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New dynamic library of reverse osmosis plants with fault simulation

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ABSTRACT

This paper presents an update of a dynamic library of reverse osmosis plants (ROSIM). This library has been developed in order to be used for optimization, simulation, controller testing or fault detection strategies and a simple fault tolerant control is tested. ROSIM is based on a set of components representing the different units of a typical reverse osmosis plant (sand filters, cartridge filters, exchanger energy recoveries, pumps, membranes, storage tanks, control systems, valves, etc.). Different types of fouling (calcium carbonate, iron hydroxide, biofouling) have been added and the mathematical model of the reverse osmosis membranes, proposed in the original library, has been improved.

Keywords: Reverse osmosis; Desalination plant; Simulation library; Dynamic simulation; Fault simulation; Fouling modelling

1. Introduction

ROSA© [1] and TorayDS© [2] are perhaps the most common software packages for the design of reverse osmosis (RO) plants. They have been developed by two important membrane manufactures (Dow Chemical and Toray, respectively) and are very powerful tools for static simulation of RO membranes. First, the user defines the characteristic of the feed water (solutes concentration, pH, temperature, etc.) and the required characteristic of the permeate (flow, TDS, boron concentration, etc.). Next, the software helps the user to choose the best membrane and configuration for the plant: number of pressure vessels, number of membranes per pressure vessel, possibility of a second pass, feed pressure, etc.

This software responds to the typical methodology of operation for RO plants. These plants, especially the high production ones (50,000–200,000 m^3/d of permeate), usually have a constant operation point [3]. However, this operation method looks incoherent if the fact that water consumption varies during the course of the day and year is taken into account. Fig. 1 shows a typical water demand curve over two days. Typical RO plants solve the daily variation of water demand by using big freshwater tanks at the end of the production line, and the annual variation by switching on/off membrane banks. It is easily understood that, a priori, this operation methodology is not optimal. On the other hand, using a variable operation point, that is producing more potable water when more is consumed; it will be possible to decrease the size of the supply tanks, reducing the evaporation and minimizing the consumption of chemical products and the cost of equipment [4].

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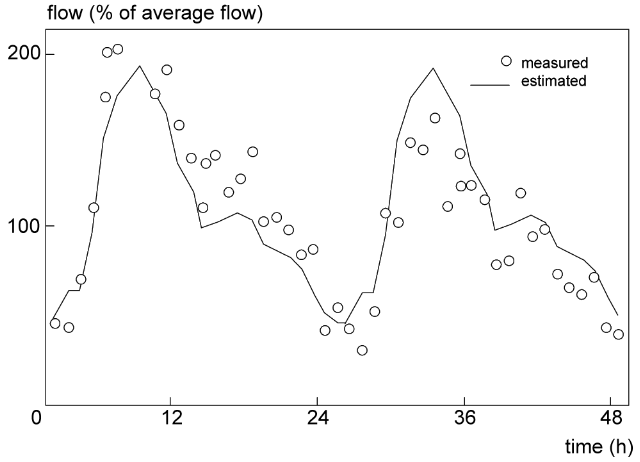

Fig. 1. Typical water demand curve.

From a viewpoint of energy consumption, a variable operation point also looks more adequate. It is very common that the availability and cost of electric energy varies along a day. This indicates that producing more permeate water when the energy cost is cheaper will decrease the total water price. In order to find the best operation point curve, both effects must be taken into account: the variation of the water demand and the energy cost.

Unfortunately, using static simulation tools, such as ROSA© or TorayDS©, it is not possible to design an RO plant with a variable operation point and better performance. In order to do this, this paper presents the update of the dynamic library of the RO plant ROSIM. This library was presented in [5] and several improvements have been added and more effects taken into account. The objective of ROSIM is not to help the user to choose the best membrane for a special plant (for this, ROSA© or TorayDS© are the best option), but to help the user to design advanced control strategies for a real plant. As seen in [6,7], the lack of dynamic tools limits the use of advanced control in RO plants. Some interesting applications of advanced control in desalination plants can be seen in [8–11].

Besides, the update ROSIM has been developed incorporating anomalies during the operation (such as calcium carbonate precipitation, iron hydroxide precipitation or bio-fouling), so it can be used to test fault detection strategies [12] and fault-tolerant control [13,14].

This paper is organized as follows: section 2 presents the library ROSIM, its objectives and components. Next, section 3 shows a simulation of normal operation obtained with the library. Finally, an example of fault detection of scaling is shown in section 4.

2. ROSIM: library for dynamic simulation of RO plants

ROSIM has been developed in the simulation environment EcosimPro© [15]. EcosimPro© is a powerful modelling and simulation tool that follows an advanced methodology for modelling and dynamic simulation. It provides an object oriented and non causal approach that allows new simulations to be created that interconnect reusable component libraries. EcosimPro© is based on very powerful symbolic and numerical methods capable of processing complex systems represented by DAE equations and discrete events. Moreover, it has a graphic friendly and easy to use interface. EcosimPro© shares the same structure and philosophy as other last generation simulation tools, such as Modelica©. Besides, a free version is available for use in universities and for non-commercial purposes [15].

ROSIM is based on a set of components representing the different units of an RO plant such as sand filters, cartridge filters, different types of pumps, RO membranes, storage tanks, exchanger energy recoveries, valves, control systems (such as PIDs or PLCs), etc.

Every component has been modelled using first principles and correlations from literature: Mass balances, energy balances, and physico-chemical equations are in the core of the models [16–20]. Complex elements, such as sand filters or RO membranes, have been discretized by using the finite volume method.

The models used can be parameterized to fit them to the particular conditions of a given plant. Parameter estimation can be carried out if data from a real plant are available. A detailed mathematical model of the process units describes its dynamic behaviour under a wide range of conditions.

All water characteristics, such as pH, TDS, temperature, as well as pressure, flux and flow, are calculated by ROSIM. Moreover, other interesting variables for optimization, as power consumption or membrane aging, are also simulated.

Fig. 2 shows a simplified RO plant in ROSIM. This system consists of two supply pumps, two storage tanks, several chemical additions for pre-treatment, two cartridge filters, one high pressure pump with control of permeate flow, two parallel RO membranes and finally a remineralization of permeate before being consumed.

3. Simulation of normal operation

ROSIM is used to simulate a typical RO plant with the following specification: the required permeate flow is 220 m^3/d, with a TDS of less than 300 ppm and the available water source is seawater with a concentration of TDS = 37,000 ppm, a temperature = 20°C and a pH = 8.2. The plant design is made for a recovery of 45%.

It is important to notice that the membrane permeability decreases in time because the solids are deposited on the membrane. In order to avoid this, periodical cleanings are needed. The initial permeability increases again after each cleaning, but not completely. This small but continuous loss of efficiency means that after a certain number

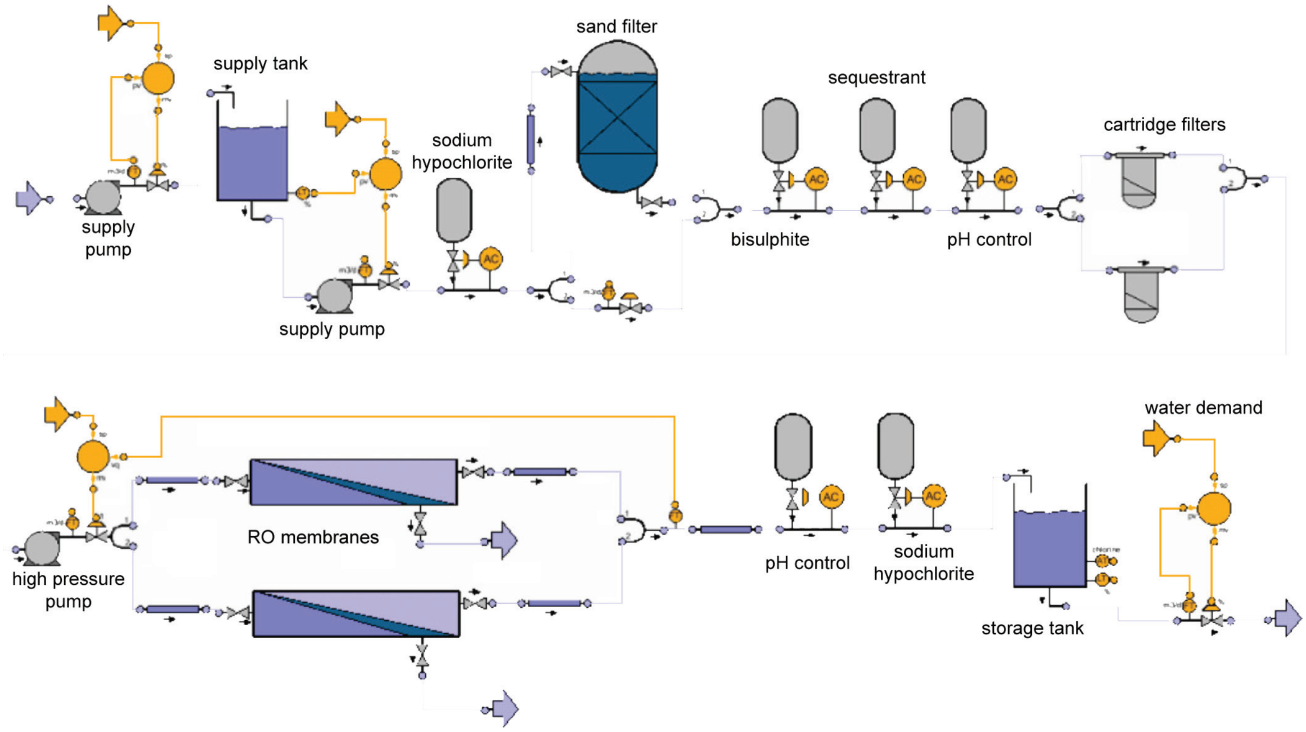

Fig. 2. Graphical simulation of a simplified RO plant in ROSIM.

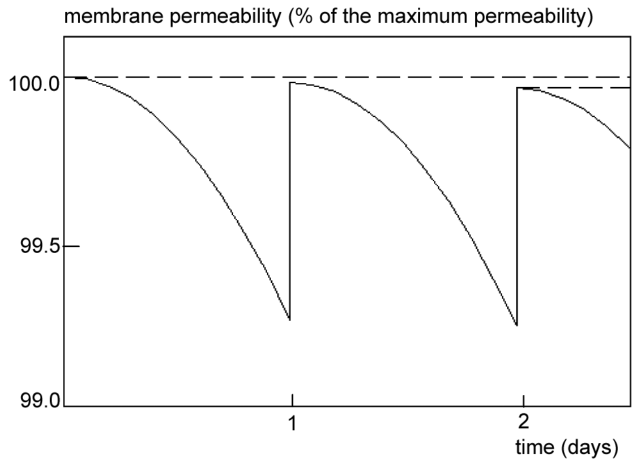

Fig. 3. Typical membrane permeability curve.

of cleanings, the membrane needs to be changed. Fig. 3 shows a typical membrane permeability curve with two cleanings.

The main cause of membrane permeability decrease is the calcium carbonate precipitation. The best way to avoid this is a good pH control of the feed flow. The Langelier Saturation Index (LSI) is the most common way to calculate the required pH to avoid the calcium carbonate precipitation. For values LSI > 0 calcium carbonate tends to precipitate, whereas for values LSI < 0 water tends to dissolve calcium carbonate. The optimal pH for operation is that pH which makes the LSI approach 0. In the case of very salty water (TDS > 10,000), use of the Stiff & Davids Stability Index (SDSI) gives a better result, but the methodology is the same.

LSI and SDSI are the most popular indexes used in an RO plant design. However, the pH calculated with these indexes is too low. A deeper and interesting study of carbonate precipitation can be seen in [21] and [22]. With the use of the new index proposed in [22], the consumption of chemical components in the RO plant can be optimized.

Fig. 4 shows the variation of feed pressure. At the initial point, with no decrease in membrane permeability, the pressure that has to be supplied by the high pressure pump at the conditions of the simulation case is 56.1 bar. However, as a result of the decrease in membrane permeability, this pressure has to increase in order to maintain a constant permeate flow rate. The feed pressure drops again after each cleaning, but it never recovers its initial value. Fig. 5 shows the pressure variation over a three year period. At the end of that time, the feed pressure has increased by close to 20%. The thickness of the line in Fig. 5 is caused by the zigzag shape of the pressure curve resulting from several cleanings.

During these three years, the permeate flow is kept constant. However, the inlet flow has been decreasing, following the increase of feed pressure and because of the high pressure pump curve. The variation of the inlet flow is shown in Fig. 6. Finally, Fig. 7 shows the evolution of the permeate quality. At initial conditions, the TDS of

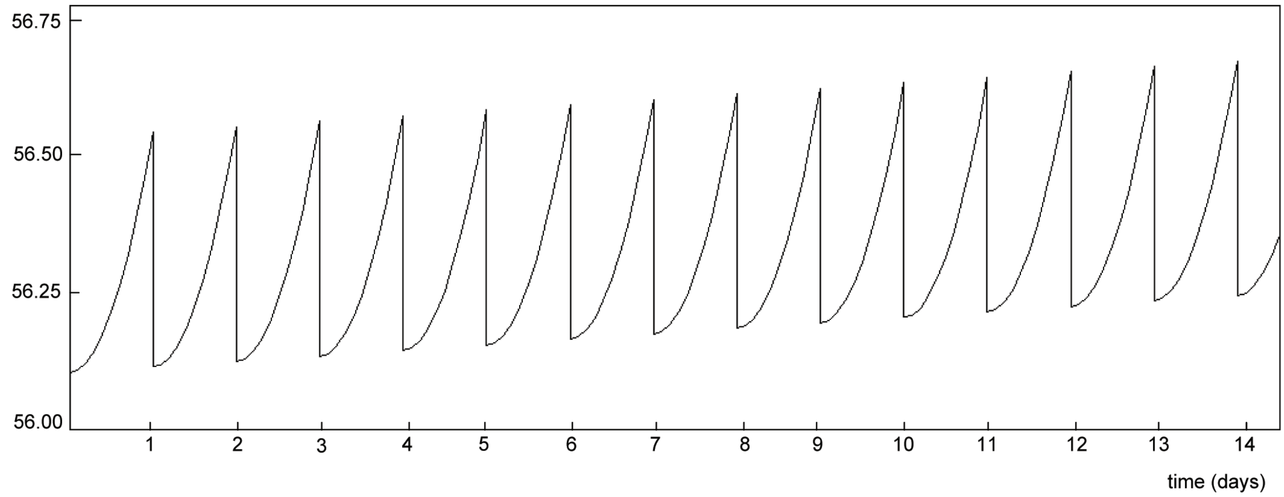

Fig. 4. Feed pressure variation over 14 days.

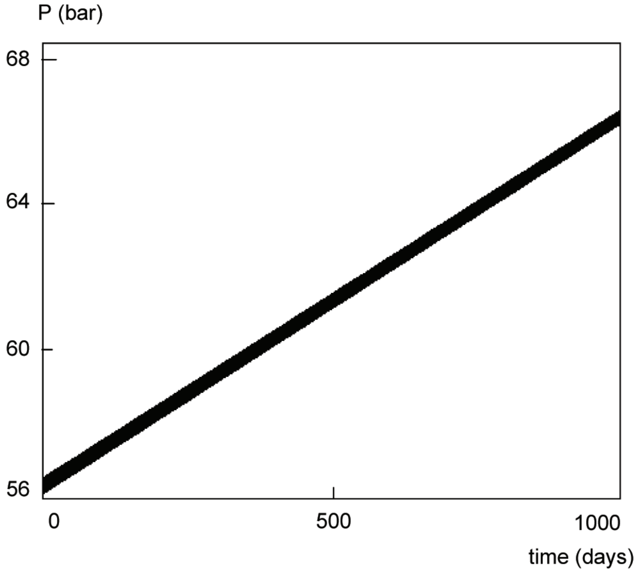

Fig. 5. Feed pressure variation over 3 years.

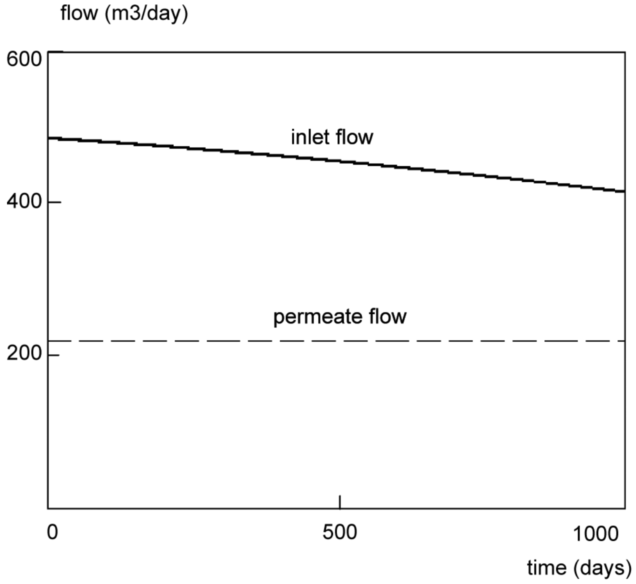

Fig. 6. Inlet flow and permeate flow over 3 years.

permeate flow takes the value of 164 ppm, lower enough to fulfill the permeate request of 300 ppm. However, this salt concentration increases slowly over time and, after 1000 d, gets a value close to the concentration limit.

This results from two effects. Firstly, the membrane is aging. Secondly, as less feed flow is treated the RO plant must yield a higher recovery, so the permeate is more concentrated and more solids pass through the membrane.

4. Fault detection simulation

A breakdown normally requires stopping the plant and changing the damaged unit. Thus, it is important to prevent breakdowns by detecting anomalies in the operation before a breakdowns happens. In process control, this is usually done by using the so-called fault detection techniques [12] and fault-tolerant control [13]. A fault means that a breakdown can happen if steps are not taken. In this last section, a calcium carbonate fouling in the membrane is simulated.

Fig. 8 shows how the pH curve has a maximum during the cleaning. This is caused by the dissolution of the scale during the cleaning. Fig. 9 shows the feed pressure variations, with and without calcium carbonate fouling. In the first case, pressure increases faster producing the undesirable decrease of the membrane life. The detection of calcium carbonate fouling from the pressure curve is complicated and the system has to be operating for a long

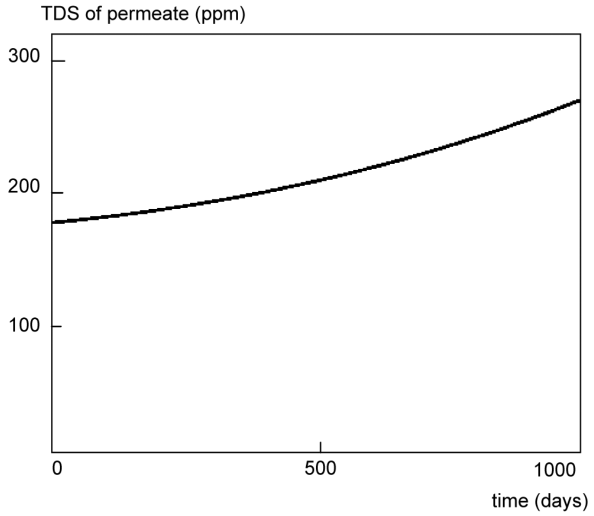

Fig. 7. TDS in permeate flow over 3 years.

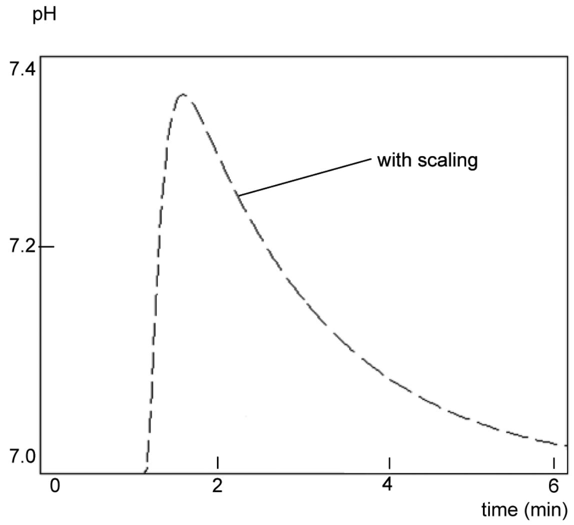

Fig. 8. pH curve during cleaning with scaling.

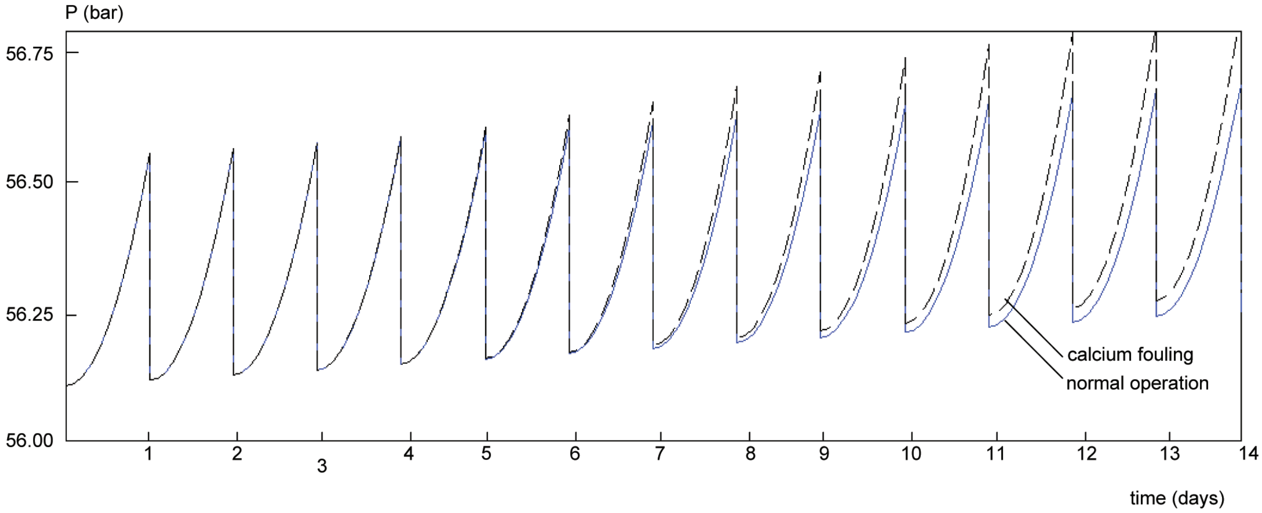

Fig. 9. Variation of feed pressure over 14 days for normal operation and for scaling.

time for this to happen. However, measurement of pH during cleanings , which is the approach proposed here, enables the prediction of calcium carbonate precipitation.

In order to increase the life of the membranes, it is important to perform an adequate pre-treatment and periodic cleanings of the membranes. There are several types of cleaning corresponding to different types of fouling [23–25]. A backflush is carried out each one-two hours in order to eliminate the big particles that reach the membranes. The backflush is done by pumping a stream of feed water through the pressure vessels, at high flow and low pressure, and takes one-two minutes. A complete cleaning of the membranes and sand filters is done daily, using permeated water and takes a few minutes. Finally, one chemical cleaning is done once or twice a year, in order to eliminate the scaling and deposition on the membranes. This cleaning is done following a special protocol, which depends on the kind of precipitated solids, and takes several hours. Typically, the chemical cleaning is done when the membrane blocking is detected by the increase in operation pressure. This increase of pressure is gradual and cannot be detected after several days. However, there are other possible strategies to detect the scaling. For example, as mentioned previously, by measuring the pH during the daily cleanings and then changing the operation strategy, in order to avoid the scaling. It is also possible to increase the number and duration of backflushes, work at a different pH, or increase the addition of anti-scaling, etc.

5. Conclusions

This paper has discussed the importance of developing dynamic simulators for designing and operating RO plants, in terms of optimizing efficiency and designing control software. For this, a library of components frequently found in this kind of plants has been presented, showing that it can be used for efficient simulation of RO plants. The library can be used for different purposes, such as "what happens if...?", comparison of control strategies, optimization, testing, capacity design, parameter estimation, data reconciliation, etc. As an example, the dynamic simulator of a simple RO plant has been developed. Finally, the simulation of a fault in the presence of calcium carbonate fouling has been demonstrated using this simulator.

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