Full-Scale Seawater Reverse Osmosis Desalination Plant Simulator ⋆

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Abstract: Reverse Osmosis (RO) is an evolving membrane-based technology for water desalination that started to gain increased popularity in the light of the increased global water demand due its high efficiency and low carbon footprint. This paper presents a full-scale Seawater Reverse Osmosis (SWRO) desalination plant simulator using MATLAB/Simulink, which is a user-friendly and commonly used simulation software. The simulator has been validated using the operational data from a local plant and it allows simulating the system behavior under different operating conditions with high flexibility and minimal cost. It can be used to analyze the plant performance under different operating conditions, and for research for health monitoring applications and in the cybersecuity area.

Keywords: Reverse osmosis, Simulation, Industrial control systems

1. INTRODUCTION

Given the increased demand on fresh water due to the worldwide population growth, technologies for seawater desalination, which is a method for producing water suitable for human use, have become essentially important. Water desalination involves producing fresh water from saline water in which the salts are concentrated in the by-product. The separation process can be thermal-based such as, Multi-Stage Flash desalination (MSF), and Multiple Effect Evaporation (MEE), or membrane-based such as, the reverse osmosis (RO) and electrodialysis (ED) (El-Dessouky and Ettouney (2002)). In the thermal-based desalination processes, the water is evaporated leaving the salts and unwanted molecules behind and then collected by condensation, and in the membrane-based processes, the salt ions are blocked by the membrane while the water modules pass through it and accumulate at the other end as fresh water. Among the existing technologies for seawater desalination, reverse osmosis has been proven to be one of the most efficient methods due to its low carbon footprint and energy requirement. Therefore, RO water desalination plants are becoming popular and widely used worldwide.

This paper presents a full-scale Seawater Reverse Osmosis (SWRO) desalination plant simulator that has been developed using MATLAB/Simulink and validated using operational data of a local plant. The main objective of this work is to develop a simulator that is capable of demonstrating the different stages of the reverse osmosis plants starting with the water intake stage, then the reverse osmosis process, and finally the distribution stage. It simulates the actual full-scale plant operation and incorporates the full control system of the plant. It can be used for several research purposes with high flexibility such as performance analysis, and research for health monitoring applications and in cybersecurity area.

There have been several works on RO plant simulations such as (Gambier et al. (2009); Bartman et al. (2009); Senthil and Subbia (2016); Joseph and Damodaran (2019); Jiang et al. (2015b); Al-Obaidi et al. (2018); Verhuelsdonk et al. (2010); Choi and Kim (2015); Jiang et al. (2015a); Park et al. (2012)). However, they do not demonstrate the operation of the full plant such that their main objective is to analyze the RO unit performance with respect to the control system design (Gambier et al. (2009); Bartman et al. (2009)), the different system configurations -RO units arrangement, number of units, etc.- (Senthil and Subbia (2016)), and the operating conditions in terms of water properties of pressure, temperature, concentration, purity, etc. (Joseph and Damodaran (2019); Jiang et al. (2015b); Al-Obaidi et al. (2018); Verhuelsdonk et al. (2010); Choi and Kim (2015); Jiang et al. (2015a); Park et al. (2012)).

In addition, it is worth noting that the simulation of the chemical dynamics of the system in terms of the

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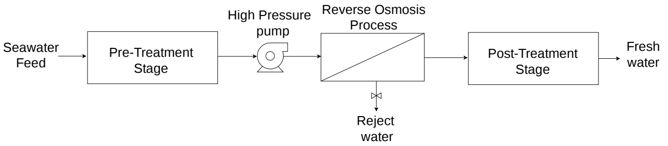

Fig. 1. Diagram of the reverse osmosis plant.

chemical dosing taking place in the pre-treatment and post-treatment stages is not possible, and has not been done in any of the previous works due to the fact that the models of these chemical processes are complex and not implementable.

The key contribution of this work with respect to the previous works is presenting a feasible solution of a full-scale SWRO desalination plant simulation testbed using a popular and user friendly software that demonstrates the operation of a large-scale plant. It is validated using operational data of an actual plant and can be used for several research purposes.

2. REVERSE OSMOSIS PLANT SIMULATOR DESIGN

As shown in Fig. 1, an RO plant is composed of three main stages, which are:

(1) The pre-treatment stage: The raw feed water is conditioned before entering the RO process. This involves different kinds of filtration in addition to chemical dosing (e.g., anti-scaling, adjusting pH level, etc.). This is used to remove/reduce the Total Suspended Solids (TSS) of the water in order to maintain the lifetime of the RO membrane (to avoid fouling) and the quality of the product water.

(2) The RO process: This is used for removing the salt and the large particles (e.g., bacteria, etc.) to produce fresh water. The RO unit has three streams, one is the feed water inflow stream and the other two are the outflow streams, which are the concentrated (brine or reject) solution stream and the product (permeate or fresh water) stream. This process consists of pressure vessels each encompassing a number of RO membranes as illustrated in Fig. 2.

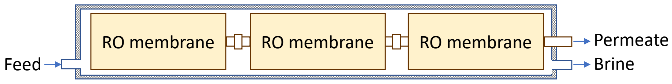

Fig. 2. Schematic of a single pressure vessel containing 3 RO membrane units.

The performance of the reverse osmosis unit is evaluated using two metrics, which are:

- Recovery rate ($\mathrm{R_r}$): This is defined as the proportion of the product (permeate) water with respect to the feed water. It is expressed as:

$$\mathrm{R_r} = \frac{M_\mathrm{p}}{M_\mathrm{f}} \times 100, \tag{1}$$

where $M_\mathrm{p}[\,\mathrm{kg/s}]$ is the permeate mass flow rate and $M_\mathrm{f}[\,\mathrm{kg/s}]$ is the feed mass flow rate.

- Salt rejection rate (SR): This is the percentage of the amount of solute that is removed due to the RO process. It is given by:

$$\mathrm{SR} = \left(1 - \frac{C_\mathrm{p}}{C_\mathrm{f}}\right) \times 100, \tag{2}$$

where $C_\mathrm{p}[\,\mathrm{ppm}]$ is the permeate concentration and $C_\mathrm{f}[\,\mathrm{ppm}]$ is the feed concentration.

(3) The post-treatment stage: This stage aims to condition the product water of the RO process for storage and human use. It involves chemical dosing of minerals, disinfection, and adjusting the pH level.

The seawater reverse osmosis desalination plant shown in Fig. 3 has been built using MATLAB/Simulink. It is a two-pass SWRO desalination plant operating with an overall salt rejection of 99.9% and a recovery rate of about 40%. The first stage of the plant is the pre-treatment process, which starts with the water intake stage in which the water is pumped from the sea to the intake storage tank followed by the Dissolved Air Flotation (DAF) system and disk filters to purify the raw water. The second stage is the reverse osmosis process, which consists of two-cascaded spiral wound RO units using membranes manufactured by TORY with models numbers TM820M-440 and TM720D-440, respectively in which the product water of the first RO unit is fed to the second one for further purification.

For the first pass RO, the feed water pressure is increased by a high pressure (HP) pump to overcome the osmotic pressure. The highly pressurized brine solution is fed to an energy recovery device (ERD), namely a pressure exchanger (PX) to recover and transfer the pressure to a portion of the main feed water. A booster pump is then used to raise this pressure to the membrane feed pressure. The product water of the first RO pass is fed to the second pass after boosting its pressure by a booster pump to overcome the osmotic pressure. For the second RO pass, the brine solution pressure is not that high and hence, it is discharged at the atmospheric pressure through a reject valve. The last stage consists of the product water storage tank and a distribution pump that supplies the fresh water based on the demand.

The salinity of the main feed water is about 45,900 ppm and its temperature is between 25 - 35 °C. Tables 1 to 3 summarize the main details of the SWRO desalination plant simulator.

2.1 *Mathematical Models*

The following subsections present the mathematical models of the SWRO desalination plant used in the simulator design.

Static Mixer: The static mixer model is approximated by a linear model deduced from the available operational data as follows:

$$M_\mathrm{in} = M_\mathrm{out}, \tag{3}$$

$$P_\mathrm{out} = P_\mathrm{in} - \Delta P, \tag{4}$$

$$\Delta P = \alpha_\mathrm{m} M_\mathrm{in}, \tag{5}$$

where P_in [kPa] and P_out [kPa] are the pressures of the inlet and the outlet streams, respectively, M_in [kg/s] and M_out [kg/s] are the inlet and the outlet flow rates, respectively, and the pressure drop across the static mixer

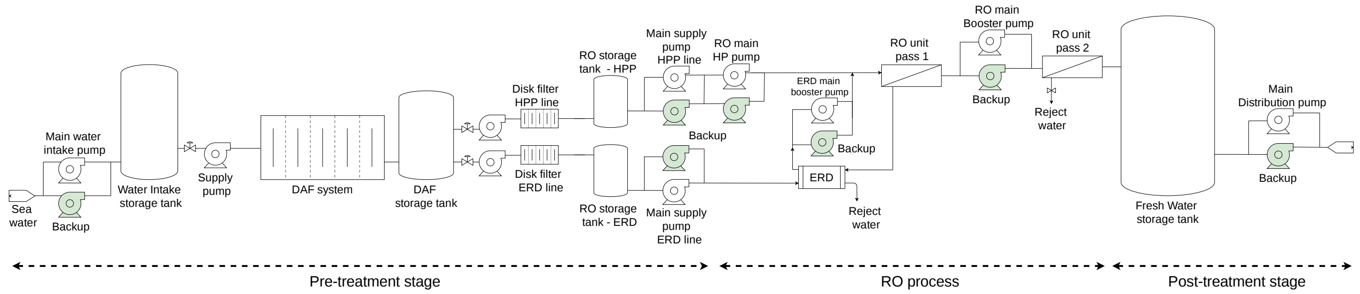

Fig. 3. Block diagram of the simulated SWRO desalination plant.

Table 1. List of the equipment used in the SWRO desalination plant simulator.

Stage	Equipment Details	
Pre-treatment		Water intake storage tank Main water intake pump Backup water intake pump DAF storage tank Disk filters pressure pumps RO storage tanks RO supply pumps
Reverse osmosis process	RO units	Main HP pump Backup HP pump Main Booster pump Backup Booster pump
	ERD - PX	Main Booster pump Backup Booster pump
Post-treatment		Product water tank Distribution main pump Distribution backup pump

Table 2. Specifications of the SWRO desalination plant simulator.

Parameter	Value
Feed water	
Temperature (°C)	25 - 35
Concentration (ppm)	45900
RO units	
Pass 1 -Recovery rate	35 - 40%
Pass 2 -Recovery rate	80 - 90%
Pass 1 - Maximum pressure	8300 kPa
Pass 2 - Maximum pressure	4100 kPa

Table 3. Specifications of the RO units.

Parameter	Value	
Membrane area per an RO element (A_m)	41 m^2	
Number of elements in a pressure vessel (n_v)	7	
Number of pressure vessels (n_e)	RO pass 1	141
	RO pass 2	52

ΔP [kPa] is proportional to the amount of the inlet flow rate with α_m as the linear model coefficient.

Pumps: There are two types of water pumps in the reverse osmosis plant, which are the pressure pump and the flow pump. Pressure pumps can be classified based on the operating pressure range as high pressure (HP) pumps and pressure booster pumps. The high pressure pump is capable of boosting the water pressure to high pressure ranges (above 5,000 kPa) and it is used to drive the high salinity feed water to the desired pressure value required to overcome the osmotic pressure. The booster pump operates at lower pressure ranges. For instance, a pressure booster pump is used to pressurize the ERD's high pressure outlet stream. The flow booster pump is used to increase the water flow rate such as the one used for water distribution.

- The model of the high pressure and the pressure booster pumps can be expressed as:

$$Q_{\text{in}} = Q_{\text{out}}, \tag{6}$$

$$P_{\text{out}} = P_{\text{in}} + P_{\text{hp}}, \tag{7}$$

$$P_{\text{hp}} = 0.102(\text{H}_\text{s} + H_\text{D}), \tag{8}$$

$$H_\text{D} = \frac{\text{K}_{\text{R pump}} V^2}{2\text{g}}, \tag{9}$$

  where $Q_{\text{in}}[\text{m}^3/\text{s}]$ is the inlet flow rate, $Q_{\text{out}}[\text{m}^3/\text{s}]$ is the outlet flow rate, $P_{\text{in}}[\text{kPa}]$ is the inlet pressure, $P_{\text{out}}[\text{kPa}]$ is the outlet pressure, $P_{\text{hp}}[\text{kPa}]$ is the pressure head developed by the pump, $\text{H}_\text{s}[\text{m}]$ is the static head of the pump, $H_\text{D}[\text{m}]$ is the dynamic head developed by the pump, $\text{K}_{\text{R pump}}$ is the pump friction loss coefficient, $V[\text{m/s}]$ is the water velocity, and $\text{g}[\text{m/s}^2]$ is the gravitational acceleration.
- The model of the flow booster pump can be described by:

$$P_{\text{in}} = P_{\text{out}}, \tag{10}$$

$$Q_{\text{out}} = \alpha_{\text{ratio}} Q_{\text{rated}}, \tag{11}$$

where $Q_{\text{rated}}[\text{m}^3/\text{s}]$ is the rated flow rate that can be supplied by the pump, and α_{ratio} is the relative increase in the pump speed.

Energy Recovery Device (ERD): The energy recovery device (ERD) aims to capture the hydraulic energy from the high pressure reject stream of the RO unit and to utilize this energy towards increasing the efficiency of the reverse osmosis plant. There are several types of ERDs, such as turbines, pressure exchangers (PXs), etc.

In the pressure exchanger, the high pressure concentrate flow (high-pressure inflow of the PX) is used via a piston to pressurize part of the main feed flow (low-pressure inflow of the PX) as demonstrated in Fig. 4. The model of the ERD-PX has four inputs, which are the flow rates of the low-pressure and high-pressure inlets $Q_{\text{LPi}}[\text{m}^3/\text{s}]$, $Q_{\text{HPi}}[\text{m}^3/\text{s}]$ and the pressures of the low-pressure and high-pressure inlets $P_{\text{LPi}}[\text{kPa}]$, $P_{\text{HPi}}[\text{kPa}]$. The outputs are the flow rates of low-pressure and high-pressure outlets $Q_{\text{LPo}}[\text{m}^3/\text{s}]$, $Q_{\text{HPo}}[\text{m}^3/\text{s}]$ and the pressures of low-pressure and high-pressure outlets $P_{\text{LPo}}[\text{kPa}]$, $P_{\text{HPo}}[\text{kPa}]$. It has the following main parameters, the ERD efficiency η_{ERD}, the ERD friction loss coefficient $\text{K}_{\text{R ERD}}$, and the lubrication flow to HP inlet flow ratio α_{Lub} given that a small portion of the HP inlet flow stream leaks through the piston edge to the LP inlet stream to lubricate the ERD's parts movement.

It can be mathematically described by (Senthil and Subbia (2016)):

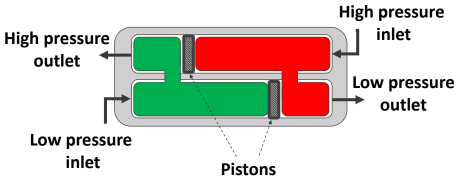

Fig. 4. Illustration of a pressure exchanger.

$$\begin{aligned} P_{\mathrm{LPo}} =& \frac{\eta_{\mathrm{ERD}}\left(Q_{\mathrm{HPi}}P_{\mathrm{HPi}} - Q_{\mathrm{HPo}}P_{\mathrm{HPo}}\right) + Q_{\mathrm{LPi}}P_{\mathrm{LPi}}}{Q_{\mathrm{LPo}}}, \\ &- \frac{K_{\mathrm{R\,ERD}}\left(\eta_{\mathrm{ERD}}Q_{\mathrm{HPo}}\rho_{\mathrm{f}}V_{\mathrm{HPi}}^{2} - Q_{\mathrm{LPo}}\rho_{\mathrm{b}}V_{\mathrm{LPi}}^{2}\right)}{Q_{\mathrm{LPo}}}, \end{aligned} \tag{12}$$

$$V = Q/A_{\mathrm{r}}, \tag{13}$$

$$Q_{\mathrm{Lub}} = \alpha_{\mathrm{Lub}}Q_{\mathrm{HPi}}, \tag{14}$$

$$Q_{\mathrm{LPo}} = Q_{\mathrm{HPi}} - Q_{\mathrm{Lub}}, \tag{15}$$

$$Q_{\mathrm{HPo}} = Q_{\mathrm{HPi}} + Q_{\mathrm{LPi}} - Q_{\mathrm{LPo}}, \tag{16}$$

where $\rho_{\mathrm{b}}[\,\mathrm{kg/m^3}]$ is the brine density, $V[\,\mathrm{m/s}]$ is the water velocity, $A[\,\mathrm{m^2}]$ is the ERD inlets cross sectional area, and $Q_{\mathrm{Lub}}[\,\mathrm{m^3/s}]$ is the lubrication flow.

Pre-treatment Stage: The modeling of the pre-treatment stage is approximated using the operational data of the local SWRO desalination plant given that the model of the pre-treatment process is complex and cannot be represented faithfully by a mathematical representation. We could not find a reliable and feasible mathematical model that can be implemented to serve our purpose. As demonstrated in Fig. 3, the pre-treatment stage is composed of the Dissolved Air Flotation (DAF) system and the disk filters. In addition, it is worth mentioning that the approximated model deduced from the operational data is concerned with changes in the flow rate and the pressure of the water, and it does not consider the dynamics of the chemical processes.

Dissolved Air Flotation (DAF) System: This is a water treatment process that purifies the water by removing the suspended matters. It is done by dissolving air in the water in the presence of applied pressure and then releasing the air at the atmospheric pressure in the flotation tank. The suspended matters adhere to the bubbles formed by the released air, and then float to the surface of the water where they can be removed. That is, the inlet water to the DAF system is divided into three water flows, which are:
1- Recirculated water through the air saturation tank,
2- Slug, which is discharged as waste carrying the removed suspended solids,
3- Main outlet stream carrying the clean water.

By examining the available data for different operational conditions in terms of the inlet concentration, total suspended solid (TSS), pressure, flow rate, and temperature, it was found that the DAF system does not affect the stream pressure such that the pressure of the inlet stream and the main outlet are equal. In addition, the main outlet stream of the filtered water was found consistently around 99.7% of the inlet stream. Hence, the DAF system's model is approximated by:

$$M_{\mathrm{out}} = 0.997\,M_{\mathrm{in}}, \tag{17}$$

where $M_{\mathrm{out}}[\mathrm{kg/s}]$ and $M_{\mathrm{in}}[\mathrm{kg/s}]$ are the flow rates of the clean outlet water and the inlet water of the DAF system, respectively.

Disk Filters: Disk filters are used to further purify the water before passing it to the subsequent stages to maintain the RO membrane lifetime. As interpreted from the operational data of the pre-treatment stage, the disk filter model is expressed as:

$$M_{\mathrm{out}} = M_{\mathrm{in}}, \tag{18}$$

$$P_{\mathrm{out}} = P_{\mathrm{in}} - \Delta P, \tag{19}$$

$$\Delta P = \alpha_{\mathrm{f1}}T^2 + \alpha_{\mathrm{f2}}T + \alpha_{\mathrm{f3}}, \tag{20}$$

where $T[^\circ\mathrm{C}]$ is the water temperature, and $\alpha_{\mathrm{f}i}$ for $i = 1, 2, 3$ are the fit coefficients.

Reverse Osmosis Unit: The model of the reverse osmosis unit is presented in (Joseph and Damodaran (2019)). As mentioned previously, the RO unit has three streams, one inlet, which is the feed stream and two outlets, which are the brine and the permeate streams. The inputs of the RO unit model are the concentration C_{f} [ppm], mass flow rate M_{f} [kg/s], temperature T_{f} [°C], and pressure P_{f} [kPa] of the feed stream. The outputs are the concentration C_{b} [ppm], C_{p} [ppm], mass flow rate M_{p} [kg/s], M_{p} [kg/s] and pressure P_{b} [kPa], P_{p} [kPa] of the brine and the permeate streams, respectively.

Brine Flow Rate:

- Without a reject valve:
  In this case, the brine solution stream is not restricted and hence, it can be determined based on the mass balance law. It can be expressed as:
  $$M_{\mathrm{b}} = M_{\mathrm{f}} - M_{\mathrm{p}}. \tag{21}$$
- Through a reject valve:
  The flow rate of the brine solution depends on the percentage opening of the reject valve and is found by:
  $$\begin{aligned} M_{\mathrm{b}} = M_{\mathrm{b\,max}} &- \left(\frac{M_{\mathrm{b\,max}} - M_{\mathrm{b\,min}}}{\mathrm{H_{max}} - \mathrm{H_{min}}}\right)\mathrm{H_{max}} \\ &+ \left(\frac{M_{\mathrm{b\,max}} - M_{\mathrm{b\,min}}}{\mathrm{H_{max}} - \mathrm{H_{min}}}\right)H, \end{aligned} \tag{22}$$
  where H is the valve opening, and $\mathrm{H_{min}}$ and $\mathrm{H_{max}}$ are the minimum and the maximum valve openings, respectively.

Brine Pressure:

- Without a reject valve:
  In the first RO pass, the brine solution is fed to the ERD to transfer the hydraulic power (pressure) from the pressurized brine solution to part of the feed water before the former being discharged at a lower pressure. The pressure of the brine in this case can be

approximated based on the expected pressure drop across the RO membrane as:

$$P_{\mathrm{b}} = P_{\mathrm{f}} - \mathrm{P}_{\mathrm{drop}}, \tag{23}$$

where $P_{\mathrm{b}}[\mathrm{kPa}]$ is the brine pressure, $P_{\mathrm{f}}[\mathrm{kPa}]$ is the RO feed pressure, and $\mathrm{P}_{\mathrm{drop}}[\mathrm{kPa}]$ is the pressure drop across the RO membrane.

- Through a reject valve:
  In the second RO pass, the brine solution is discharged at the atmospheric pressure through a reject valve. As demonstrated in Fig. 5, the brine downstream pressure $P_{\mathrm{bo}}[\mathrm{kPa}]$ is constant at 101 kPa (atmospheric pressure). However, the upstream pressure of the solution depends on the valve characteristics, the valve opening percentage H, and the brine outlet flow rate through the valve M_{b} as presented in Equation (24).

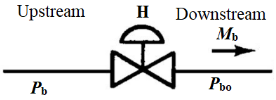

Fig. 5. Diagram of a water valve.

$$P_{\mathrm{b}} = \mathrm{R}^{2\left(1-\frac{H}{100}\right)} M_{\mathrm{b}}^2 + P_{\mathrm{bo}}, \tag{24}$$

where R is the valve rangability.

Salt Passage:

$$M_{\mathrm{s}} = \mathrm{K_s} A_{\mathrm{em}} \mathrm{T_s} \left(\beta \bar{C} - C_{\mathrm{p}}\right) \times 1000, \tag{25}$$

$$\bar{C} = \frac{M_{\mathrm{f}} C_{\mathrm{f}} + M_{\mathrm{b}} C_{\mathrm{b}}}{M_{\mathrm{f}} + M_{\mathrm{b}}}, \tag{26}$$

where $M_{\mathrm{s}}[\mathrm{kg/s}]$ is the salt passage rate, $\mathrm{K_s}[\mathrm{m^3/m^2 s}]$ is the salt permeability coefficient at the reference temperature $\mathrm{T_{ref}}[^\circ\mathrm{C}]$, $A_{\mathrm{em}}[\mathrm{m^2}]$ is the total membrane area, β is the concentration polarization factor, T_{s} is the temperature correction factor for salt permeability, $\bar{C}[\mathrm{ppm}]$ is the net concentration, and $C_{\mathrm{p}}[\mathrm{ppm}]$ is the permeate concentration.

Permeate Flow Rate:

$$M_{\mathrm{p}} = \mathrm{K_w} A_{\mathrm{em}} \mathrm{T_m} \left(\Delta P - \beta \Delta\pi\right) \rho_{\mathrm{w}}, \tag{27}$$

where $M_{\mathrm{p}}[\mathrm{kg/s}]$ is the permeate mass flow (or water passage) rate, $\mathrm{K_w}\,[\mathrm{m^3/m^2 s\,kPa}]$ is the water permeability coefficient at the reference temperature $\mathrm{T_{ref}}\,[^\circ\mathrm{C}]$, $A_{\mathrm{em}}\,[\mathrm{m^2}]$ is the total membrane area, β is the concentration polarization factor, T_{m} is the temperature correction factor for water permeability, $\Delta P\,[\mathrm{kPa}]$ is the membrane differential pressure, $\Delta\pi\,[\mathrm{kPa}]$ is the net osmotic pressure, and $\rho_{\mathrm{w}}[\mathrm{kg/m^3}]$ is the permeate density.

Permeability's temperature dependency correction factors: The parameters $\mathrm{T_s}$ and $\mathrm{T_m}$ are used in the salt and water passage equations (25) and (27) given that water and salt permeabilities are temperature dependent. The salt $\mathrm{K_s}$ and water $\mathrm{K_w}$ permeability coefficients are found at the reference temperature $\mathrm{T_{ref}}$ and the temperature correction factors are found by Arrhenius equations as:

$$\begin{aligned} \mathrm{T_m} &= \exp\left(\mathrm{a_T} \frac{T_{\mathrm{f}} - \mathrm{T_{ref}}}{T_{\mathrm{f}} + 273.15}\right), \\ \mathrm{T_s} &= \exp\left(\mathrm{b_T} \frac{T_{\mathrm{f}} - \mathrm{T_{ref}}}{T_{\mathrm{f}} + 273.15}\right), \end{aligned} \tag{28}$$

where $T_{\mathrm{f}}[^\circ\mathrm{C}]$ is the temperature of the feed water, $\mathrm{a_T}$ is the membrane water passage temperature constant, and $\mathrm{b_T}$ is the membrane salt passage temperature constant.

Effective Membrane Area: The effective membrane area is the total membrane area the water stream passes through. It is expressed as:

$$\mathrm{A_{em}} = \mathrm{n_v n_e A_m}, \tag{29}$$

where $\mathrm{n_v}$ is the number of pressure vessels, $\mathrm{n_e}$ is the number of membrane elements in a single pressure vessel, and $\mathrm{A_m}\,[\mathrm{m^2}]$ is the area of a single membrane element.

Permeate Concentration: The concentration of the permeate $C_{\mathrm{p}}[\mathrm{ppm}]$ is given by:

$$C_{\mathrm{p}} = \frac{\mathrm{K_s} C_{\mathrm{b}}}{\frac{J}{\exp(J/k)} + \mathrm{K_s}}, \tag{30}$$

$$J = \frac{\Delta P - \Delta\pi}{\eta\left(\mathrm{R_m} + \mathrm{R_c}\right)} = \frac{Q_{\mathrm{p}}}{A_{\mathrm{em}}}, \tag{31}$$

where $J\,[\mathrm{m/s}]$ is the permeate flux, $k\,[\mathrm{m/s}]$ is the mass transfer coefficient, $\eta\,[\mathrm{kPa.s}]$ is the seawater dynamic viscosity, $\mathrm{R_c}\,[\mathrm{m^{-1}}]$ is the cake layer resistance, and $\mathrm{R_m}\,[\mathrm{m^{-1}}]$ is the intrinsic membrane resistance.

Brine Concentration: The brine concentration $C_{\mathrm{b}}[\mathrm{ppm}]$ is given by:

$$C_{\mathrm{b}} = \frac{C_{\mathrm{f}} M_{\mathrm{f}} - C_{\mathrm{p}} M_{\mathrm{p}}}{M_{\mathrm{b}}}. \tag{32}$$

Membrane Differential Pressure: The membrane differential pressure $\Delta P[\mathrm{kPa}]$ is calculated by:

$$\Delta P = \frac{P_{\mathrm{f}} + P_{\mathrm{b}}}{2} - P_{\mathrm{p}}, \tag{33}$$

where $P_{\mathrm{f}}\,[\mathrm{kPa}]$ is the feed water pressure, $P_{\mathrm{b}}\,[\mathrm{kPa}]$ is the brine pressure, and $P_{\mathrm{p}}\,[\mathrm{kPa}]$ is the permeate pressure.

Net Osmotic Pressure: The osmotic pressure is a colligative property driven bythe chemical potentialdifferences of the solvent. It is the minimum pressure needed to cancel out osmosis. The net osmotic pressure is calculated by:

$$\Delta\pi = \frac{\pi_{\mathrm{f}} - \pi_{\mathrm{b}}}{2} - \pi_{\mathrm{p}}, \tag{34}$$

and for each stream, the osmotic pressure $\pi\,[\mathrm{kPa}]$ can be calculated based on the stream concentration $C\,[\mathrm{ppm}]$ as,

$$\pi = 75.84 \times 10^{-3} C, \tag{35}$$

where $\pi_{\mathrm{f}}\,[\mathrm{kPa}]$ is the feed water osmotic pressure, $\pi_{\mathrm{b}}\,[\mathrm{kPa}]$ is the brine osmotic pressure, and $\pi_{\mathrm{p}}\,[\mathrm{kPa}]$ is the permeate osmotic pressure.

Tank: The dynamics of the tank can be expressed in terms of the water level $H_{\mathrm{t}}\,[\mathrm{m}]$ and the concentration of the tank outlet water stream $C_{\mathrm{t,out}}\,[\mathrm{ppm}]$, and they are formulated as (Jiang et al. (2015b)):

$$\frac{\mathrm{d}H_{\mathrm{t}}}{\mathrm{d}t} = \frac{(Q_{\mathrm{in}} - Q_{\mathrm{out}})}{A_{\mathrm{t}}}, \tag{36}$$

$$\frac{\mathrm{d}C_{\mathrm{t,\,out}}}{\mathrm{d}t} = \frac{Q_{\mathrm{in}}\left(C_{\mathrm{in}} - C_{\mathrm{t,\,out}}\right)}{A_{\mathrm{t}} H_{\mathrm{t}}}, \tag{37}$$

where $Q_{\mathrm{in}}[\,\mathrm{m}^3/\mathrm{s}]$ is the tank inlet flow rate, $Q_{\mathrm{out}}[\,\mathrm{m}^3/\mathrm{s}]$ is the tank outlet flow rate, C_{in} [ppm] is the tank inlet water concentration, and A_{t} [m^2] is the cross-sectional area of the tank.

Table 4. Parameters of the SWRO desalination plant simulator.

Parameter	Value
α_{m}	0.01
α_{f1}	-0.01
α_{f2}	0.77
α_{f3}	-8.25
R	2.67
$\mathrm{P_{drop}}$	110 kPa
$\mathrm{H_{min}}$	10%
$\mathrm{H_{max}}$	100%
$\mathrm{H_s}$	0.10 m
$\mathrm{K_{R\,pump}}$	15
$\mathrm{K_{R\,ERD}}$	0.001
η_{ERD}	96.3%
α_{Lub}	0.01
RO 1 - $\mathrm{K_w}$	$2.19\times10^{-8}\mathrm{m^3/m^2skPa}$
RO 2 - $\mathrm{K_w}$	$1.03\times10^{-7}\mathrm{m^3/m^2skPa}$
$\mathrm{K_s}$	$1.63\times10^{-4}\mathrm{m^3/m^2s}$
$\mathrm{a_T}$	9.00
$\mathrm{b_T}$	8.08
$\mathrm{T_{ref}}$	30 °C
$\mathrm{R_m}$	$9.00\times10^{13}\ \mathrm{m^{-1}}$
$\mathrm{R_c}$	$2.26\times10^{16}\ \mathrm{m^{-1}}$
$\mathrm{A_r}$	0.8 m^2
$\mathrm{A_t}$	150 m^2

Controllers: The plant is controlled using Proportional Integral Derivative (PID) controllers and digital controllers. The PID controllers, using the feedback control theory as shown in Fig. 6, are used to control the pressure of the water to bring it up to the desired set-point by modulating the speed of the pump, as well as to control the flow of water from the pre-treatment stage to the reverse osmosis process, and the amount of distributed fresh water based on the demand in the same manner. The PID controller has three main parameters to tune, which are the proportional gain, the integral gain, and the derivative gain. The output of the controller is bounded between 0 and 1. The digital controllers are used for the tanks water level control by turning ON or OFF the actuator, which can be the pump or the valve. Algorithms 1 - 4 present the digital controllers' logic of the tanks level and the backup pumps. In reference to Fig. 3 and Table 1, the list of the plant's controllers used is presented in Table 5.

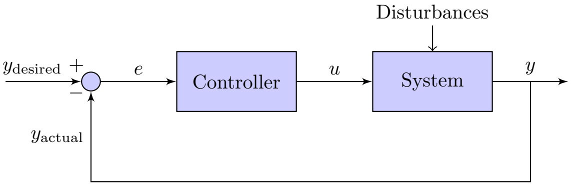

Fig. 6. A typical Feedback controller.

Table 5. List of the controllers of the reverse osmosis plant simulator.

Stage	Controlled equipment	Controller
Pre-treatment	Intake pumps	D
	Intake tank valves	D
	DAF tank valves	D
	Disk filter pump - HP pump line	PID
	Disk filter pump - ERD line	PID
	RO supply pumps - HP pump line	PID
	RO supply pumps - ERD line	PID
Reverse osmosis	RO 1 high pressure pumps	PID
	ERD pressure booster pumps	PID
	RO 2 pressure booster pumps	PID
Post-treatment	Distribution pumps	PID

Algorithm 1 Control of water level of the intake tank.

```
Input: $L$ - Tank level, $L_{\mathrm{max}}$ - Maximum tank level, $L_{\mathrm{min}}$ - Minimum
  tank level, $\bar{P}_{\mathrm{main}}$ - Current status of main pump
Output: $P_{\mathrm{main}}$ - Main pump status, $P_{\mathrm{backup}}$ - Main pump status
  if $L \leq L_{\mathrm{min}}$ then
    $P_{\mathrm{main}}$ is ON
  else if $L \geq L_{\mathrm{max}}$ then
    $P_{\mathrm{main}}$ is OFF
  else
    $P_{\mathrm{main}}$ status does not change
  end

  if $L < L_{\mathrm{min}}$ and $\bar{P}_{\mathrm{main}}$ is OFF then
    $P_{\mathrm{backup}}$ is ON
  else
    $P_{\mathrm{backup}}$ is OFF
  end
```

Algorithm 2 Control of water level of the DAF tank.

```
Input: $L$ - Tank level, $L_{\mathrm{max}}$ - Maximum tank level, $L_{\mathrm{min}}$ - Minimum
  tank level
Output: $P_{\mathrm{intake}}$ - Status of supply pump from intake tank, $V_{\mathrm{intake}}$
  - Intake tank valve status
  if $L \geq L_{\mathrm{max}}$ then
    $P_{\mathrm{intake}}$ is OFF, $V_{\mathrm{intake}}$ is CLOSED
  else
    $P_{\mathrm{intake}}$ is ON, $V_{\mathrm{intake}}$ is OPENED
  end
```

Algorithm 3 Control of water level of the RO tank.

```
Input: $L$ - Tank level, $L_{\mathrm{max}}$ - Maximum tank level, $L_{\mathrm{min}}$ - Minimum
  tank level
Output: $P_{\mathrm{DAF}}$ - Status of supply pump from DAF tank, $V_{\mathrm{DAF}}$ -
  DAF tank valve status
  if $L \geq L_{\mathrm{max}}$ then
    $P_{\mathrm{DAF}}$ is OFF, $V_{\mathrm{DAF}}$ is CLOSED
  else
    $P_{\mathrm{DAF}}$ is ON, $V_{\mathrm{DAF}}$ is OPENED
  end
```

Algorithm 4 Control of backup pumps.

```
Input: $Y_{\mathrm{d}}$ - Set-point of controlled variable, $Y$ - Current value of
  controlled variable, $\bar{P}_{\mathrm{main}}$ - Current status of main pump
Output: $P_{\mathrm{backup}}$ - Status of backup pump
  if $Y < Y_{\mathrm{d}}$ and $\bar{P}_{\mathrm{main}}$ is OFF then
    $P_{\mathrm{backup}}$ is ON
  else
    $P_{\mathrm{backup}}$ is OFF
  end
```

3. SIMULATION RESULTS

As demonstrated in Fig. 3, the MATLAB/Simulink-based simulator consists of the three main stages, which are the pre-treatment stage, the reverse osmosis process, and the post-treatment stage, respectively. The pre-treatment stage contains the intake tank with two supply pumps, the main and a backup pump and both control the intake tank water level. In addition, the tank outlet is equipped with a motorized valve that turns off if the DAF tank in the subsequent step is full.

The DAF unit consists of the DAF system connected to a storage tank, and the latter has two outlets for the HPP line and the ERD line, each controlled by a motorized valve that operates according to the RO tanks status (full or not). Then comes the disk filter in which the outlet water of the DAF unit is pressurized by a pressure booster pump then fed to the disk filter. The model of the disk filter has three inputs, which are the inlet stream's temperature, flow rate, and pressure, while the outputs are the outlet stream's pressure and flow rate, respectively. The outputs of the pre-treatment stage are fed to the two-pass RO process, and finally the water distribution step in the post-treatment stage is based on the time-varying water demand.

The plots shown in Figures 7 to 10 demonstrate a sample of the simulation results for the two RO units in terms of the concentration and flow rate of the permeate water at a feed temperature of 30 °C and concentration of 45,901.2 ppm. In addition, Table 6 presents a summary of the comparison between the actual and the simulated steady-state operation of the SWRO desalination plant.

The observed differences can be attributed to approximations in the mathematical models used to develop the simulator. However, given that it is less than 4% for the majority of the system variables, it can be considered acceptable. In addition, the approximated model used for the disk filter resulted in an error of around 5% in the pressure of the ERD-line disk filter output. The errors on the high pressure inlet and the low pressure outlet flow rates of the ERD are found to be about 7% and 6%, respectively because the stream split to the HP pump and ERD lines was approximated in which the average values were used. Although the error on the pressure measurement of the ERD low pressure outlet - about 17% - is quiet high, this variable is redundant with respect to the other pressure readings of the ERD. Hence, it can be disregarded to avoid any performance degradation due to this simulator error. It was found that the errors on the readings of RO 2 are higher than those of RO 1 given that the mathematical model results are more accurate when operating at a sizable scale operation. Overall, the performance of the simulator with respect to the majority of the variables of interest was found acceptable.

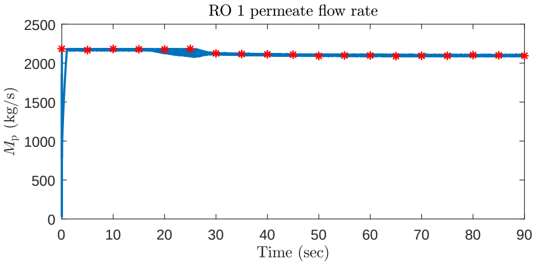

Fig. 7. RO pass 1 permeate flow rate.

Table 6. Comparison result between the actual and the simulated SWRO desalination plant.

RO unit	Variable	Actual	Simulation	Error
DAF	M_{in}	5141	5140	0.02%
	M_{out}	5125	5125	0.00%
Disk Filter 1	M_{in}	2279	2288	0.39%
	M_{out}	2279	2288	0.39%
	P_{in}	870	870	0.00%
	P_{out}	780	739	5.26%
Disk Filter 2	M_{in}	2847	2853	0.21 %
	M_{out}	2847	2853	0.21%
	P_{in}	520	520	0.00%
	P_{out}	470	453	3.62%
ERD	M_{HPi}	2874	3070	6.80%
	M_{HPo}	2810	2770	1.43%
	M_{LPi}	2753	2740	2.64%
	M_{LPo}	2875	3040	5.76%
	P_{HPi}	7100	7102	0.03%
	P_{HPo}	6970	6840	1.87%
	P_{LPo}	120	100	16.67%
	P_{LPi}	290	304	4.83%
RO 1	M_{f}	5010	5171	3.21%
	C_{f}	45817	45900	0.18%
	P_{f}	7210	7210	0.00%
	M_{p}	2178	2150	1.29%
	C_{p}	252	242	3.97%
	P_{p}	50	50	0.00%
	M_{b}	3033	3065	1.06 %
	P_{b}	7100	7100	0.00 %
RO 2	M_{p}	1474	1570	6.51%
	C_{p}	3.80	3.46	8.95%
	P_{p}	130	130	0.00 %
	M_{b}	550	528	5.52%
	P_{b}	1100	1000	0.91 %

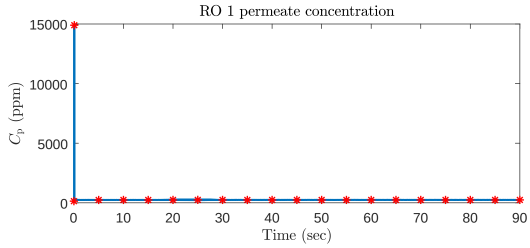

Fig. 8. RO pass 1 permeate concentration.

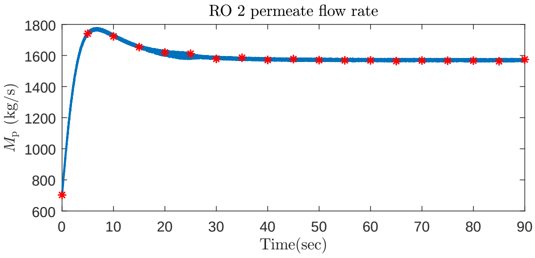

Fig. 9. RO pass 2 permeate flow rate.

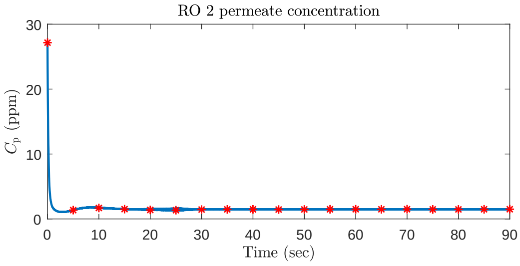

Fig. 10. RO pass 2 permeate concentration.

4. CONCLUSION

In this paper, we presented a full-scale seawater reverse osmosis desalination plant simulator that has been developed using MATLAB/Simulink, which is a well-known and user-friendly software. It has been validated using operational data from a local plant and found capable of simulating the actual plant operation with an average error of less than 5% for the majority of the system variables. The simulator was able to represent the full-scale operation of the RO plant and hence, it provides a feasible, low-cost, and flexible solution for analyzing the plant performance, and promoting research in the area of health monitoring and cybersecurity of industrial control systems.

For future work, we plan to introduce hardware in-the-loop. That is, some of the control system will be implemented using actual hardware to improve the fidelity of the simulator.

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