2.04 ■
6.07	26.13	3.50	75.00	99.65	99.46	2.15 ■

CP: ■ normal, ■ transition, ■ operational risk.

Table 2. Salt rejection and polarization of seawater at 35,522 mg L^{-1}.

P (MPa)	T_{Perm} (°C)	Q_v (L min^{-1})	J_v (Lm^{-2} h^{-1})	R_{obs} (%)	R_{int} (%)	Γ
3.44	25.76	0.75	16.07	99.41	99.39	1.02 ■
4.00	27.6	1	21.42	99.60	99.58	1.04 ■
4.82	27.84	1.5	32.14	99.67	99.62	1.15 ■
6.06	28.72	2	42.85	99.68	99.59	1.30 ■

CP: ■ normal, ■ transition, ■ operational risk.

Table 2 shows polarization factors lower than those presented in Table 1, because the permeate flows used for the concentration of 35,522 mg L^{-1} are lower; according to Medina (2000) the lower the recovery, the lower the CP for both concentrations (Table 1 and 2), it is concluded that the CP value of 1.2 should not be exceeded, regardless of whether it is brackish or seawater.

It is also observed that the desalination plant has a high salt rejection of seawater, despite working at low pressures (3.44, 4.00 and 4.82 MPa), with a salt rejection above 99%, which indicates that the plant can be operated at a lower permeate flow with similar efficiencies when operating at typical seawater pressures (6.06MPa).

The intrinsic rejection of salts shown in Table 2, is in accordance with the data reported by the technical sheet of the SW30-2540 membrane module (Lenntech, 2023), under very similar conditions the rejection was 99.4% (conditions: 5.5 MPa, 2600 L d^{-1}, 2.8 m^2 and 32,000 mg L^{-1} of NaCl), all the salt rejections were higher, except the one obtained at 3.44 MPa, which was of 99.39%, which is very similar to that proposed by the manufacturer's technical sheet Lenntech (2023).

The rejection of salts shown in Table 1, in the case of the lowest rejection, which was 99.46%. Therefore, the concentration of the permeate flow was 73 mg L^{-1} which, according to NOM-127-SSA1-2021, is a low-salt water which is approved for human consumption. It can also be used in agriculture and industry.

In the case of Table 2, the lowest rejection is still taken, which was 99.39%. Therefore, the concentration of the permeate flow was 217 mg L^{-1}, NOM-127-SSA1-2021 indicates that it is approved for human consumption.

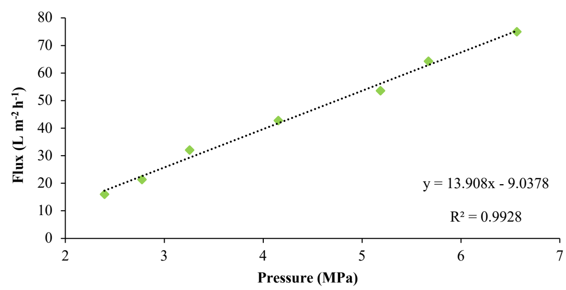

Figure 4. Pressure (MPa) versus flux (L m^{-2} h^{-1}) of the brackish water experiment (13,535 mg L^{-1}).

Figure 4 shows that the permeate flux is directly proportional to the pressure increase (Andrade Salazar *et al.*, 2013; Nolasco Medrano, 2019). The linear regression mathematical model ratifies the linear behavior of the pressure versus permeate flux data, the R^2 of 0.9928 demonstrates the linearity of the model. According to Martínez-Pérez (2023) "The correlation coefficient allows measuring the general agreement between two or more measurements involving quantitative variables, obtained with different measuring instruments or evaluators".

Figure 5 shows that the relationship of pressure versus CP has a nonlinear behavior with an R^2 value of 0.926, so when a polynomial model was applied, it was adjusted to a fourth order model, with an R^2 adjustment equal to 0.9984, where the pressure in MPa corresponds to the X axis, while CP is indicated on the Y axis, for brackish water as feed water to the reverse osmosis process.

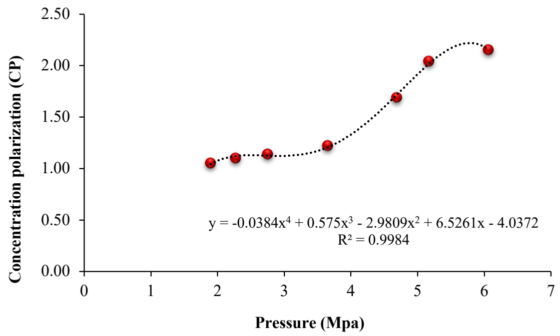

Figure 5. Polynomial Pressure Adjustment (MPa) versus CP of the brackish water experiment (13,535 mg L^{-1}).

More complex models such as the Boltzmann lattice method have been evaluated by Hu *et al.* (2023), for the analysis of fluid dynamics and transfer phenomena. As well as Nguyen *et al.* (2022), for calculating the ion flux of a feed water to reverse osmosis processes with emphasis on the polarization factor, where the Poisson-Nernst-Planck equations were implemented.

Considering the values in Table 1, the model obtained from Figure 5 and not exceeding the CP values suggested in this research, the following water supply projection is presented. At a pressure of 2.76 MPa the CP value calculated by the model was 1.13, which corresponds to that recommended by Kucera, 2015b. With the above pressure and using the equation in Figure 4, we have a permeate flow of 82.20 L h^{-1}, which represents 1,972 L in a day, which according to Tello-Moreno (2008) the minimum water consumption requirement for a person in a developing country is 50 L d^{-1}, therefore, the plant in such conditions would supply 39 people with 24 h of work.

In the model obtained, the resulting CP value was adjusted to different pressures, obtaining very similar theoretical and experimental values, restricted to brackish water. The usefulness of the model will be useful in decision making for the control or prevention of CP at certain pressures in the industrial, human consumption and research sectors.

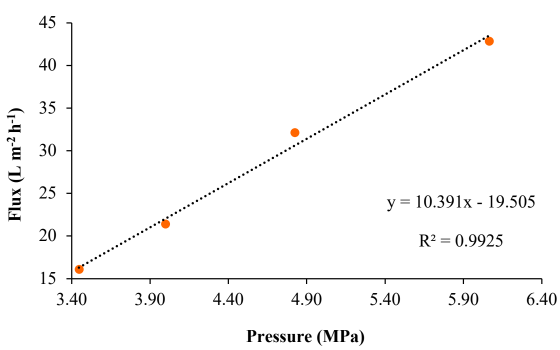

Figure 6. Pressure (MPa) versus flux (L m^{-2} h^{-1}) of the seawater experiment (35,522 mg L^{-1}).

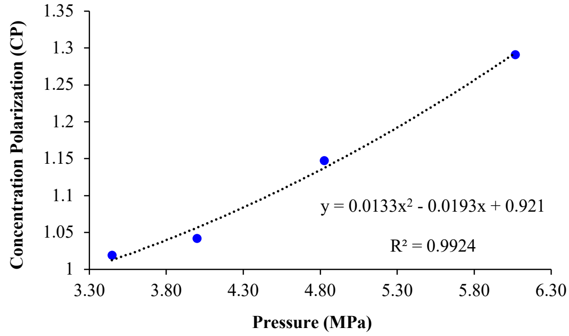

Figure 7. Polynomial Pressure Adjustment (MPa) versus CP with seawater (35,522 mg L^{-1}).

Although the experimental results behave in a linear way with an R^2 value of 0.9841, a second order polynomial model was applied, resulting in an R^2 of 0.9924 (see Figure 7), so it is suggested to use the latter model, due to the closeness of the experimental results with respect to the modeled data. Suggested model for seawater as feed water for the reverse osmosis process.

Considering the values in Table 2, the model obtained from Figure 7 and not exceeding the CP values suggested in this research, the following water supply projection is presented. At a pressure of 4.82 MPa the CP value calculated by the model was 1.14, which corresponds to that recommended by Kucera (2015). With the above pressure and using the equation in Figure 6, we have a permeate flow of 30.58 L h^{-1}, which represents 734 L in one day, which according to Tello-Moreno (2008) the minimum water consumption requirement for one person in a developing country is 50 L d^{-1}, therefore, the plant in such conditions would supply 14 people with 24 h of work.

Table 3 describes the different ways in which the CP can be obtained experimentally and theoretically. It is observed with descriptive statistics standard deviation values which according to Ruiz-Espejo (2017) standard deviation is defined as the square root of the variance of a population or of a random variable that represents it, it is well known that less than 10% is allowed and reliable. It has a great importance in classical inference, especially in relation to the study of the normal distribution as one of the parameters that determine the distribution in addition to the population mean, but its interest is more reduced in traditional inference in finite populations values less than 10%, which according to is allowed and acceptable. The variance value has the same tendency with values close to zero, which indicates the reliability of the model. This shows us that the obtained models potentiate the decision making to predict the CP, without having to instrument, or stop the operation process of a reverse osmosis plant. Under this context, process control, time savings due to stoppages or damages will be avoided. On the other hand, if the model predicts high

Table 3. Concentration polarization results: Theoretical and experimental.

Pressure (MPa)	Γ Experimental	Γ Theoretical	Standard deviation	Variance	R^2 Linear	R^2 Polynomial
Brackish water calculations at 13,535 mg L^{-1}						
1.9	1.05	1.04	0.0071	0.0001		
2.27	1.10	1.12	0.0141	0.0002		
2.76	1.14	1.13	0.0071	0.0001		
3.65	1.22	1.22	0.0000	0.0000	0.926	0.9984
4.69	1.69	1.74	0.0354	0.0013		
5.17	2.04	2.05	0.0071	0.0000		
6.07	2.15	2.21	0.0424	0.0018		
Seawater calculations at 35,522 mg L^{-1}						
3.44	1.02	1.01	0.0071	0.0001		
4.00	1.04	1.06	0.0141	0.0002	0.9841	0.9924
4.82	1.15	1.14	0.0071	0.0001		
6.06	1.30	1.29	0.0071	0.0001		

CP values, adjustments can be made to the antiscalant dosage and frequency to be applied. These examples of the application of the model will be the results and contributions to the scientific community for its implementation and prevention.

Conclusions

The results found in this study confirm that the concentration polarization factor is directly related to the nominal operating pressure, permeate flux and membrane active area. A fourth-degree polynomial model was determined that allows to quickly calculate the polarization factor of brackish water at 13,535 mg L^{-1} in a range of pressures from 1.9 to 6.07 MPa, in the same way a second-order model was obtained for a seawater concentration of 35,522 mg L^{-1} with pressure range from 3.9 to 6.06 MPa, the model obtained CP values very close between experimental and theoretical data, which indicates the veracity of these, supported by the descriptive statistical analysis.

Additionally, it is ratified that these suggested models are a quick tool for the quantification of the polarization factor, which could be useful in future research for the analysis of this phenomenon and avoid the difficulties of its calculation in real life. In addition, by predicting this phenomenon, it will be possible to apply the knowledge acquired for the good of society by providing quality and quantity of water, but with the help of the model to prevent problems during operation.

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Nomenclature

CT	electrical conductivity of water at the measured temperature, μS cm^{-1}
T	temperature at which conductivity was measured in the seawater, K
Q_p	permeate flow rate, m^3 s^{-1}
A_m	membrane area, m^2
J_v	flux, m s^{-1}
μ_w	viscosity, Pa s
$\% R_{obs}$	salt rejection observed, %
Ca	feed water concentration, mg L^{-1}
Cp	permeate water concentration, mg L^{-1}
R_m	membrane resistance, 1 m^{-1}
β	experimental constant with a value of 4.10×10^{-7} for salt from instant ocean sea salt.
α_0	constant for instant ocean sea salt of 0.0209026.
α_1	constant for instant ocean sea salt of 0.0347997.
ω	is the result of the iteration of the previous equation.
$b_1,\ldots,b_5$	constants for solution viscosity calculation.

References

Al-Amshawee, S. K. A., & Mohd Yunus, M. Y. B. (2023). Impact of membrane spacers on concentration polarization, flow profile, and fouling at ion exchange membranes of electrodialysis desalination: Diagonal net spacer vs. ladder-type configuration. *Chemical Engineering Research and Design 191*, 197-213. doi: https://doi.org/10.1016/j.cherd.2023.01.012

Alsayed, A. F. M., & Ashraf, M. A. (2021). 2 - Modified nanofiltration membrane treatment of saline water. In P. Samui, H. Bonakdari & R. Deo (Eds.). *Water Engineering Modeling and Mathematic Tools* (pp. 25-44): Elsevier. doi: https://doi.org/10.1016/B978-0-12-820644-7.00005-0

Andrade Salazar, R. Y., & Hormaza Rodriguez, S. A. (2013). Efecto de la presión y concentración en el porcentaje de rechazo para aguas contaminadas con Cromo por Ósmosis inversa a nivel de laboratorio. Tesis de licenciatura. doi: http://hdl.handle.net/20.500.12894/1487

Armendáriz-Ontiveros, M. M., Álvarez-Sánchez, J., Dévora-Isiordia, G. E., García, A., & Fimbres Weihs, G. A. (2020). Effect of seawater variability on endemic bacterial biofouling of a reverse osmosis membrane coated with iron nanoparticles (FeNPs). *Chemical Engineering Science 223*, 115753. doi: https://doi.org/10.1016/j.ces.2020.115753

Armendáriz-Ontiveros, M. M., Dévora-Isiordia, G. E., Rodríguez-López, J., Sánchez-Duarte, R. G., Álvarez-Sánchez, J., Villegas-Peralta, Y., & Martínez-Macias, M. D. (2022). Effect of temperature on energy consumption and polarization in reverse osmosis desalination using a spray-cooled photovoltaic system. *Energies 15*(20). Retrieved from doi: 10.3390/en15207787

Bai, W., Samineni, L., Chirontoni, P., Krupa, I., Kasak, P., Popelka, A., . . . Kumar, M. (2023). Quantifying and reducing concentration polarization in reverse osmosis systems. *Desalination 554*, 116480.doi: https://doi.org/10.1016/j.desal.2023.116480

Dévora-Isiordia, G. E., Cásares-De la Torre, C. A., Morales-Mendívil, D. P., Montoya-Pizeno, R., Velázquez-Limón, N., Aguilar-Jiménez, J. A., & Ríos-Arriola, J. (2023). Evaluation of concentration polarization due to the effect of feed water temperature change on reverse osmosis membranes. *Membranes 13*(1). Retrieved from doi: 10.3390/membranes13010003

Dévora-Isiordia, G. E., González-Enríquez, R., & Ruiz-Cruz, S. (2013). Evaluación de procesos de desalinización y su desarrollo en México. *Tecnología y Ciencias del Agua 4*(3), 27-46. .doi: http://www.revistatyca.org.mx/index.php/tyca/article/view/364

Fane, A. G. (2018). A grand challenge for membrane desalination: More water, less carbon. *Desalination 426*, 155-163.doi: https://doi.org/10.1016/j.desal.2017.11.002

Farahat, M. A., Faiad, H. A., Ahmed, S., & Rashad, M. I. (2023). Experimental investigation of freezing desalination using silicon oil for ice production. *Desalination 560*, 116664.doi: https://doi.org/10.1016/j.desal.2023.116664

Galicia, A., Lopez, M., García-Castro, M. A., Varela Caselis, J., Solís-Martínez, C., & Ortega-Pérez, J. (2020). Effect of the concentration of glycerin in the performance of chitosan membranes utilized in aqueous phase permeation. *Revista Mexicana de Ingeniería Química 20*, 87-96. doi: http://rmiq.org/iqfvp/Numbers/V20/No1/Mat1198.pdf

García, D. J. C. (2016). Proceso de desalacion de agua de mar mediante un sistema de osmosis inversa de muy alta conversión en tres etapas con recirculacion, recirculacion con permeado y doble sistema de recuperacion de energía. doctoral, Universidad del país Vasco, Escuela Técnica Superior de Ingenieria en Bilbao. https://addi.ehu.es/bitstream/handle/10810/18530/TESIS_CABERO_GARCIA_JULEN.pdf?sequence=1.

Ghosh, N. (2022). Water-scarce economies and scarcity values: can water futures trading combat water scarcity? *ORF, Observer Research Foundation 342*. https://www.orfonline.org/wp-content/uploads/2022/01/ORF_OccasionalPaper_342_WaterFuturesTrading.pdf

Gobierno del estado de Sonora. (2023). Agua para todos. Desaladora Guaymas-Empalme, 2023, from https://desaladora.sonora.gob.mx/images/transparencia/estudios/memoria-descriptiva-proyecto-planta-desaladora.pdf

Hu, X., Li, X., Yu, S., Lin, P., & Zhu, Z. (2023). Hydrodynamic effects of the flow-induced vibrations on the mass transfer and permeate flux in a desalination membrane. *Desalination 564*, 116710. doi: https://doi.org/10.1016/j.desal.2023.116710

Huang, Z., Yuan, X., & Liu, X. (2021). The key drivers for the changes in global water scarcity: Water withdrawal versus water availability. *Journal of Hydrology 601*, 126658. doi: https://doi.org/10.1016/j.jhydrol.2021.126658

Jalili, B., Rezaeian, A., Jalili, P., & Ganji, D. D. (2023). The hybrid absorption cooling-desalination and reverse osmosis system to boost energy utilization efficiency. *Energy Reports 9*, 5101-5110. doi: https://doi.org/10.1016/j.egyr.2023.04.049

Jiang, J., & Sandler, S. I. (2003). A New Model for the Viscosity of Electrolyte Solutions. *Industrial & Engineering Chemistry Research 42*(25), 6267-6272. doi: 10.1021/ie0210659

Jrad, A., Olson, M. A., & Trabolsi, A. (2023). Molecular design of covalent organic frameworks for seawater desalination: A state-of-the-art review. *Chem 9*, 1413-1451. doi: https://doi.org/10.1016/j.chempr.2023.04.012

Kucera, J. (2015). *Reverse Osmosis: Industrial Processes and Applications*. 2nd Edition: Scrivener Publishing LLC. doi: 10.1002/9781119145776

Lenntech. (2023). FilmTec^{TM} Membranes. Product Data Sheet. Hoja técnica SW30-2540 Dow-FilmtecTM (Publication no. https://www.lenntech.com/Data-sheets/DuPont-FilmTec-SW30-2540-L.pdf).

Liu, J., Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., . . . Oki, T. (2017). Water scarcity assessments in the past, present, and future. *Earth's Future 5*(6), 545-559.doi: https://doi.org/10.1002/2016E\T1\textexclamdownF000518

Matthiasson, E., & Sivik, B. (1980). Concentration polarization and fouling. *Desalination 35*, 59-103.doi: https://doi.org/10.1016/S0011-9164(00)88604-X

Medina, J. A. (2000). *Desalación de Aguas Salobres y de Mar, Ósmosis Inversa*. Editorial Mundi Prensa. doi: https://dialnet.unirioja.es/servlet/libro?codigo=63677

Mi, J., Wu, X., Capper, J., Li, X., Shalaby, A., Wang, R., . . . Zuo, L. (2023). Experimental investigation of a reverse osmosis desalination system directly powered by wave energy. *Applied Energy 343*, 121194. doi: https://doi.org/10.1016/j.apenergy.2023.121194

Morin-Crini, N., Lichtfouse, E., Liu, G., Balaram, V., Ribeiro, A. R. L., Lu, Z., . . . Crini, G. (2022). Worldwide cases of water pollution by emerging contaminants: a review. *Environmental Chemistry Letters 20*(4), 2311-2338. doi: 10.1007/s10311-022-01447-4

Nguyen, D. T., & Pham, V.-S. (2022). Ions transport in electromembrane desalination: A numerical modeling for the return flow ion-concentration-polarization desalination system. *Chemical Engineering Research and Design 184*, 366-377. doi: https://doi.org/10.1016/j.cherd.2022.06.013

NIST. (2018). *Thermophysical Properties of Fluid Systems*. Retrieved from https://webbook.nist.gov/chemistry/fluid/.

Nolasco Medrano, I. (2019). Estudio del efecto de la velocidad y la presión transmembrana en el Flux másico en la ultrafiltración de suero de leche. *Benemérita Universidad Autónoma de Puebla*. doi: https://hdl.handle.net/20.500.12371/5128

Ríos-Arriola, J., Velázquez, N., Aguilar-Jiménez, J. A., Dévora-Isiordia, G. E., Cásares-de la Torre, C. A., Corona-Sánchez, J. A., & Islas, S. (2022). State of the art of desalination in Mexico. *Energies 15*(22). Retrieved from doi: 10.3390/en15228434

Ruiz-Espejo, M. (2017). Estimación de la desviación estándar. *Estadística Española 59*(192), 37-44. doi: https://www.researchgate.net/publication/319332721

Ruutenhuch, R. (1992). Membrane separation systems - Recent developments and future directions. Von R. W. Baker u.a. Noyes Data Corp., Park Ridge 1991. XV, 451 S., zahlr. Abb. u. Tab., geb., US-$64. *Chemie Ingenieur Technik 64*(6), 584-584. doi: https://doi.org/10.1002/cite.330640633

Saeed, R., Konsowa, A. H., Shalaby, M. S., Mansour, M. S., & Eloffy, M. G. (2023). Optimization of integrated forward - reverse osmosis desalination processes for brackish water. *Alexandria Engineering Journal 63*, 89-102. doi: https://doi.org/10.1016/j.aej.2022.07.054

Saleem, H., & Zaidi, S. J. (2020). Nanoparticles in reverse osmosis membranes for desalination: A state of the art review. *Desalination 475*, 114171. doi: https://doi.org/10.1016/j.desal.2019.114171

Secretraría de Salud. Norma Oficial Mexicana NOM-127-SSA1-2021. Salud ambiental, agua para uso y consumo humano-Límites permisibles de calidad y tratamientos a que debe someterse el agua para su potabilización (1994).

Sandin, R., Ferrero, E., & Malfeito, J. (2012). Evaluación de anti-incrustantes para disminuir el ensuciamiento producido por sílice en membranas de ósmosis inversa. *Retema: Revista Técnica de Medio Ambiente 24*, 24. doi: https://www.researchgate.net/publication/260601185_Evaluacion_de_anti-incrustantes_para_disminuir_el_ensuciamiento_producido_por_silice_en_membranas_de_osmosis_inversa

Tello-Moreno, L. F. (2008). *El acceso al agua potable como derecho humano:Comisión Nacional de los Derechos Humanos* (Vol. 1): Comisión Nacional de los Derechos Humano.doi: https://appweb.cndh.org.mx/biblioteca/archivos/pdfs/DH_69.pdf

Villarino, M. (2010). Introducción a la ósmosis inversa. 1, 9-12