Flow Reversal Reverse Osmosis Spaciotemporal Model

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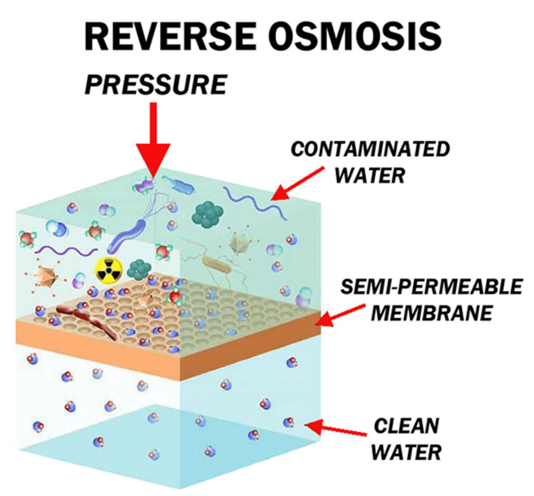
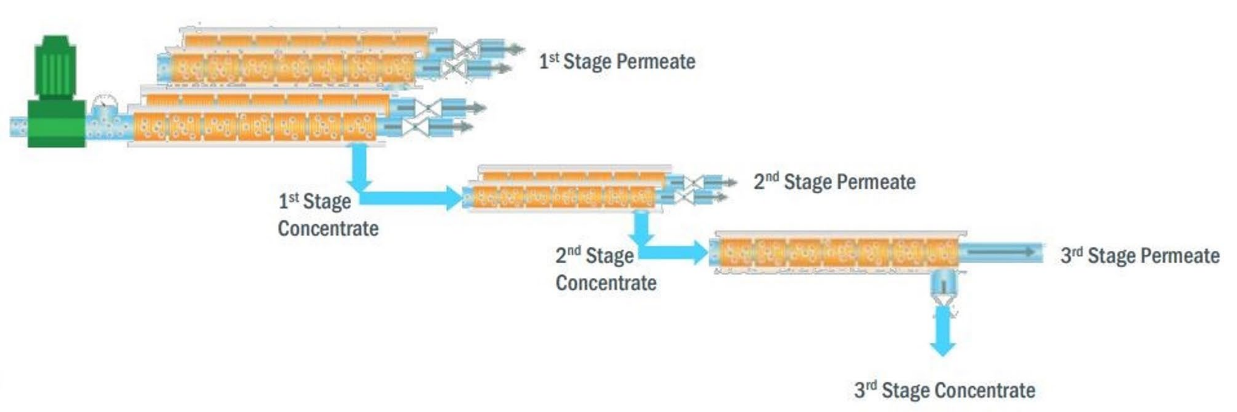
Motivation

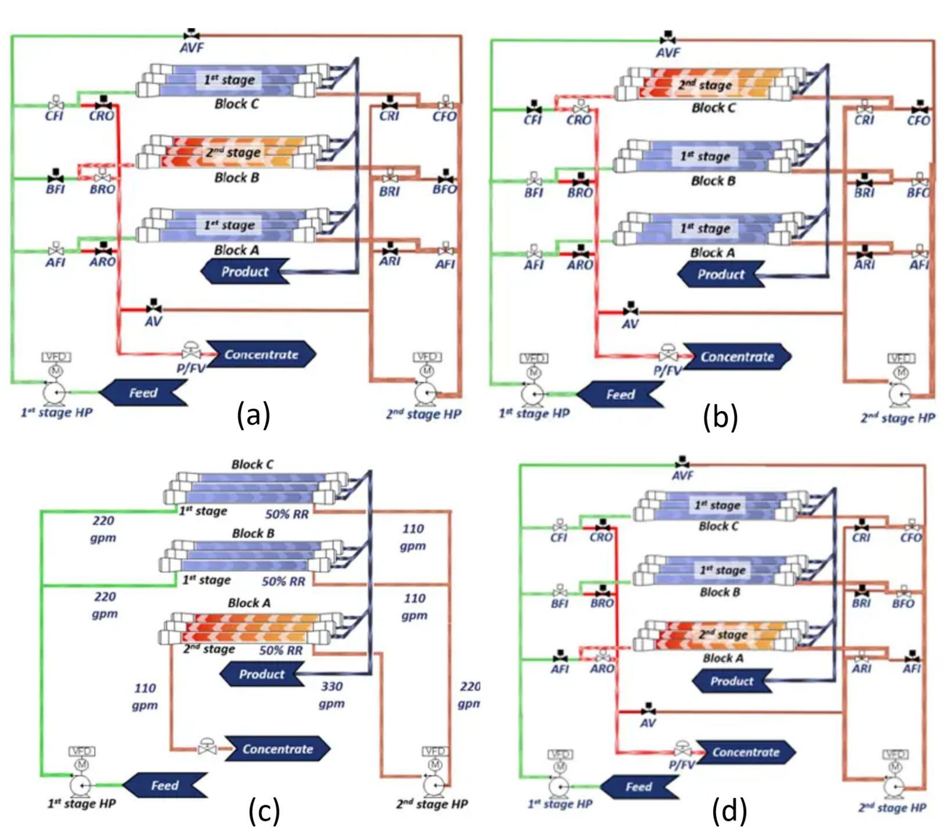
- Most of the Earth is covered in water, but regrettably only about a third of a percent of the Earth's water is usable. The Earth's population grows bigger as the years go by. Consequently, the demand for this limited resource will increase in intensity.
- Reverse Osmosis, or RO, is a textbook solution to the low supply of usable water. RO can take the previously unusable sea or salt water and brackish water and convert it to usable water. To fulfill this demand, the operation, construction, and mathematics behind the RO process must be analyzed and new ways of filtering water must be created.
- Reverse osmosis is a purification process that pumps water through a semi-permeable membrane. The membrane allows water to pass through but prevents most of the bacteria, salt, or any unwanted elements in the water.





Background

- The traditional RO system operates at steady state. The feed is pressurized by a pump and pushed into a system of 6 to 8 RO membranes. While conventional RO systems do offer a solution, water demand requires a higher recovery rate than the traditional model can deliver without using an absurd amount of energy.
- However, a problem arises with high recovery RO systems. That when the concentration of the salt rises above the saturation point, it begins to deposit on the membrane surface which is known as scaling. This severely limits the life of the membrane and degrades the economic cost of the operation.



Objective

The objective of this research is to investigate a potential mitigation for scaling through a process called flow-reversal reverse osmosis or FRRO. I will produce a mathematical model for FRRO using COMSOL with respect to position and time to analyze the concentration flowrate and pressure across multiple RO elements. This will lead us to better understand the production characteristics of this new reverse osmosis process.

Theory

- Flow Reversal Reverse Osmosis or FRRO takes a process controls approach to mitigate the scaling problem. It periodically and frequently changing the flow route in between each stage of pressure vessels.
- FRRO mitigates this by changing the flow route therefore making the last stage into the first. This exposes the high amounts of salt to an undersaturated solution and therefore reduces the salt deposits. The flow is also reversed when the vessel changes positions which helps remove the salt from the membrane as it changes the flow's angle of attack on the deposits.
- In order to create a model for this flow reversal strategy, many PDE's must be solved. These PDE's were derived by Dr. Mingheng Li and detail the concentration, flowrate, and pressure across multiple membranes in the pressure vessel all with respect to position and time.

$$0 = \frac{\partial q^*}{\partial x^*} + \frac{\gamma}{1 + \frac{L_p \pi_0}{k_m} c^*}(\theta - c^*)$$

B.C. (1)

$$q^*(x^*, t^*)\big|_{x^*=0} = q^*(0, t^*)$$

$$\frac{\partial c^*}{\partial t^*} = -q^* \frac{\partial c^*}{\partial x^*} - c^* \frac{\partial q^*}{\partial x^*} + \frac{1}{Pe_D}\frac{\partial^2 c^*}{\partial x^{*2}}$$

B.C. (2)

$$c^*(0^-, t^*) = \left(c^* - \frac{1}{Pe_D}\frac{\partial c^*}{\partial x^*}\right)\Big|_{x^*=0^+}$$

$$\frac{\partial c^*}{\partial x^*}\Big|_{x^*=1} = 0$$

$$0 = \frac{\partial \theta}{\partial x^*} + \frac{a_2}{\pi_0} {q^*}^{n_2}$$

B.C. (3)

$$\theta(x^*, t^*)\big|_{x^*=0} = \theta(0, t^*)$$

COMSOL

- The coefficient form PDE is needed as the equations need to be solved simultaneously. Due to the three PDE's, matrixes are used to plug in the coefficients for each term in the COMSOL equation. The flowrate dependent variable was also encased in an absolute value sign wherever it appeared. The flowrate is never negative but is needed for COMSOL to execute the solution.

$$e_a \frac{\partial^2 \mathbf{u}}{\partial t^2} + d_a \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (-c\nabla \mathbf{u} - \alpha \mathbf{u} + \gamma) + \beta \cdot \nabla \mathbf{u} + a\mathbf{u} = f$$

$$\mathbf{u} = [c, q, theta]^T$$

$$\nabla = \frac{\partial}{\partial x}$$

- The boundary conditions on the left-hand side or when position is equal to 0 is 1, 1, and 7 for concentration, flowrate, and pressure respectively.
- For the right-hand side, or when position is equal to 1, the boundary condition is $\frac{\partial c^*}{\partial x^*} = 0$ which must be inputted into COMSOL as $\frac{\partial c^*}{\partial x^*}$ +c as the Dirichlet boundary condition sets the boundary equal to its corresponding independent variable.
- To obtain the effect of the flow reversal, first a steady state must be established. To do this, the initial conditions are set as 1, 1, and 7 for concentration, flowrate, and pressure respectively. Then use the time dependent solver with a time in excess of 5 in order to achieve steady state. By exporting the data of the concentration at the final time and reversing the data points, flow reversal can be simulated by importing the modified data into the initial values for concentration and keeping everything else the same.

Conclusions

- This model allows us to predict the conditions for reversing the flow using mathematical methods with respect to position and time for concentration, pressure, and flowrate.
- This model can accurately simulate a full reverse osmosis stage and predict the outcome of FRRO in an industry setting.
- The only significant deviation by using the FRRO technique is the overshoot in concentration. Therefore, this approach of reversing the flow to reduce scaling will enable RO plants to run at higher recoveries without the downfall of the membrane and therefore be able to operate much more economically.

Acknowledgements

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References

- (2013) Reverse Osmosis Optimization Prepared for the U.S. Department of Energy Federal Energy Management Program By By Pacific Northwest National Laboratory K. L McMordie Stoughton, X. Duan, and E.M. Wendel
- (2018) Can Closed Circuit Desalination Boost Brackish Groundwater and Recycled Water Recovery by Squeezing Concentrate?
- *Ultra-high recovery rate technology fr-ro - rotec by WFI*. WFI. (2021, October 24). Retrieved January 6, 2022, from https://wfi-water.com/group/rotec/technology/
- Uchymiak, Bartman, A. R., Daltrophe, N., Weissman, M., Gilron, J., Christofides, P. D., Kaiser, W. J., & Cohen, Y. (2009). Brackish water reverse osmosis (BWRO) operation in feed flow reversal mode using an ex situ scale observation detector (EXSOD). Journal of Membrane Science, 341(1), 60–66. https://doi.org/10.1016/j.memsci.2009.05.039
- Li. (2021). A spatiotemporal model for dynamic RO simulations. Desalination, 516, 115229–.https://doi.org/10.1016/j.desal.2021.115229

Results and Discussion

- The results can be plotted with both position and time by using a surface graph. Figure 3 details the operation of a traditional RO process. The concentration, pressure and flowrate are still in their dimensionless forms.
- The two figures demonstrate the transition between start up and steady state operation.
- Figure 1 (a) details the concentration across the whole RO stage from a position of 0, which is the entrance of the pressure vessel, to 1 which is the exit from the stage. the dimensionless time was selected to be a range of 0 to 5 to be sure that steady state operation is including in the results which occurs between 1 and 2 units of dimensionless time.
- The concentration profile becomes fairly linear at steady state. The other dependent variables of pressure and flowrate do not vary much with time, but both decrease with position as shown in figure 1 (b) and (c). All of these results do correlate with expectations. As water is being removed, the concentration with increase and the flowrate will decrease. The pressure drop indicates that the osmotic pressure is increasing which occurs as the concentration increases.

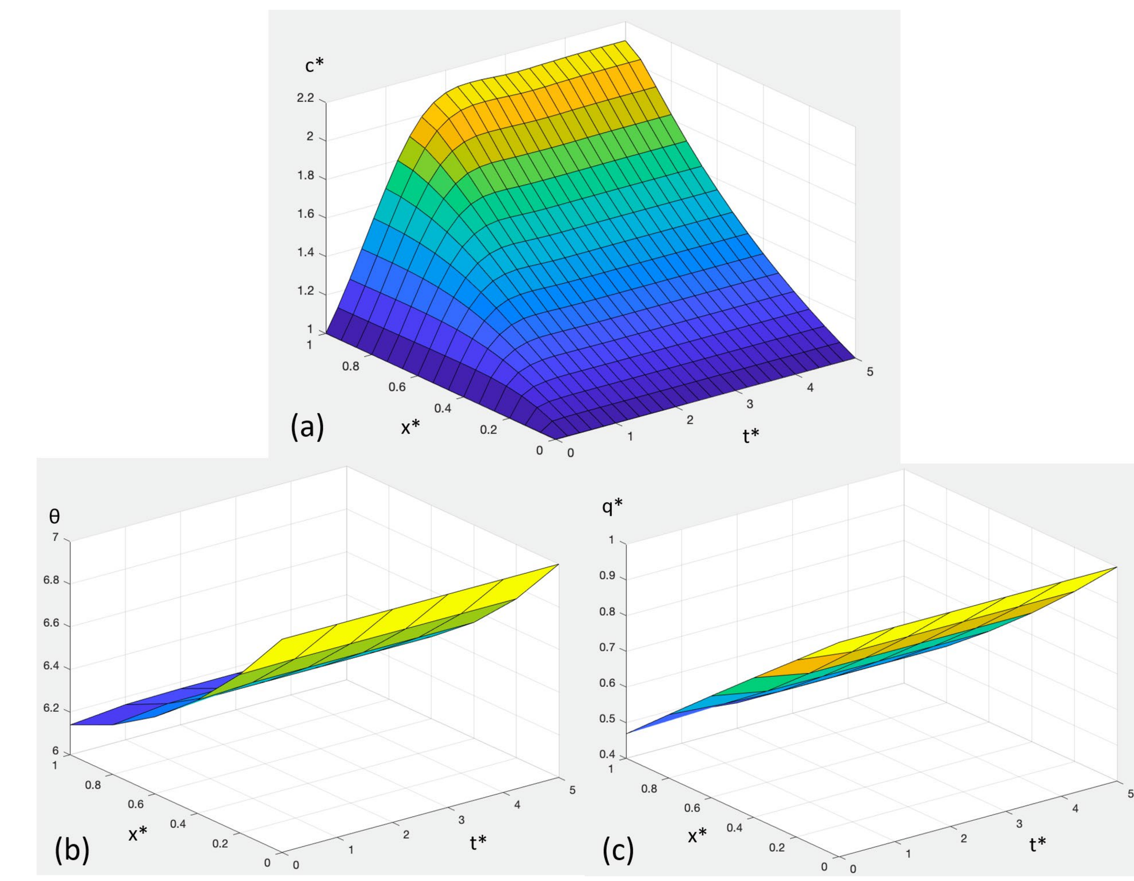

Figure 1: Traditional RO transient to steady state concentration (a), pressure (b), and flowrate (c)

- The concentration profile at time of 5 was flipped and used as the initial conditions for the reverse flow. The flow reversal flips the inlet and outlet conditions at steady state and its results are shown in figure 2. The graphs are in the same form as figure 1.
- Figure 2 (a) demonstrates the flow reversal effects on concentration. The result is an overshoot of concentration from a steady state of a little higher than 2 to around 2.6. The overshoot lasts until about 1 dimensionless time and then returns to the steady state conditions which was the same as the traditional RO steady state profile. Figure 2 (b) and (c) detail the pressure and flowrate respectively and the impact of the flow reversal on them. These two dependent variables do not vary much as the flow reversal occurs as they reach steady state almost immediately.
- The resulting overshoot from the flow reversal can be explained by the normal concentration profile being developed on top of the existing high concentration at the previous exit now inlet. The previous exit's low flowrate explains the slight deviation between the normal and flow reversal's flowrate and pressure characteristics.

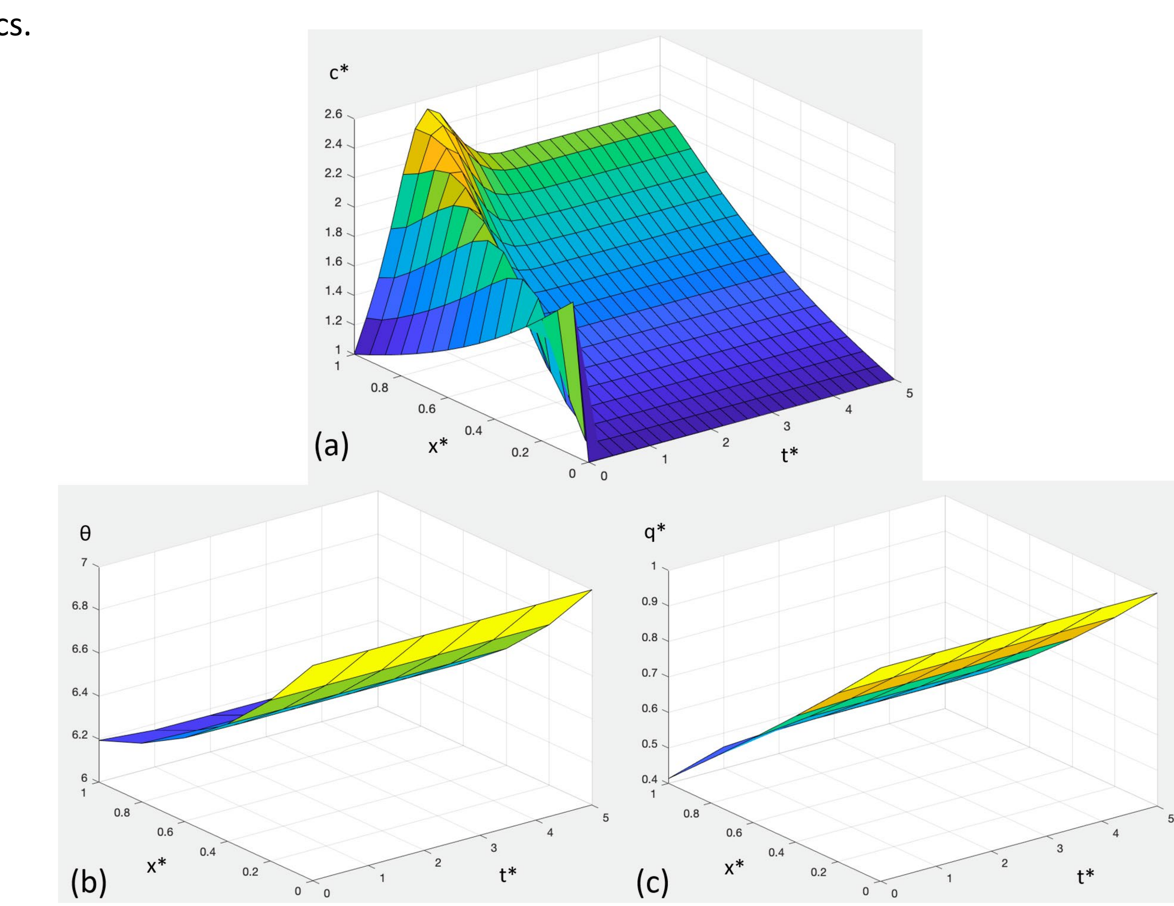

Figure 2: Flow Reversal RO transient to steady state concentration (a), pressure (b), and flowrate (c)