Single Stage against Batch (RO) brackish water desalination

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Abstract

The present study is a comparison between two different configurations (single stage) and (batch) of a reverse osmosis process (RO). For this purpose a RO pilot was run with different salts (NaCl, $MgSO_4$, $CaCO_3$) under different concentrations, with the aim to determine the characteristic of each configuration (salts rejection R, recovery Y and the minimum energy efficiency ES) in order to find the best configuration for a brackish water reverse osmosis (RO) desalination, depending on each salt and concentrations under different operating conditions .

Keywords: *(Batch) RO, Brackish Water (BW), Minimum Energy Efficiency ES, RO Desalination,, Salts Rejection, (Single Stage continuous) RO.*

I. Introduction

Freshwater scarcity is one of the most severe problems of the present time. Although the total water storage on the earth is 1.4 Gm^3, usable freshwater including rivers, lakes and ground water occupies only a tiny fraction of 0.65% of the total water storage. Because of population growth and on-going urbanization, over two thirds of the human population will be facing freshwater scarcity in the near future to a smaller or larger extent **[1]**.

As water resources become more limited, desalination of seawater and brackish water is becoming important **[2]**. Different membrane methods have been used for water treatment, including microfiltration (MF), ultra-filtration (UF), nano-filtration (NF), reverse osmosis (RO) and membrane distillation (MD). UF and MF are well-developed techniques used for water treatment, whereas RO is widely used for water desalination and purification. MD is a new developing technique and it has potential for desalinating highly saline water.

The membranes play a key role in membrane-based water treatment processes and determine the technological and economic efficiency of the aforementioned technologies; membrane improvement can greatly affect the performance of current technology. The material selection and pore size of the membranes depend on the application for which it would be used. Figure 1 represents the average pore size corresponding with different pressure requirement for membranes for different water treatment processes **[3]**.

RO membrane processing removes ions and organic chemicals, and its treatment efficiency and performance are stable and predictable.RO has been shown to be adequate for producing water for potable and industrial uses from seawater and brackish water for reasonable costs **[1]**.

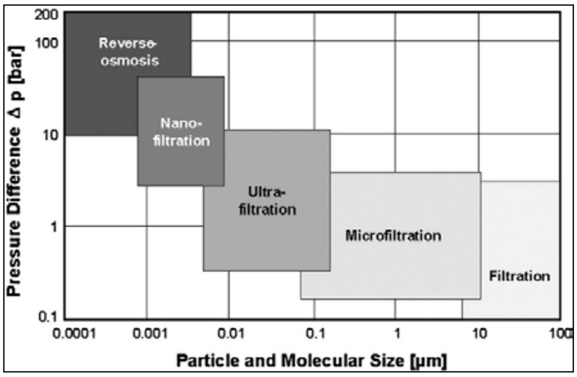

Figure 1: Separation capability of membrane methods with the corresponding differential pressure **[4]**.

This work is devoted to study the parameters of the rejection of the majors salts existed in brackish water especially NaCl, $MgSO_4$, $CaCO_3$ corresponding with minimum energy efficiency and recovery we use both modes a single stage (continuous) RO and Batch RO. The objective of the work is therefore to check and control the parameters imposed by the manufacturer on the one hand and on the other for what is the mode that gives the best results for a real case of desalination.

This study is being conducted at the University of Bouira for a case specifies: spiral wound reverse osmosis membrane type Dow Film Tec ***TW30.2540***.

I. Theoretical background:

The RO membrane model is developed based on the following basic assumptions:

1. Pressure drop along the permeate channel is neglected. This assumption is reasonable for 8 in. spiral wound module that has 37 membrane leaves with a length of 1m.

2. The feed channels of spiral wound element are flat. Feed stream flows along the channel parallel to the central line of the module and the curvature of membrane module was reported to have insignificant effect on system's performance. Therefore, an unwound flat sheet membrane with same channel height and spacers would adequately represent characteristics of the corresponding spiral wound RO module **[5,6,7,8]** .

II.1 The minimum specific energy:

The specific energy for desalination can be broadly broken down into 2 major categories:

1. Technology independent specific energy required for desalination — the thermodynamic minimum energy barrier: The technology independent specific energy for desalination is defined by thermodynamics and is the thermodynamic minimum energy needed for salt water separation irrespective of the technology used. This energy is the thermodynamic minimum energy barrier that one will need to overcome to achieve separation of salt from water and can be calculated from Gibbs free energy of un mixing **[7, 8]**.

2. Technology dependent specific energy required for desalination: The technology dependent components will depend on the technology used to achieve this separation and will depend on the efficiency of the technology in inputting in the thermodynamic minimum energy into the salt–water system, additional work to achieve separation and overcome the energy losses that are incurred during the process. For example, in case of reverse osmosis this energy will depend on membrane and module performance, in efficiency of feed pump and energy recovery device and losses in system design. In case of thermal desalination, it will be a function of the efficiency of energy source, thermal losses in the system and the efficiency of the inherent processes employed to achieve the salt water separation.

In this paper the interest is the thermodynamic minimum energy barrier to calculate the minimum specific energy for two different RO configurations: single stage (continuous) RO and close circuit (CC) RO.

The following table 1 we summarize the basic equations of the reverse osmosis RO model.

In a batch membrane system, water is recovered from the system as the concentrate is recycled to the feed tank; as a result, if the solute is rejected the feed concentration C_F continuously increases over time. For a continuous membrane system, fresh feed is continuously supplied to the membrane.

Water and salt fluxes via the membrane is estimated by Kimura–Sourirajan model **[5]**.

$$J_W = A_w\,(\Delta P - (\pi_m - \pi_p)) \tag{1}$$

$$J_S = B\,(C_m - C_p) \tag{2}$$

The volume and mass balance equations around the spiral wound element are given by:

$$Q_f = Q_c + Q_r \tag{3}$$

$$Q_f\, C_f = Q_c\, C_c + Q_r\, C_r \tag{4}$$

The water permeate concentration and flow are expressed as:

$$C_p = J_s / J_w$$

(5)

$$Q_p = S \,.\, J_w$$

(6)

The permeate product water recovery for the RO process, Y, is an important indicator of the process productivity, defined as:

$$Y = Q_p/Q_f$$

(7)

The rejection ratio R depends on the relationship between the permeate and feed concentration:

$$R = 1 - C_p/C_f$$

(8)

SE is a function of the initial osmotic pressure, π_0, and the final recovery, Y according to the following equations:

$$SE_{sigle\ stage}\ (Y) = \ \pi_0 \ / \ 1\text{-}Y$$

(9)

$$SE_{close\ circuit}\ (Y) = \pi_0\ (1 + Y/(1 - Y\ ))$$

(10)

II.2. Single stage (continuous) RO:

Most exiting RO systems operate in single-stage (or single-pass) configuration. In a single-stage RO, the feed solution concentration along the membrane channel increases as water permeates across the semi-permeable membrane under an applied hydraulic pressure that is higher than the local osmotic pressure (Figure. 2) **[9]** .

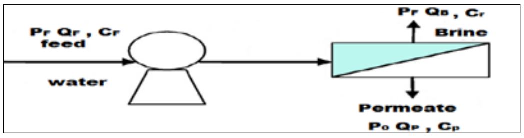

Figure 2: schematic representation of the single stage RO process.

II.3. Batch RO:

In a closed-circuit reverse osmosis (batch-RO) process, the retentate (brine) solution of the module (stream S_3 in Figure. 3) recirculates in closed circuit where it mixes with the feed solution of the system (S_1) to become the influent solution to the module (S_2). Here, the feed solution of the system (S_1) represents the source water to be desalinated, which has an osmotic pressure of π_0.

The influent solution to the module (S_2), resulting from mixing the retentate solution (S_3) with the feed water (S_1), has an increasing osmotic pressure as the solutes accumulate in the circuit. To maintain a positive driving force across the membrane, the applied hydraulic pressure must be increased along with the increasing osmotic pressure **[9]**.

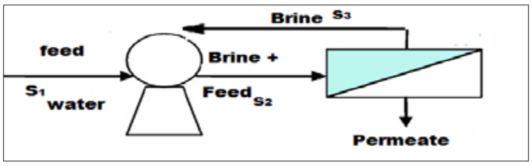

Figure 3: schematic representation of the closed circuit RO process.

In this process we describe the evolution of the mixture concentration (feed +concentrate) for all the salts considered in this work by means of Figure 4 (evolution of the mixture osmotic pressure during the operation time) **[10]** .

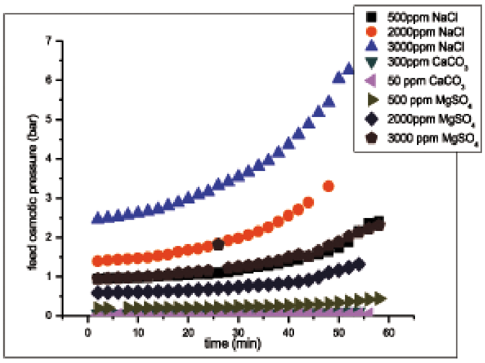

Figure 4: the feed osmotic pressure as function of the time for the batch process.

II. Materials and experimental:

II.1. Description of the pilot:

A multi-cellular centrifugal pump high pressure (16 bars to 800 L / h) feeds a circuit including a reverse osmosis cartridge. This circuit consists of a power supply, a discharge and a Permeate.

The tank containing the solution to be treated is 100 L capacity; the drip tray has a capacity of 20 L. They are both transparent PVC. The feed tank is filled via a filter 25 µm and an active carbon filter (5µm). The driver can thus operate independently from the input tray. The pump stops automatically when the low level of the tank is reached. Figure 5 shows the main layout, the back and the front view of reverse osmosis DELTA Lab pilot:

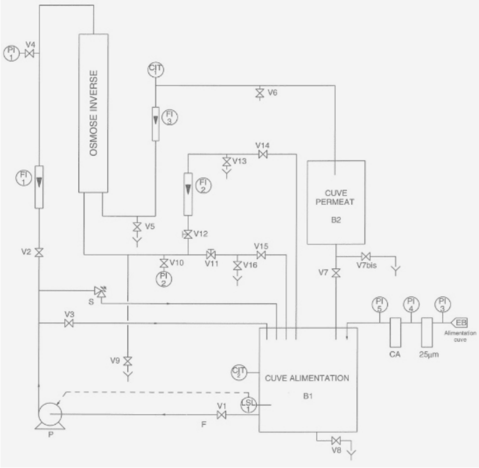

Figure 5: layout of the principle operation of the delta lab pilot.

We obtains the two process batch and Single stage (continuous) RO configuration

By the following step:

III.1.1. Single stage (Continuous) RO :

For this configuration the concentrate was rejected by closing the valve V_{13} and opening the valve V_{14} or closing the valve V_{15} and opening the valve V_{16}; and the permeate was stored in the tank B_2 by closing the valve V_7 / V_{7bis} .

III.1.2. Batch RO :

For the closing circuit configuration the concentrate was mixed with the feed water into the tank B_1 by opening the valve V_{15} and closing the valve V_{13} and all the concentrate passed to the tank B_1 (feed water) but the permeate remained stored into the tank B_2 by closing the valve V_7/$V_{7\,bis}$.

II.2. RO Membrane:

The cartridge type RO membrane used in this study was provided by DOW Chemical Company (Dow-Filmtec, TW30-2540) ; The membranes were spiral wound modules each with an active surface area of 2.6 m^2, allowing a permeate flow of 3.2 m^3/ day with a salt rejection of 99.5 % .

The operating characteristics of the membrane are shown in Table 1 as follows:

Table 1: present the membrane characteristic.

Membrane Type Thin-Film Composite	Polyamide
Maximum Operating Temperature ^{a} 11	3°F (45°C)
Maximum Operating Pressure	600 psig (41bar)
Maximum Feed Flow Rate	6 gpm (1.4 m^3/hr)
Maximum Pressure Drop	13 psig (0.9 bar)
pH Range, Continuous Operation	2 - 11
pH Range, Short-Term Cleaning (30 min.)^{b}	1 - 13
Maximum Feed Silt Density Index	SDI 5
Free Chlorine Tolerance ^{c} <0.1	ppm

a- Maximum temperature for continuous operation above pH 10 is 95°F (35°C).

b- Refer to Cleaning Guidelines in specification sheet 609-23010.

c- Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure.

Feed water:

In this study several times deionized water was prepared and used. The sources and grades of the salts are:

- NaCl (BIOCHEM chemo-pharma, Canada) at three salinities: (500mg/l, 2000mg/l, 3000mg/l).

-$CaCO_3$ (BIOCHEM chemopharma, Canada) at two salinities: (50mgl,300mg/l).

-$MgSO_4$ ($MgSO_4$,$7H_2O$ Riedel–deHaen, Germany) at three different salinities : (500mg/l,2000mg/l,3000mg/l).

Electrical conductivity (EC, mS/cm; mS/cm) of feed, Permeate and concentrate was measured using conductivity electrode and converted into concentration , as measured using salts (NaCl; $CaCO_3$, $MgSO_4$ dissolved in deionized water at 17 C°.

IV. Results and discussion:

IV.1. Performance of the RO membrane in rejecting salts:

The rejections were depicted as a function of the water flux.

In this paper, water flux was expressed as the produced permeate volume per unit membrane area per unit time (unit L/ h m^2); For the different considered salts and concentrations it was observed that the rejection always started with lower values (at the first operation pressure) and the gradually increased with time. The first pressure was always near to the osmotic pressure and to increase the rejection values it was necessary to increase the force into the membrane surface i.e. (increase operation pressure) .

with the batch RO process we worked with various salts and concentrations NaCl (500mg, 2000mg, 3000mg), $CaCO_3$ (50mg, 300mg), and $MgSO_4$ (500mg, 2000mg, 3000mg), the rejection ratio in NaCl salt with those concentration it is varying between [93.15%-92.91%-96.11%] respectively with a water flux [5.78 l/hm^2,4.61 l/hm^2, 7.69 l/hm^2] at the first operation pressure [2 bar, 3 bar, 4.5bar] and gradually increased to get [26.92l/hm^2, 25 l/hm^2, 23.07 l/hm^2] with a rejection ratio of [98.24%, 97.72%, 97.37%]. In general it was observed that the rejection in NaCl salt was between 500 ppm to 3000 ppm varying with decreases and increases of 1%.

About $CaCO_3$ salt or the hardness a low rejection ratio was observed compared to NaCl that it varying between [88.40%, 94.24%] with decrease of 6%.

For MgSO4 it was observed that the rejection was the highest one compared to the other salts (NaCl and $CaCO_3$) with increases from [98.46% , 98.89%; 99.11%] ± 0.5%; Therefore this TW30-2540 membrane was more performing with $MgSO_4$.

As shown in section 2 (Equation 1-5) the water flux J_w was related to permeate flow rate Q_p, trans membrane pressure and the osmotic pressure. This explains the obtained low values for water flux J_w (4.61 l/hm^2) due to the two parameters: the flow rate (12 l/h) and the operation pressure (2 bar). For the same reason a high value of the water flux (26.92l/hm^2) was obtained for the (500ppm NaCl) flow rate (70 l/h) and the operation pressure (8 bar).

For the continuous (single stage) RO process (MP20 pilot) a 1% decrease was observed for almost the three salts (NaCl, $CaCO_3$, $MgSO_4$). This decline was caused by the pressure drop during this process.

Concerning the water flux no difference was noted between the two processes, excepted the difficulties encountered and related to the brine flow during this operation .

Generally, for the two considered configurations consisting of batch RO and continuous single stage RO, the rejection R increased when water flux increased.

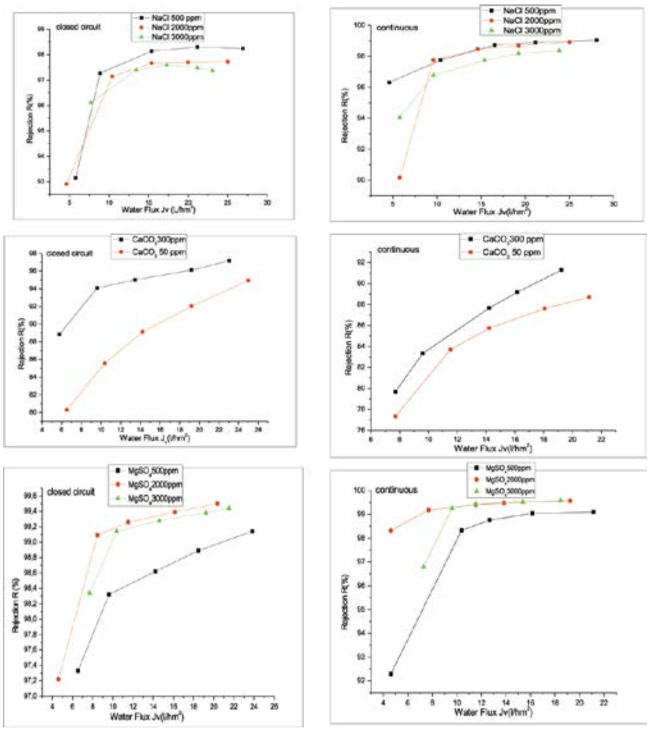

Figure 6: Rejection results of TW30-2540 with the (NaCl ,$CaCO_3$ and $MgSO_4$) salts at the following concentrations NaCl(500ppm,2000ppm,3000ppm), $CaCO_3$(50ppm,300ppm),$MgSO_4$(500ppm,2000ppm,3000ppm) for the two process Batch and continuous RO in function of water flux J_w.

IV.2. Hydro-dynamical approach:

Figure 7 shows a similar trend for the permeate concentration as function of the initial operation pressure, comparatively to the experimental results obtained for the both processes (Batch RO and Continuous RO.

For the Continuous RO process a continuous decrease of the permeate concentration Cp i.e. (increase Rejection R %) was observed with increasing operation pressure i.e. (increasing Water flux J_w).

For the Batch RO the same evolution was observed but with a slight increase of the permeate concentration i.e. (decrease Rejection R) with increasing of operation pressure i.e. (increasing Water flux J_w), as shown Figure 3. For the batch process the feed + the concentrate were treated in the same time so the feed concentration increase was due to an increase of the osmotic pressure for the treated water as a function of operation time. This was due to an increase in the permeate concentration as can be seen from Equation 4. However for the continuous RO process (Figure 3) only the water feed was treated (a constant feed concentration), explaining the absence of any permeate concentration increase.

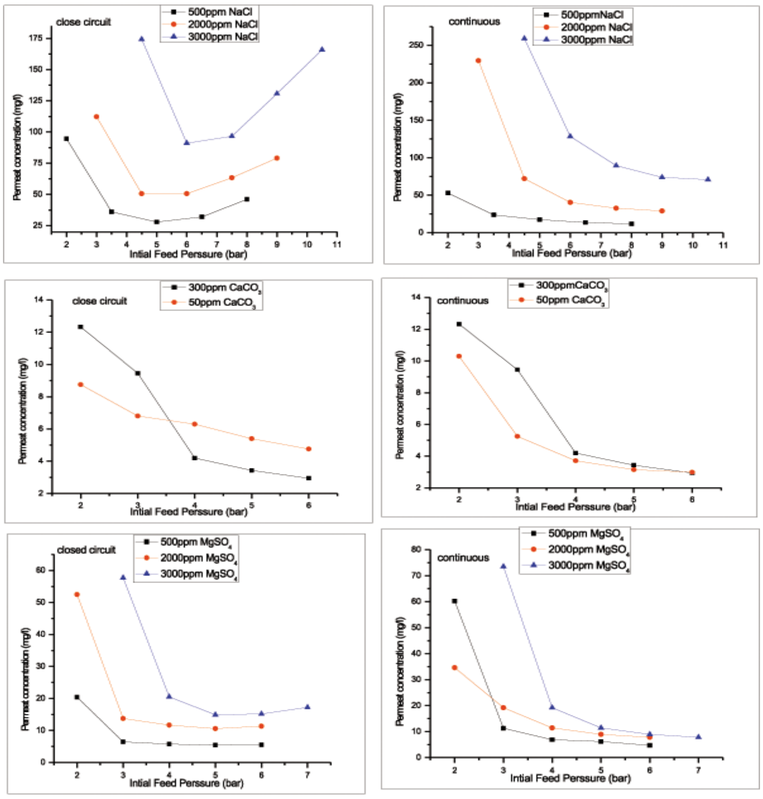

Figure 7: The permeate concentration C_p against initial feed pressure for the both process (Batch /Continuous RO).

IV.3. Pressure-recovery evolution:

For the evolution of the operating pressure as function of the recovery rate for the two process configurations (batch and continuous RO), in general an increase of the operation pressure always accompanied an increase of the recovery rate, giving almost a straight line.

For, the continuous RO process a significant increase in the recovery rate compared with the batch RO was noticed, with for example (NaCl 500 ppm, $CaCO_3$ 300ppm, $MgSO_4$ 500ppm). For a pressure of 2 bar in batch RO the values (8.33%, 8.75%, 6.88%) were obtained respectively. For the continuous RO the obtained values were (11.76%, 14.28%, 8.27%), hence with more than 3% increase. This can be explained by the hard stability of the feed flow rate for this process where with a minimum value we can have a high value of the permeate flow rate, as shown in Equation 7.Therefore a decrease of the feed flow rate led to an increase of the recovery due to the high energy (pressure) drop in this process.

The energy spent in RO process can be analyzed graphically as different characteristic fractions by means of the pressure recovery diagram.

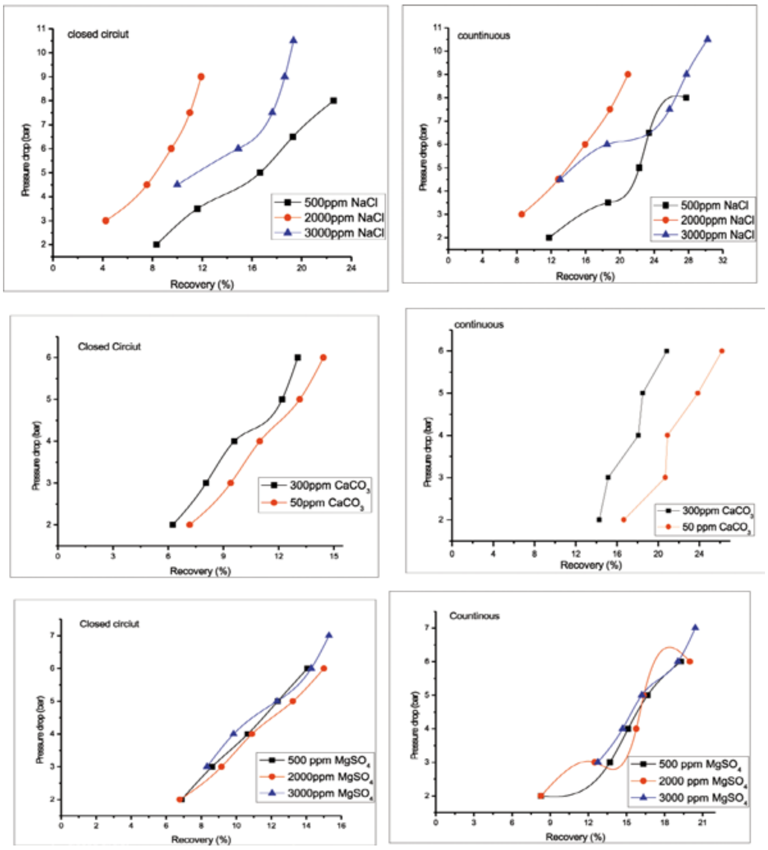

Figure 8: performance of RO membrane feed pressure against the recovery rate.

IV.4. The minimum specific energy comparison between Batch RO and Continuous RO process:

In this section we present a comparison between both processes for brackish water desalination with the minimum specific energy with theoretical expressions aid (Equations 8, 9).

As mentioned previously for the continuous RO process the feed solution concentration along the membrane channel increased as water permeates across the semi-permeable membrane under an applied hydraulic pressure that was higher than the local osmotic pressure. For the batch RO the retentate (brine) solution of the module recirculated in closed circuit where it mixed with the feed solution of the system to become the influent solution into the module.

For both processes the minimum specific energy increase was observed as function of feed concentration (osmotic pressure) and the recovery (cross flow rate) increase for each salt. The highest values of the minimum specific energy were obtained for NaCl.

The minimum specific energy is related to the recovery Y and the osmotic pressure $\Delta\pi_0$, through Equations 8 and 9 where if the recovery rate or the osmotic pressure increase, the energy also increases.

For both configuration it was observed that for the closing circuit RO the high and regular values were obtained, with the osmotic pressure having almost no influence on the energy value, except for the case of (2000ppm.3000ppm,) NaCl and (3000ppm) $MgSO_4$.

In the continuous RO process significant values were obtained compared to the previous process. This may be due to the effect of the osmotic pressure as shown in Figure 9.

In general it can be considered that the closing circuit process was more performing (saving energy) with the high brackish water, than the single stage RO process.

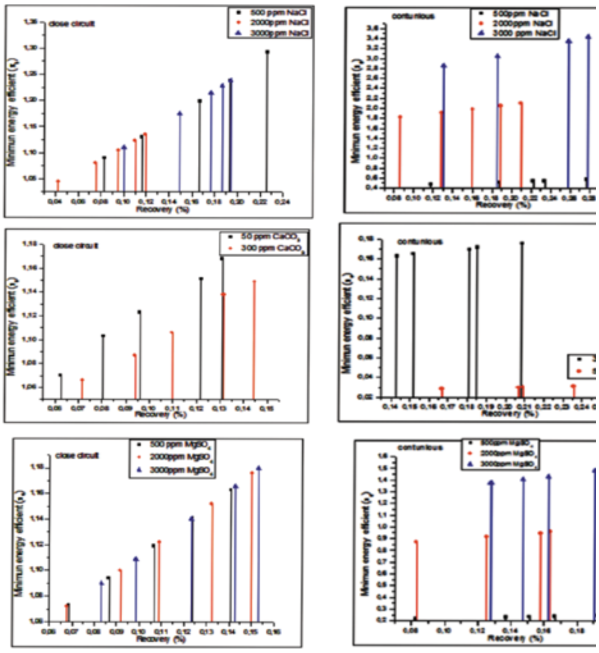

Figure 09: The minimum specific energy as a function of recovery for two different operation modes: (continuous RO) and (closing circuit RO) with different salts and concentrations.

V. Conclusion:

For the different brackish waters studied in this work for the **MP20** pilot and **TW30-2540** membrane sheet with process configurations, batch and continuous reverse osmosis, advantages and disadvantages can be mentioned.

For the batch reverse osmosis the benefit of this process are as followed:

- A process that gives a good amount of permeates volume and a great operation time.
- For the rejection salts this process can give a significant value of permeate quality.
- For the recovery rate and with the closing batch, the low values may decrease the concentration polarisation factor.
- For the energy it was observed that with this process a high brackish water quality was obtained.

The continuous reverse osmosis process may have many disadvantages which may be classified as follows:

- A short operation time mostly 30 min and a small amount of permeate volume so that for 100 l of feed water only 15 l of permeate water could be obtained.
- In spite of working with constant concentration feed water low values of salts rejections, decreasing by about 1 % compared with the previous process, were obtained.
- A high recovery rate value that can increase the concentration polarisation factor.
- Energy can be saved in this process when working with a low brackish water quality. But for the high quality of feed water remarkable specific energy consumption was observed compared with the closing circuit reverse osmosis.

Finally it can be assured that the batch process was the best configuration process for desalting brackish water reverse osmosis.

Nomenclature:

BW: brackish water.
RO: reverse osmosis.
ES: specific energy.
MF: micro-filtration.
UF: ultra-filtration.
NF: nano- filtration.
MD: distillation membrane.
PVC : poly vinyle chlore .
V: valve.
B_2: permeate tank.
B_1 : feed tank.

CC: closing circuit.
S_1 : feed solution.
S_2: permeate solution.
S_3: retentate solution.
J_W : water flux ($l/h.m^{-2}$).
J_S : salt flux ($kg·m^{-2}·s^{-1}$).
A_w: water permeability ($m^3·m^{-2}·s^{-1}·bar$)
B : salt permeability(m/s).
ΔP : difference operation pressure (bar).
C : concentration (g/l).
N: number of stage.
π : osmotic pressure (bar).
Q: flow rate (l/h).
Y : recovery rate.
p : permeate.
r: retentate.
f: feed.
w: water

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