

## Chemical and Hydrodynamic Modelling of a Reverse Osmosis Desalination System Using Pseudo Bond Graph Approach

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## ABSTRACT

The reverse osmosis desalination system is defined by mutual interaction between several phenomena from different natures. Therefore, such modelling requires a unified approach to have the possibility to correlate the different dynamic situation in our system. We performed experiments at three concentrations (10 mg/ml, 15 mg/ml and 18 mg/ml). Permeate conductivity, retentate conductivity, permeate concentration, retentate concentration, salt permeate concentration, and salt retentate concentration were extracted according to the values of the pressure. This paper presents a bond graph model of a reverse osmosis desalination system taking account of hydraulic and chemical phenomena. The construction procedure was based on the law that the optimized model can be generalized to any reverse osmosis desalination system with simple parameter variation. Simulation results and experimental data are also compared and discussed. This article aims to present the reliability and efficiency of the model bond graph to simulate this kind of industrial systems that brings together the hydraulic and chemical aspects at the same time. People would like to establish that, unlike some of the other functions choosing to ignore the chemical aspect is not suitable because of its significance in the desalination system.

Keywords: Reverse osmosis; Desalination system; Hydraulic system; Chemical system; Bond graph; Permeate concentration; Retentate concentration

Abbreviations: I: Number of Ion Species Constituting the Solute; M: Concentration of the Solute (mol m<sup>-3</sup>); T: Temperature (K); R: Gas constant (8.31 J.mol<sup>-1</sup>.K<sup>-1</sup>);  $\pi$ : Osmotic Pressure of Electrolytes (P<sub>a</sub>);  $\mu_0$ : Chemical Potential of Water in the Diluted Solution (J mol<sup>-1</sup>); R: Molar Gas Constant (R = 8.314 J mol<sup>-1</sup> K<sup>-1</sup>); T: Thermodynamic Temperature (K); A: Permeability of the Membrane to the Solvent (m<sup>-1</sup>.s); S: Surface of the Membrane (m<sup>2</sup>); P: Density of the Solvent (kg.m<sup>-3</sup>);  $\Delta P$ : Difference Pressure Side of the Membrane (P<sub>a</sub>);  $\Delta \pi$ : Pressure Difference Osmotic Either Side of the Membrane (P<sub>a</sub>): B: The Permeability of the Membrane to the Solute (ms<sup>-1</sup>); M<sub>0</sub>: Concentration of Solute in Feed (g.l<sup>-1</sup>); M<sub>p</sub>: Permeate of Either Side to the Membrane (g.l<sup>-1</sup>)

## INTRODUCTION

Desalination of seawater is now a conceivable principle to obtain drinking water due to the increasing number of people and the rising standards of living [1-6]. Due to interactions between different parameters, the desalination industry is a very complex process, so that it is becoming increasingly important for the operation of desalination plants as close as possible. Reverse osmosis is the most widely used system to treat desalination of brackish water and seawater and provides drinking water with very limited energy consumption [7-8]. It consists of filtering water by its passage through a semi-permeable extremely fine membrane which separated two solutions of different concentrations [9-11]. Sveral preliminary studies could be found in the literature where many modelling approaches of desalination units are given. Robertson has developed a dynamic matrix control algorithm based on the manipulation of pH and pressure, in order to control a Reverse Osmosis (RO) desalination system [12]. However, this approach cannot be used in the case of reverse osmosis plant for the desalination of brackish water. Indeed, the potable water salinity is lower than that of seawater and the variation of the pH is not remarkable. Mandler has developed a Single In Single Out approach (SISO) for the small reverse osmosis desalination systems [13]. Dynamic recreation of complex mechanical frameworks is talked about and an outline of work in displaying, reproduction

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and control of cryogenic division and liquefaction procedures is exhibited. Although this model can be used for control techniques, it does not allow the control of the salinity which is the most important quality parameter.

Thomson and Infield have developed a Matlab-Simulink model of a photovoltaic-reverse osmosis system [14]. A bond graph model of a reverse osmosis desalination system was developed by taking into account only the hydraulic part of the system while neglecting the chemical [15-30]. Demonstrating and reenactment of a framework are intuitive activities. To demonstrate a dynamic framework, bond graph modeling is one of the most integral assets especially in a framework where various sorts of physical subsystems interface together. It obviously portrays the progression of vitality between subsystems of a complex co-ordinated framework [31-43]. The studied system is a small process of desalination by reverse osmosis. The reverse osmosis process is essentially composed of a vertical multistage centrifugal pump and a two-stage reverse osmosis module device [44]. The results of the simulation by the bond graph approach are presented to examine the performance of the system. The authors focused their simulation work only on the hydraulic aspect (pressure and flow) of each component of the system.

Motivated by the previously mentioned considerations, the purpose of this work is to provide a bond graph model of a reverse osmosis desalination system taking account of both hydraulic and chemical phenomena. The parameters of the model are then computed based on experimental data gathered from the experimental reverse osmosis desalination system, to minimize errors between model and experimental system responses.

### MATERIALS AND METHODS

#### Experimental set up

The work is focusing the reverse osmosis for three samples of water salinities (18 mg/ml, 15 mg/ml and 10 mg/ml). This choice of these concentrations is determined by the assumption that our initial water is passed through a petrification system to reduce the concentration.

The reverse osmosis water desalination system with reference (OSM/2000) given by PIGNAT on which experimental tests were carried out is given by the figure below [45]. The below figure presents the experimental device with designation of the different components depicted in Figure 1(A). The below figure explanatory diagram of the operating principle of the system and the flow direction of the water depicted in Figure 1(B). The retentate flow rate should first be set at 1000 l/h and the pressure P is varied from 2 to 15 bars, then the permeate and retentate flow rates  $Q_{\rm p}$  and  $Q_{\rm r}$  as well as their conductivities must be recorded each time. A pressure manometer was used to measure the input pressure P and two flow meters to measure the flow rates  $Q_{\rm p}$  and  $Q_{\rm r}$ .

## Theoretical approach

The transfer of solvent (water in most cases) through a membrane due to the action of a concentration gradient is called osmosis [46-50]. Considering a system with two compartments separated by a perm selective membrane and containing two solutions of different concentrations [51-59]. The phenomenon of osmosis will lead to a water flow directed from the diluted to the concentrated solution. If an attempt is made to prevent this flow of water by applying pressure to the concentrated solution, the amount of water transferred by osmosis will decrease (Figure 2). At some point, the applied pressure will be such that the flow of water will cancel out. If we assume for simplicity that the diluted solution is pure water, this equilibrium pressure is called osmotic pressure. An increase in pressure beyond the osmotic pressure will result in a flow of water directed in the opposite direction to the osmotic flow, i.e. from the concentrated to the diluted solution: this is the phenomenon of reverse osmosis. In other word, reverse osmosis a partition procedure that utilizations strain to drive a dissolvable through a semi-porous film that holds the solute on one side and enables the unadulterated dissolvable to go to the opposite side, compelling it from an area of high solute fixation through a layer to a locale of low solute focus by applying a weight in abundance of the osmotic weight. Jacobus van 't Hoff found a quantitative connection between osmotic weight and solute focus, communicated in the accompanying condition [60].



Figure 1A: Reverse osmosis water desalination system. PIGNAT experimental reverse osmosis water desalination system OSM/2000. 1) Brackish water storage tank with copper-coil cooling circuit fed with cold water; 2) High-pressure pump feeding the osmosis module; 3) Osmosis module supply circuit with bypass line, control and pressure measuring valve; 4) RO membrane; 5) Retentate circuit with control valve, sampling valve, flow, conductivity and temperature measuring valve; 6) Permeate circuit with sampling valve, flow, conductivity and temperature measuring valve; 7) Tank water-supply; 8) Particle retaining filter.





The osmotic pressure is calculated with the following formula:

 $\pi = R.T.i.M\tag{1}$ 

$$Q = \frac{A.S}{\rho} (\Delta P - \Delta \pi) \tag{3}$$

Where  $\Pi$  is the osmotic pressure (bars), R the ideal gas constant, T the absolute temperature (K), i is the van't Hoff factor, the factor express the proportion between the salt amount of real issue in arrangement and the salt amount of obvious issue, this is the factor which explain the chemical aspect, M the molar concentration of the solute (Figure 3). For progressively thought arrangements the van't Hoff condition can be reached out as a power arrangement in solute concentration. In reverse osmosis, the solvent and solute transfers are carried out by solubilisation–diffusion: All molecular species (solute and solvent) dissolve through the membrane and diffuse inside there of as in a liquid under the action of a concentration and pressure gradient. The transfer therefore no longer depends on the particle size but on their solubility in the membrane medium. The separations are therefore of chemical origin and are related to the solvent power of the membrane.



The solvent mass flux  $J_{s_v}$  (kg.m<sup>-2</sup>.s<sup>-1</sup>) and the solvent volume flux (m<sup>3</sup>.s<sup>-1</sup>) passing through the membrane are given by the relations:  $J_{sv} = A.(\Delta P - \Delta \pi)$  (2) where A is the permeability of the membrane to the solvent (m.s<sup>-1</sup>), S the membrane surface (m<sup>2</sup>),  $\rho$  the volume mass of the solvent (kg.m<sup>-3</sup>),  $\Delta P$  the pressure difference on either side of the membrane and  $\Delta \Pi$  is the difference in osmotic pressure on either side of the membrane.  $\Delta \Pi$  is the osmotic pressure of the feed flux if the permeate is a very dilute solution. The solute mass flux Jsl (kg.m<sup>-2</sup>.s<sup>-1</sup>) passing through the membrane is given by the following relation:

$$J_{sl} = B(\Delta P - \Delta \pi) \tag{4}$$

Where B is the average permeability of the membrane to the solute  $(m.s^{-1})$ ,  $M_0$  and  $M_P$  are respectively the solute concentration of the feed and the permeate on either side of the membrane. It is thus shown that the solvent flux is proportional to the effective pressure  $\Delta P \cdot \Delta \Pi$  while the solute flux is independent of it. It is also shown that the rejection rate of a membrane increases as the effective pressure increases. Membrane clogging is the most acute problem encountered in membrane filtration of surface water. This issue has been the subject of much research on modelling, indicators and mechanisms clogging [61-64]. Clogging results from the accumulation of material on the surface of the membranes. When a membrane system is operated at constant trans-membrane pressure, the most problematic consequence of clogging is a reduction, sometimes extremely accentuated, of the permeation flux over time. Other direct or indirect consequences of clogging are a decrease in the active life of the membranes, more frequent washing, and therefore consumption of larger chemicals and the management/ disposal of wastewater, and additional energy expenditure to compensate for the decrease in membrane permeability caused by clogging. In the absence of clogging, for a solute free solution that can be retained by the membrane, the permeate volume flow  $J(m^3s^{.1}m^2)$  can be written in the form:

$$J_{sv} = A.(\Delta P - \Delta \pi) = \frac{\Delta P - \Delta \pi}{\mu.R_{m}}$$
(5)

It is possible to follow the increase of the restriction R to the flow of water through the membrane. However, since each membrane has an intrinsic pure water restriction, it is useful to consider two restrictions: a restriction associated with the clean membrane and another associated with the deposition of clogging substances. When the membrane clogs, an additional restriction  $R_s$  is added to the restriction of the membrane  $R_m$ :

$$J_{sv} = \frac{(\Delta P - \Delta \pi)}{\mu (\mathbf{R}_{m} + \mathbf{R}_{c})}$$
(6)

This means that the process will need more and more pressure over time, and therefore energy, to produce a constant permeate flow rate. The clogging thus progressively decreases the permeability of the membranes during a filtration cycle.

#### Bond graph model of reverse osmosis

Reverse osmosis desalination is carried out physically which represents from the point of view hydraulic system a reservoir of hydraulic capacity  $C_h$  with two restrictions (controlled valve noted  $MR_h$  and membrane noted  $R_{mh}$  (Figure 4). From the point of view of the chemical system is a chemical potential of the molar concentration  $C_c$  with two molar restriction (controlled valve  $MR_c$  and membrane  $R_{mc}$ ), these hydraulic and chemical elements are well discussed as elements of the bond graph model (Figure 5).



#### Main reverse osmosis element

#### R element:

*Hydraulic part:* The R element reflects energy dissipation through a restriction for the hydraulic system. According to Faissendier, the equation of this element is different when the flow is laminar or turbulent [65-68]. This flow is classified according to the Reynolds value:

$$R_e = \frac{v.d}{\mu} \tag{7}$$

Where v is the Average fluid speed (ms), d is the Diameter of the passage section (m), $\mu$  is the Kinematic viscosity of the fluid (m<sup>2</sup>/s). If Re  $\leq$  1000 then the flow is laminar, if not turbulent.

Chemical part: The R element reflects a dissipation of energy

through a restriction for the chemical system. This dissipation is given by the relation:

$$J_s = B.(\mathbf{M}_1 - \mathbf{M}_2) \tag{8}$$

Where  $J_s$  is the Solute flow (kg.m<sup>-2</sup>.s<sup>-1</sup>), B is the Average permeability of the membrane with solute (m.s<sup>-1</sup>), M<sub>1</sub> is the Solute concentration before the membrane (kg.m<sup>-3</sup>), M<sub>2</sub>: Solute concentration after the membrane (kg.m<sup>-3</sup>).

#### C element:

*Hydraulic part:* Element C reflects a potential energy build-up for the hydraulic system in Figure 6 (A). This accumulation is given by the constitutive relation of a capacity for a reservoir:

$$P_h = \frac{1}{C_s} \int \mathcal{Q}_h dt \tag{9}$$

Where  $P_h$  is the Hydraulic pressure (bar),  $Q_h$  is the Hydraulic flow (m<sup>3</sup> s<sup>-1</sup>),  $C_h$  is the Hydraulic capacity.

**Chemical part:** Element  $C_c$  reflects a potential energy accumulation for the chemical system in Figure 6 (B). This accumulation is given by the constitutive relation of a capacity for a solute:

$$M = \frac{1}{C_s} \int J_s dt \tag{10}$$

Where  $J_s$  is the Solute flow (kg.m<sup>-2</sup>.s<sup>-1</sup>), B is the Average permeability of the membrane with solute (m.s<sup>-1</sup>),  $M_1$  is the Solute concentration before the membrane (kg.m<sup>-3</sup>).

The bond graph model of the reverse osmosis desalination system is given in Figure 6. The most important parameters to be controlled are the pressure P and the flow rates of permeate  $Q_p$  and retentate  $Q_r$ . The reverse osmosis link graph model shown in the figure above has two parts: The hydraulic and chemical parts. It contains six sensors, three sensors for the hydraulic part (P: pressure sensor,  $Q_p$ : permeate flow sensor,  $Q_r$ : retentate flow sensor) and three sensors for the chemical part (M<sub>p</sub>: molar concentration sensor). The solvent flow of the reverse osmosis (water) is modeled by a flow source (Sf: Q), the reservoir is represented by a storage element (C:  $C_p$ ) of the quantity of produced water (permeate). The solute molar flow (salt water) is modeled by a flow source (Sf: J), the reservoir is represented by a storage element (C: C<sub>r</sub>) of the quantity of water rejected (retentate).



Figure 6A: Pseudo bond graph model of the reverse osmosis. Hydraulic part.



# Determination of equations in the hydraulic and chemical parts

The equations of the different elements constituting the pseudobond graph model are given as follows:

#### Hydraulic part:

$$(\mathbf{R}: MR_{h}) \begin{cases} f_{8} = \frac{1}{MR_{h}} e_{8} = \frac{1}{MR_{h}} (e_{4} - e_{9}) \\ Q_{r} = \frac{1}{MR_{h}} (P_{4} - P_{9}) = \frac{1}{MR_{h}} (P - P_{r}) \\ e_{3} = \frac{1}{C_{mh}} \dot{f}_{3} = \frac{1}{C_{mh}} (\dot{f}_{1} - (\dot{f}_{2} + \dot{f}_{4})) \end{cases}$$
(11)

$$(\mathbf{R}:R_{mh}) \begin{cases} P = \frac{1}{C_{mh}} \left( Q - \left( Q_r + Q_p \right) \right) \\ f_6 = \frac{1}{R_{mh}} e_6 = \frac{1}{R_{mh}} (e_2 - e_5) \\ Q_p = \frac{1}{P_0} P_6 = \frac{1}{P_0} (P_2 - P_5) = \frac{1}{P_0} (P - P_p) \end{cases}$$
(12)

$$(\mathbf{C}:C_{p_h}) \begin{cases} e_7 = \frac{1}{C_{ph}} \dot{f}_7 = \frac{1}{C_{ph}} \dot{f}_5 = \frac{1}{C_{ph}} \dot{Q}_5 = \frac{1}{C_{ph}} \dot{Q}_p \\ 1 & \vdots \end{cases}$$
(13)

$$\left[P_{p} = \frac{1}{C_{ph}}\dot{Q}_{p}\right]$$
(14)

$$(C:C_{rh}) \begin{cases} e_{10} = \frac{1}{C_{rh}} \dot{f}_{10} = \frac{1}{C_{rh}} \dot{f}_{9} = \frac{1}{C_{rh}} \dot{Q}_{9} = \frac{1}{C_{rh}} \dot{Q}_{r} \\ P_{r} = \frac{1}{C_{rh}} \dot{Q}_{r} \end{cases}$$
(15)

Chemical part:

$$\left(\mathbf{R}:MR_{c}\right)\left\{ \begin{aligned} f_{18} &= \frac{1}{MR_{c}}e_{18} = \frac{1}{MR_{c}}(e_{14} - e_{19}) \\ J_{r} &= \frac{1}{MR_{c}}M_{18} = \frac{1}{MR_{c}}(M_{14} - M_{19}) = \frac{1}{MR_{c}}(M - M_{r}) \end{aligned} \right.$$
(16)

$$(C:C_{mc}) \begin{cases} e_{13} = \frac{1}{C_{mc}} \dot{f}_{13} = \frac{1}{C_{mc}} (\dot{f}_{11} - (\dot{f}_{12} + \dot{f}_{14})) \\ M = \frac{1}{C_{mc}} (\dot{J} - (\dot{J}_r + \dot{J}_p)) \end{cases}$$
(17)

$$(\mathbf{R}:R_{mc}) \begin{cases} f_{16} = \frac{1}{R_{mc}} e_{16} = \frac{1}{R_{mc}} (e_{12} - e_{15}) \\ J_{p} = \frac{1}{R_{mc}} M_{6} = \frac{1}{R_{mc}} (M_{12} - M_{15}) = \frac{1}{R_{mc}} (M - M_{p}) \end{cases}$$
(18)

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$$(\mathbf{C}:C_{pc}) \begin{cases} e_{17} = \frac{1}{C_{pc}} \dot{f}_{17} = \frac{1}{C_{pc}} \dot{f}_{15} = \frac{1}{C_{pc}} \dot{Q}_{15} = \frac{1}{C_{pc}} \dot{J}_{p} \\ M_{p} = \frac{1}{C_{pc}} \dot{J}_{p} \\ M_{p} = \frac{1}{C_{pc}} \dot{J}_{p} \end{cases}$$
(19)  
$$(\mathbf{C}:C_{rc}) \begin{cases} e_{20} = \frac{1}{C_{rc}} \dot{f}_{20} = \frac{1}{C_{rh}} \dot{f}_{19} = \frac{1}{C_{rc}} \dot{J}_{19} = \frac{1}{C_{rc}} \dot{J}_{r} \\ M_{r} = \frac{1}{C_{rc}} \dot{J}_{r} \end{cases}$$
(20)

Where  $P_i$  is the pressure (bars);  $Q_i$  is the water flow rate (m<sup>3</sup>.s-1);  $M_i$  is the concentration (g.l<sup>-1</sup>);  $n_i$  is the molar flow (mol.s<sup>-1</sup>).

## **RESULTS AND DISCUSSION**

#### Simulations and experimental results

Permeate concentration as a function of pressure  $(M_p = f(P))$ : Figure 7 shows the curves of the permeate concentration  $(M_p)$  as a function of pressure (P) (the black dots shows the experimental data and the red line shows the numerical simulations) respectively for 10 mg/ml, 15 mg/ml and 18 mg/ml (Figure 7). From these curves, we observe that changes in the permeate concentration are similar to the retentate conductivity. This observation can be shocking because there is a discrepancy between the conductivity and the permeate concentration. We think that the key word is the coherence between the pressure and the network of the membrane. The force of the increase of the pressure causes the diminution of the nerve of the large molecular passivity by the membrane on the one hand, and on the other hand causes the increase of the number of small molecules passing through this membrane. By the same token, the ionic conductivity is proportional to the large molecular passivity by this membrane. Figure 7 presents the sum of the permeate concentration experimental data versus pressure. We observe that the behavior of permeate concentration is the same of retentate conductivity at fixed pressure.



Retentate concentration as a function of pressure ( $M_r = f(P)$ ): Figure 8 shows the curves of the retentate concentration ( $M_r$ ) versus of pressure (P) (the black dots shows the experimental data and the red line shows the numerical simulations) respectively for 10 mg/ ml, 15 mg/ml and 18 mg/ml (Figure 8). From these curves, we

note the same observation of the retentate conductivity. This result confirms that the number of big dimension molecules (clusters) not passing through the membrane increases when the pressure increases. In addition, we note that there is an order of magnitude difference between the permeate concentration and the retentate concentration, this confirms our interpretation. Figure 8 presents the sum of the retentate concentration experimental data versus pressure. We observe the same behavior of retentate conductivity at fixed pressure.



**Permeate flow as a function of pressure**  $(Q_p = f(P))$ **:** Figure 9 shows the curves of permeate flow  $(Q_p)$  versus pressure (P) (black dots for experimental data and red lines for numerical simulations) respectively for 10 mg/ml, 15 mg/ml and 18 mg/ml (Figure 9). From these curves, it is observed that the variations in permeate flow as a function of pressure are linear and increasing for the two first concentrations. For the third concentration, the curve of permeate flow as a function of pressure is divided into three zones. The first zone exhibits a small increase in permeate conductivity and this is in the range 3-8 bar, whereas the second zone has a strong increase and this is in the range 8-12 bar, the third zone is a zone of saturation. We think for the first two concentrations (10 mg/ml and 15 mg/ml). The number of large molecule is not very important so not important areas of congestion. Then, when the pressure increases, the average velocity of the fluid increases, at this stage we think that all the molecules work with almost the same speed. There is no difference between small and large aggregates, so there is no provocation of the viscosity problem. For the third concentration (18 mg/ml), we admit that the appearance of these three zones is the important difference between the average speed of small molecules and the average speed of large molecules. In addition the concentration increases the possibility of formation of cluster clutter areas. So this can cause the possibility of nonhomogenous fluid. We can say that in the first zone the difference between the average velocities of the small and large molecules is important, whereas this difference decreases for the second zone and almost disappears for the third zone. Figure 9 presents the sum of the permeate flow experimental data versus pressure. We observe that the permeate flow decrease at fixed pressure but not with the same way. We know that the permeate flow is directly related to the diameter of the holes in the membrane, or when the concentration increases, the possibility of formation of large aggregates increases, so the flow rate of permeate decreases.



Retentate flow as a function of pressure  $(Q_r = f(P))$ : Figure 10 shows the curves of the retentate flow  $(Q_r)$  versus pressure (P) (black dots shows experimental data and red line shows the numerical simulations) respectively for 10 mg /ml, 15 mg/ml and 18 mg/ml (Figure 10). From these curves, it is observed that the variations of the permeate flow as a function of the pressure are linear and decreasing. It is clear that the decrease in the flow rate of retentate is directly related to the permeate flow rate for the first two concentrations where the average fluid flow rate is almost the individual flow rate of each fluid constituent, in other words, or the viscosity is approximately homogenous in an approximate manner. For the highest concentration, the retentate flow is directly related to the permeate flow but not directly to the diameter of the membrane holes. Unlike the permeate flow that is related to this parameter. Figure 10 presents the sum of the retentate flow experimental data versus pressure. We observe that the permeate flow increase at fixed pressure with the same way.



The below Table shows the physical parameters of reverse osmosis for the three concentrations (Table 1).

We note that the elements of storage ( $C_{mh}$ ,  $C_{mc}$ ,  $C_{ph}$ ,  $C_{pc}$ ,  $C_{rh}$  and  $C_{rc}$ ) do not vary and this choice to limit the completeness of the system. This choice is based on industrial models that require

Symbols	Designations	Nominal values for 10 mg/ml	Nominal values for 15mg/ml	Nominal values for 18 mg/ml
Q	Source flow (l.h <sup>-1</sup> )	103	103	103
J	Molar flow (l.h <sup>-1</sup> )	0.467	0.655	0.895
C <sub>mh</sub>	Feed water storage hydraulic part (m <sup>3</sup> .N <sup>1</sup> )	18.104	24.104	28.104
C <sub>mc</sub>	Feed water storage chemical part (m <sup>3</sup> .N <sup>-1</sup> )	20.10-6	26. 10-6	28.10-6
$C_{ph}$	Permeate water storage hydraulic part (m <sup>3</sup> .N <sup>-1</sup> )	4.10-3	8.10-3	10.10-3
C <sub>pc</sub>	Permeate water storage chemical part (m <sup>3</sup> .N <sup>-1</sup> )	2.10-6	6. 10 <sup>-6</sup>	8.10%
C <sub>rh</sub>	Retentate water storage hydraulic part (m <sup>3</sup> .N <sup>-1</sup> )	12.103	16.10-3	18.10-3
C <sub>rc</sub>	Retentate water storage chemical part $(m^3.N^{-1})$	16.10%	18. 10-6	20.10-6
R <sub>mh</sub>	Hydraulic permeability (l.h <sup>-1</sup> )	32	28	26
R <sub>mc</sub>	Chemical permeability (l.h <sup>-1</sup> )	1.10-3	0.4.10-3	0.6.10 <sup>-3</sup>
MR <sub>h</sub>	Control valve hydraulic part (m <sup>3</sup> .s <sup>-1</sup> )	9.10 <sup>2</sup>	7.10 <sup>2</sup>	6.10 <sup>2</sup>
MR <sub>c</sub>	Control valve chemical part (m <sup>3</sup> .s <sup>-1</sup> )	1.10-1	0.4.10-1	0.6.101

the invariance of the storage areas whatever the pressure or the concentration. The control valves (MR<sub>h</sub> and MR<sub>c</sub>) are valves used to control the flow of fluid by varying the size of the flow passage as indicated by the signal from a controller. In fact, each position coincides with an instantaneous molar concentration and for ease of work we admit that they are constant. The flow of permeate  $(Q_p)$  increases as a function of the pressure (P) and decreases as a function of the concentration (M). While the flow (Q) decreases as a function of the pressure and increases in function the concentration (M). Based on Figure 2 and the previously noted results, the values of hydraulic restriction (R<sub>mh</sub>) will be varied at each pressure and at each concentration (Figure 2). Indeed at constant pressure, the evolution of the restriction is inversely proportional to the flow of permeate. Whereas in relation to retentate flow it is proportional. Also the results obtained can be explained by the reality that increase of the concentration means the increase of the numbers of the molecules that causes the variation of the instantaneous pressures before and after the membrane. We note that the permeate and retentate concentrations increase as the pressure increases. Also these concentrations increase when the initial concentration of water increases. The permeate and retentate concentrations change with an order of magnitude difference. Based on equation 8, Solute Flows  $(J_p \text{ and } J_r)$  increase as the initial concentration of water increases. The rate of evolution of solute flow  $(J_p \text{ and } J_r)$  is not the same, this can be explained by the presence of the small molecule in the permeate and large molecules in the retentate. Increasing the initial concentrations of the water will vary the flow retentate clearly but not in the same way the retentate flow.

## CONCLUSION

In this article we were able to show how to use the linkage graph approach to model the reverse osmosis desalination system element by element not only the hydraulic part but also the chemical part. The introduction of the chemical aspect more precisely the effects of the Jacobus van't Hoff factor in the modeling is essential in the desalination system. We managed to compare the results of the theoretical simulation with the experimental results for both the hydraulic aspect and the chemical aspect. In addition, we believe that our proposal to model this reverse osmosis desalination system can be generalized and used in industrial life for the monitoring, control and supervision of the hydraulic and chemical aspects of this system. In addition, the configuration of our system is directly and explicitly linked to the types of fluids, the type of membrane materials and the capacity of the tanks of the desalination system. These parameters are clearly explicit in our model, which opens the door to generalization to industrial systems. But our model does not deal with the service life of the membrane. Thus, the effects of temperature are not valued in our case, which opens the door to their introduction into the model equations. In addition, the emphasis on robust diagnostic strategy using linkage graph modeling should be discussed for the future.

#### REFERENCES

- Rahaman MM. Water wars in 21<sup>st</sup> century: Speculation or reality? Int J Sustainable Society. 2012;4(1-2):3-10.
- Arfanuzzaman M, Syed A. Water demand and ecosystem nexus in the transboundary river basin: A zero-sum game. Environ Dev Sustain. 2018;20(2):963-974.
- Akinaga T, Generalis SC, Paton C, Igobo ON, Davies PA. Brine utilization for cooling and salt production in wind-driven seawater greenhouses:Design and modelling. Desalination. 2018;426:135-154.
- Voutchkov N. Energy use for membrane seawater desalination-current status and trends. Desalination. 2018;431:2-14.
- Yang Z, Ma XH, Tang CY. Recent development of novel membranes for desalination. Desalination. 2018;434:37-59.
- Missimer TM, Maliva RG. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination. 2018;434:198-215.
- 7. Merten U. Desalination by reverse osmosis. 1966.
- 8. Rautenbach R, Albercht R. Membrane processes. 1989.
- 9. Lacey RE, Loeb S. Industrial processing with membranes. 1972.
- Das R, Ali ME, Hamid SB, Ramakrishna S, Chowdhury ZZ. Carbon nanotube membranes for water purification: A bright future in water desalination. Desalination. 2014;336:97-109.

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- Robertson MW, Watters JC, Desphande PB, Assef JZ, Alatiqi IM. Model based control for reverse osmosis desalination processes. Desalination. 1996;104(1-2):59-68.
- Mandler JA. Modelling for control analysis and design in complex industrial separation and liquefaction processes. J Process Control. 2000;10(2-3):167-175.
- 13. Thomson M, Infield D. A photovoltaic-powered seawater reverse-osmosis system without batteries. Desalination. 2003;153(1-3):1-8.
- 14. Paynter HM. Analysis and design of engineering systems. 1961.
- 15. Verge M, Jaume D. Modelisation structuree des systemes avec les Bond Graphs. Editions Technip. 2003.
- Karnopp D, Margolis D, Rosenberg R. System Dynamics: A Unified Approach. 1990.
- 17. Dauphin-Tanguy G. Les bond graphs, Paris, Fance: Hermes Science Publications.2000.
- Borutzky W. Bond graph methodology: Development and analysis of multidisciplinary dynamic system models. Springer Science & Business Media. 2009.
- Dauphin-Tanguy G, Tagina M. La méthodologie bond graph: Principes et applications. Centre de Publication Universitaire. 2003.
- Boudon B, Dang TT, Margetts R, Borutzky W, Malburet F. Simulation methods of rigid holonomic multibody systems with bond graphs. Adv Mech Eng. 2019;11(3):1687814019834153.
- Chen H, Jiang B, Lu N, Mao Z. Multi-mode kernel principal component analysis-based incipient fault detection for pulse width modulated inverter of China Railway High-speed 5. Adv Mech Eng. 2017;9(10):1687814017727383.
- 22. Lee K, Ha H, Ahn S, Hong S, Kang H, Heo S, et al. Development of a pressure control algorithm without a pressure sensor for a four-wheel drive unit. Adv Mech Eng. 2018;10(5):1687814018771740.
- Zrafi R, Ghedira S, Besbes K. A bond graph approach for the modeling and simulation of a buck converter. J Low Power Electron Appl. 2018;8(1):2.
- Harry Asada H, Sotiropoulos FE. Dual faceted linearization of nonlinear dynamical systems based on physical modeling theory. J Dyn Syst Meas Control. 2019;141(2):021002.
- 25. Pan M, Gawthrop PJ, Tran K, Cursons J, Crampin EJ. Bond graph modelling of the cardiac action potential: implications for drift and nonunique steady states. Proc Math Phys Eng Sci. 2018;474(2214):20180106.
- Gibson TJ, Barth EJ. Design, Model, and Experimental Validation of a Pneumatic Boost Converter. Journal of Dynamic Systems, Measurement, and Control. 2019;141(1).
- Janevska G. Bond Graphs Approach to Modeling Thermal Processes. Int j sci eng res. 2017;8(5):736-740.
- Pan M, Gawthrop PJ, Tran K, Cursons J, Crampin EJ. Bond graph modelling of the cardiac action potential: Implications for drift and nonunique steady states. Proc Math Phys Eng Sci. 2018;474(2214):20180106.
- Gawthrop PJ, Cursons J, Crampin EJ. Hierarchical bond graph modelling of biochemical networks. Proc R Soc A: Math Phys Eng Sci. 2015;471(2184):20150642.
- Mahamadi A, Sastry S. Bond graph models for human behavior. In 2016 Conference of Basic Sciences and Engineering Studies (SGCAC) 2016; pp. 110-115.
- Boerlage SF, Kennedy M, Aniye MP, Schippers JC. Applications of the MFI-UF to measure and predict particulate fouling in RO systems. J Membr Sci. 2003;220(1-2):97-116.
- Sallami A, Chaabene AB, Sallami A. Robust fault diagnosis of a reverse osmosis desalination system modeled by bond graph approach. IJCSNS. 2011;11(12):105.
- 33. SALLAMI A, Mzoughi D, Mami A. Diagnosis of reverse osmosis desalination water system using bond graph approach. Turk J Electr Eng Comput Sci. 2018;26(3):1638-1650.

- 34. Chaabene AB, Ouelhazi K, Sellami A. Novel design and modeling of a Photovoltaic Hydro Electromagnetic Reverse Osmosis (PV-HEMRO) desalination system. J Desalin Water Treat. 2017;66:36-41.
- 35. Schippers JC, Verdouw J. The modified fouling index, a method of determining the fouling characteristics of water. Desalination. 1980;32:137-148.
- Chudacek MW, Fane AG. The dynamics of polarization in unstirred and stirred ultrafiltration. J Membr Sci. 1984;21(2):145-160.
- Lahoussine-Turcaud V, Wiesner MR, Bottero JY. Fouling in tangentialflow ultrafiltration: The effect of colloid size and coagulation pretreatment. J Membr Sci. 1990;52(2):173-190.
- Wiesner MR, Chellam S. Mass transport considerations for pressured driven membrane processes. J Am Water Works Assoc. 1992;84(1):88-95.
- Hong S, Elimelech M. Chemical and physical aspects of Natural Organic Matter (NOM) fouling of Nano filtration membranes. J Membr Sci. 1997;132(2):159-181.
- Jacangelo JG, Challam S, Bonacquisti TP. Treatment of surface water by double membrane systems: Assessment of fouling, permeate water quality and costs. In Technical papers. 1999;pp.4447.
- 41. Guigui C, Bonnelye V, Durand-Bourlier L, Rouch JC, Aptel P. Combination of coagulation and ultrafiltration for drinking water production: Impact of process configuration and module design. Water Sci Technol: Water Supply. 2001;1(5-6):107-118.
- 42. Boerlage SF, Kennedy MD, Dickson MR, El-Hodali DE, Schippers JC. The Modified Fouling Index using Ultrafiltration Membranes (MFI-UF): Characterisation, filtration mechanisms and proposed reference membrane. J Membr Sci. 2002;197(1-2):1-21.
- 43. Turki M, Belhadj J, Roboam X. Design and Energy management of a small-scale reverse osmosis desalination unit powered by PV-Wind hybrid system without battery storage. In International conference on Electrical Engineering Design and Technologies (ICEEDT). 2007;pp. 5-6.
- 44. OSM.Reverse osmosis.2000.
- 45. Yasukawa M, Mishima S, Tanaka Y, Takahashi T, Matsuyama H. Thinfilm composite forward osmosis membrane with high water flux and high pressure resistance using a thicker void-free polyketone porous support. Desalination. 2017;402:1-9.
- 46. Das R, Ali ME, Abd Hamid SB, Ramakrishna S, Chowdhury ZZ. Carbon nanotube membranes for water purification: A bright future in water desalination. Desalination. 2014;336:97-109.
- 47. Atab MS, Smallbone AJ, Roskilly AP. An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination. 2016;397:174-184.
- Mohammad AW, Teow YH, Ang WL, Chung YT, Oatley-Radcliffe DL, Hilal N. Nano filtration membranes review: Recent advances and future prospects. Desalination. 2015;356:226-254.
- 49. Alkhudhiri A, Darwish N, Hilal N. Membrane distillation: A comprehensive review. Desalination. 2012;287:2-18.
- 50. Rautenbach R, Albercht R. Membrane processes. 1989.
- Schippers JC, Verdouw J. The modified fouling index, a method of determining the fouling characteristics of water. Desalination. 1980;32:137-148.
- Chudacek MW, Fane AG. The dynamics of polarisation in unstirred and stirred ultrafiltration. J Membr Sci. 1984;21(2):145-160.
- Lahoussine-Turcaud V, Wiesner MR, Bottero JY. Fouling in tangentialflow ultrafiltration: The effect of colloid size and coagulation pretreatment. J Membr Sci. 1990;52(2):173-190.
- Wiesner MR, Chellam S. Mass transport considerations for pressured driven membrane processes. J Am Water Works Assoc. 1992;84(1):88-95.
- Hong S, Elimelech M. Chemical and physical aspects of Natural Organic Matter (NOM) fouling of Nano filtration membranes. J Membr Sci. 1997;132(2):159-181.

- 56. Jacangelo JG, Challam S, Bonacquisti TP. Treatment of surface water by double membrane systems: Assessment of fouling, permeate water quality and costs. In Technical papers. 1999.pp. 4447.
- 57. Guigui C, Bonnelye V, Durand-Bourlier L, Rouch JC, Aptel P. Combination of coagulation and ultrafiltration for drinking water production: Impact of process configuration and module design. Water Sci Technol: Water Supply. 2001;1(5-6):107-118.
- 58. Boerlage SF, Kennedy MD, Dickson MR, El-Hodali DE, Schippers JC. The Modified Fouling Index Using Ultrafiltration Membranes (MFI-UF): Characterization, filtration mechanisms and proposed reference membrane. J Membr Sci. 2002;197(1-2):1-21.
- 59. Rautenbach R, Albercht R. Membrane processes. 1989.
- Boerlage SF, Kennedy M, Aniye MP, Schippers JC. Applications of the MFI-UF to measure and predict particulate fouling in RO systems. J Membr Sci. 2003;220(1-2):97-116.
- Lanteri Y. Lanteri Y. Transport a Travers des membranes de Nano filtration: Caracterisation des proprietes electriques et dielectriques. 2009.

- 62. Kecili K. Etude et characterization de membranes synthetiques organiques immergees de Micro Filtration (MF) et d'Ultra Filtration (UF) employees pour la production d'eau destinee a la consommation humaine: intensification des operations de deconditionnement et de nettoyage. 2006.
- 63. Richards LA. The removal of inorganic contaminants using Nano filtration and reverse osmosis. 2012.
- 64. Richards LA, Vuachere M, Schafer AI. Impact of pH on the removal of fluoride, nitrate and boron by nanofiltration/reverse osmosis. Desalination. 2010;261(3):331-337.
- 65. Faisandier J, Blot M. Mecanismes hydrauliques et pneumatiques. 1999.
- Tardu SF, Binder G, Blackwelder RF. Turbulent channel flow with largeamplitude velocity oscillations. J Fluid Mech. 1994;267:109-151.
- He S, Jackson JD. An experimental study of pulsating turbulent flow in a pipe. Eur J Mech B/Fluids. 2009;28(2):309-320.
- 68. Uchida S. The pulsating viscous flow superposed on the steady laminar motion of incompressible fluid in a circular pipe. J Appl Math and Phys. 1956;7(5):403-422.