BATCH REVERSE OSMOSIS PILOT DEMONSTRATION

Author: Quantum J. Wei[1], Michael J. Plumley[2], Kei L. Chua[3], Audrey R. Abraham[4], John H. Lienhard V[5], Emily W. Tow[6]

[1]Harmony Desalination, Founder, USA, water@harmonydesal.com
[2]Coast Guard Academy, Professor, USA, michael.plumley@uscga.edu
[3]Olin College of Engineering, Student, USA, kchua@olin.edu
[4]Olin College of Engineering, Student, USA, aabraham@olin.edu
[5]Massachusetts Institute of Technology, Professor, USA, lienhard@mit.edu
[6]Olin College of Engineering, Professor, USA, etow@olin.edu

Presenter: Quantum J. Wei – Harmony Desalination - USA

EXTENDED ABSTRACT

Batch reverse osmosis is a unique process that uses standard equipment to recover water from scaling-prone reverse osmosis (RO) concentrate. Batch RO avoids scaling by operating in cycles that are too short for scalants to nucleate. Batch RO can efficiently reduce inland desalination plants' concentrate disposal costs while recovering potable water. We have demonstrated batch RO at the pilot scale as part of the US Bureau of Reclamation's More Water Less Concentrate Challenge. The pilot system demonstrated more than 80% water recovery from RO brine for less than 2.5 kWh/m^3. By leveraging batch RO's cyclical operation and demonstrating its efficacy with the Yuma Desalting Plant's challenging RO brine, we hope to expand the capabilities of RO for low-energy, high-recovery desalination.

Keywords: batch reverse osmosis, pilot demonstration, concentrate management, scaling mitigation

I. INTRODUCTION

Batch RO leverages the thermodynamics and timescales of cyclical operation to improve upon the state of the art in desalination: RO. Batch RO has the lowest energy consumption of any RO process [1], and our scalant nucleation models predict that batch RO can achieve higher water recovery without membrane damage than conventional RO or semi-batch RO. Batch RO uses standard equipment and off-the-shelf RO membranes, and it scales up as seamlessly as conventional RO [2-3]. Our goal is to validate the scaling theory, push the limits of water recovery that can be achieved with RO, and enable affordable, environmentally benign, high-recovery desalination of wastewater such as brine from inland RO facilities.

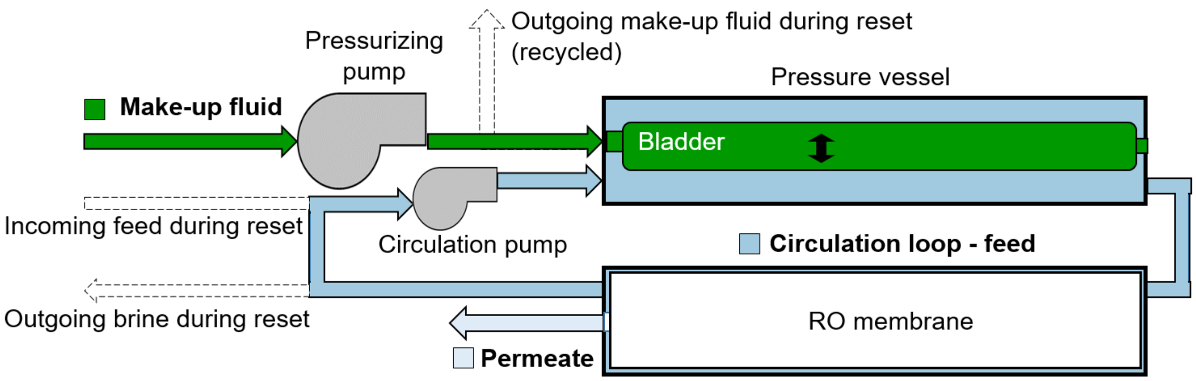

Figure 1. Illustration of the permeate production phase of a batch RO desalination process. The pressurizing pump fills up the bladder with a make-up fluid which pressurizes the circulation loop, causing permeate to leave the system through the RO membrane. The reset phases are not depicted explicitly, but the incoming and outgoing flows are shown with the dotted arrows.

II. MORE WATER LESS CONCENTRATE CHALLENGE

The United States Bureau of Reclamation has organized the More Water Less Concentrate Challenge to encourage the development of innovative concentrate management technologies. Five finalist teams were awarded $115,000 in funds and invited to demonstrate their technology at the Yuma Desalting Plant in Arizona, USA during the summer of 2022.

The goals of the concentrate challenge may be summarized by looking at the point allocation during the demonstration event:

- Reduction in concentrate volume (25 points)
- Technology feasibility at full scale (25 points)
- Product water recovery (15 points)
- Product water quality (15 points)
- Power consumption (10 points)
- Innovation (10 points)

All pilots will treat real water for 7 days of continuous testing. The water source is brackish agricultural drainage water from the Main Outlet Drain Extension (MODE) canal in Yuma, AZ.

The Yuma MODE water (approximate TDS = 2,200 mg/L) is treated by the Yuma Desalting plant and discharged as concentrate (approximate TDS = 7,600 mg/L), which is fed to our pilot system for further concentration and water recovery.

III. SCALING MITIGATION IN BATCH REVERSE OSMOSIS

Batch RO can achieve higher recoveries than conventional RO as a result of its time-variant nature (Figure 1), which minimizes the contact time between scaling-prone water and the membrane [4], and due to the osmotic backwashing that occurs between cycles [5]. Additional water recovery could be achieved at a cost ($0.10-0.30/m^3) and energy consumption (approximately 0.8 kWh/m^3 for a large-scale plant) similar to semi-batch RO and well below thermal brine concentration methods.

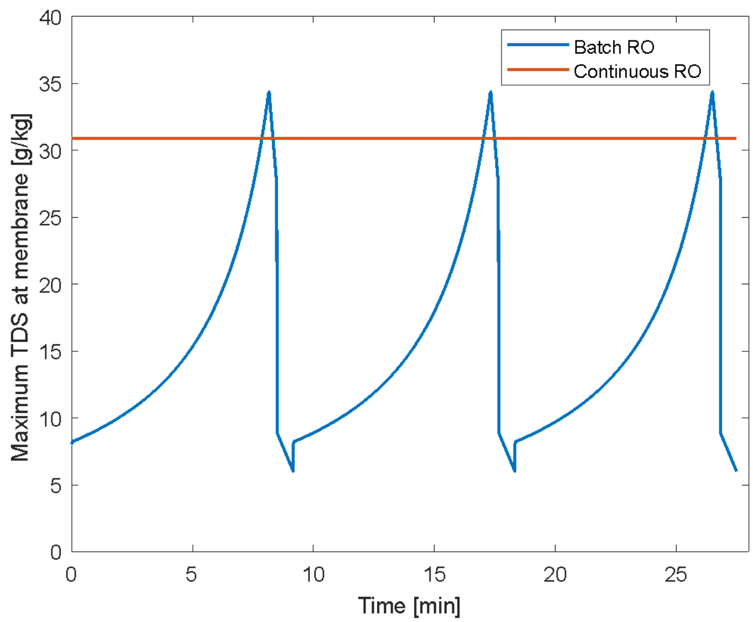

Figure 2: In continuous RO, the last element is prone to scaling because it is constantly exposed to supersaturated conditions. In batch RO, the membrane is only exposed to the highest concentrations for a minute at a time.

The design of a batch RO system for treating an inland desalination facility's RO concentrate is determined by predicting the system's maximum recovery without scalant nucleation. According to our water chemistry analysis using PHREEQC, the most supersaturated salts in MODE RO concentrate at ambient temperature are fluorite (assuming concentration near the lower detection limit), barite, hematite, hydroxyapatite, and goethite. The last three can be controlled by reducing pH with sulfuric acid at <12 ppm, depending on brine pH. Barite's nucleation induction time at the relevant concentration is very long relative to a batch RO cycle, so it is unlikely to precipitate in batch RO. Fluorite, therefore, was the primary scalant of concern in the MODE RO concentrate that we considered in our system design, with a saturation index (SI) of 2.3 or greater at the end of each cycle in our proposed system. For lack of fluorite nucleation induction time data, we currently model fluorite induction time as that of barite at the same SI. At each time step in our scaling model, we attempt to capture how scaling might unfold in the spatial and temporal concentration gradients of batch RO: we estimate the highest SI at the membrane [6], find the nucleation rate as the inverse of estimated induction time for that SI, and advance the nucleation progress (which might be thought of as a probability) accordingly, as shown in Figure 2. Through control of the system recovery, the cycle should be designed to end before nucleation progress reaches an unacceptable probability.

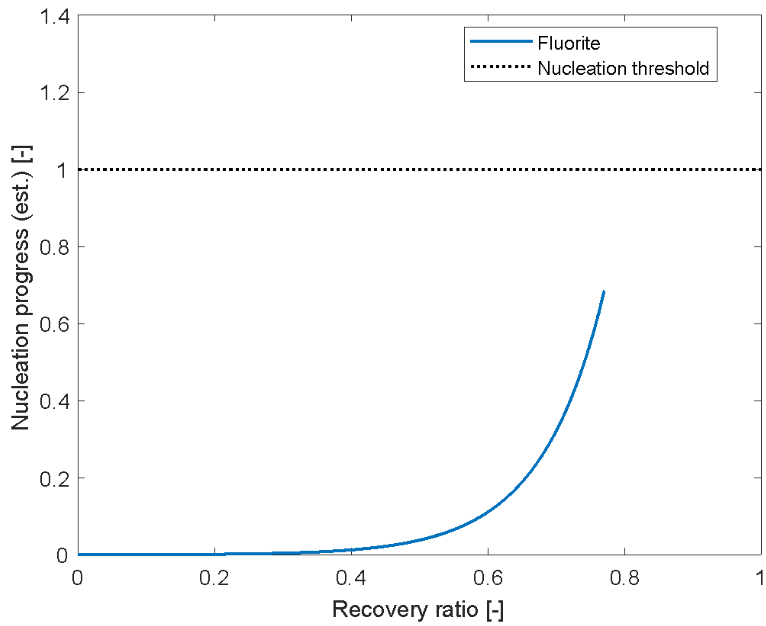

Figure 3: We estimate the likelihood of nucleation by tracking the cumulative effect of time-varying concentration. The relatively lower concentrations in batch RO (as compared to semi-batch RO) prevent nucleation.

We predict (see Figure 3) that the likely scalants in the MODE RO concentrate will not nucleate in the short (~10 minute) cycle time of batch RO, enabling batch RO to reach greater than 75% recovery from MODE RO concentrate, bringing the total facility recovery to over 95% (from 80%). The ability of semi-batch RO to minimize concentrate volume has already been proven in the field by Desalitech [7]. Although similar in principle, batch RO has a lower time-average salinity than semi-batch RO, which has the potential to maximize the water recovery possible without scaling.

IV. PILOT

This pilot demonstration builds upon our knowledge from building and operating a bench-scale batch RO system at MIT [2]. The production capacity of this pilot is 20 times that of our bench-scale prototype. The pilot uses two standard 4x40 membrane elements and commercially available pressure vessels to house the membranes and the bladder.

Figure 4: Photograph of the batch RO pilot built at Olin College (Needham, MA) while in operation at the Yuma Desalting Plant in Yuma, AZ. It is pictured separating the plant's brine stream into permeate (left tank) and a more concentrated brine (right tank). The pilot has a permeate production capacity of 5 m^3/day (0.9 GPM) and maximum operating pressure of 34 bar (500 psi).

Several aspects of the pilot system improve upon our previous bench-scale version to address issues identified in explorations of batch RO to date:

1. We reduced the complexity of the batch RO design by eliminating several actuated valves.
2. We introduced a mechanism of resetting the system faster, leading to a downtime of <15% between cycles.
3. We redesigned our flexible bladder, which resides in an RO housing, to stand in for an RO membrane. It is stiff enough not to get pulled into the concentrate port and it is field-reparable.
4. We used a stainless steel permeate port with a 600-psi pressure rating for our bladder pressure vessel to pump pressurized water (up to 500 psi) into the bladder. In contrast, standard RO head assemblies generally have a maximum permeate pressure of 125 psi.
5. We refined the geometry of the fluidic system to minimize salt retention.

V. RESULTS

We tested the prototype on synthetic saltwater (sodium chloride in water) at Olin as well as RO concentrate at the Yuma Desalting plant. As we will discuss in this section, initial results show the batch RO system running autonomously and performing as expected. It has been tested for more than 100 batch cycles under a range of feedwater salinities and water recoveries.

For the purposes of testing and research, we used four sensors (absolute pressure [Wika], two flowmeters [ProSense and McMillan], and differential pressure [Dwyer]) to monitor the system. A commercial system would need, at minimum, a differential pressure sensor to prevent overfilling the bladder.

Although the permeate flowmeter (McMillan) only measures flow in one direction, we used it to measure both permeate production and backwash through the use of several check valves to direct backwash in the proper direction through the flowmeter.

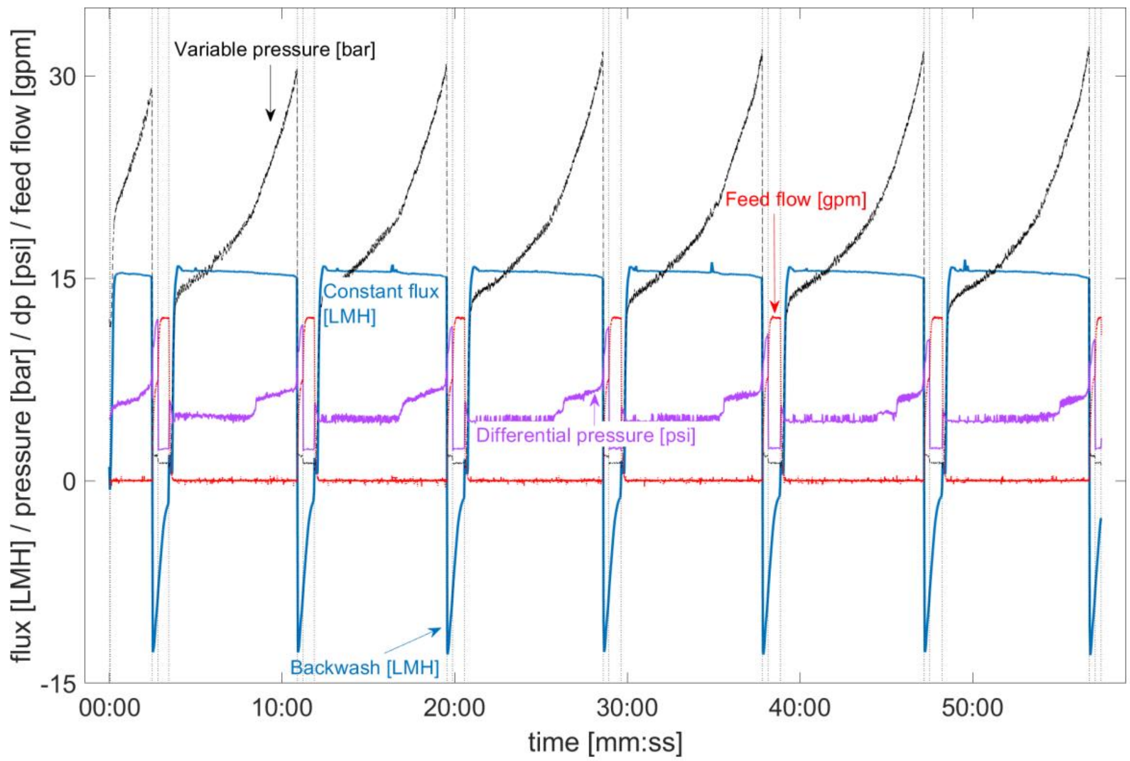

Figure 5: Sensor data from a typical laboratory test of the prototype using as feed an NaCl solution comparable in osmotic pressure to a typical sample of MODE concentrate.

Figure 5 shows system performance with a salt solution of 6700 mg/kg TDS. Cycle downtime is brief (11%) relative to the cycle time. There is significant backwash at the beginning of each flush phase, but this reduces quickly. New feed is introduced during the flush and recharge phases. Transitions between phases are indicated by the dotted vertical lines. The cumulative water recovery from the six complete batch cycles is 79% (accounting for permeate loss due to backwashing during cycle resets). Measurements of permeate conductivity show salt rejection of 98-99%, which is slightly lower than the 99.2% average rejection specified for the membranes, but this is expected because we are operating at a lower water flux than the membranes' test conditions.

Figure 6 shows a single batch cycle from a different trial in closer detail. Over the course of the permeate production phase, the system produces a constant permeate flux (~15 LMH) while the system pressure increases from ~14-32 bar. We measure the differential pressure across the bladder surface to detect when to end the permeate production phase.

The electrical power consumption of the prototype (measured by Kill-A-Watt meters) in lab tests has been approximately 600 W, with the high-pressure pump and circulation pump drawing approximately the same power. While the small-scale circulation pump does very little hydraulic work, it still requires almost 300 W to run at maximum RPM. This inefficiency would need to be addressed at full-scale. Trials over a range of salinities and water recoveries have resulted in specific electricity consumptions (SECs) of 3.0−3.2 kWh/m^3; while this SEC is high for brackish water desalination, it is reasonable for a small desalination system (<1 GPM).

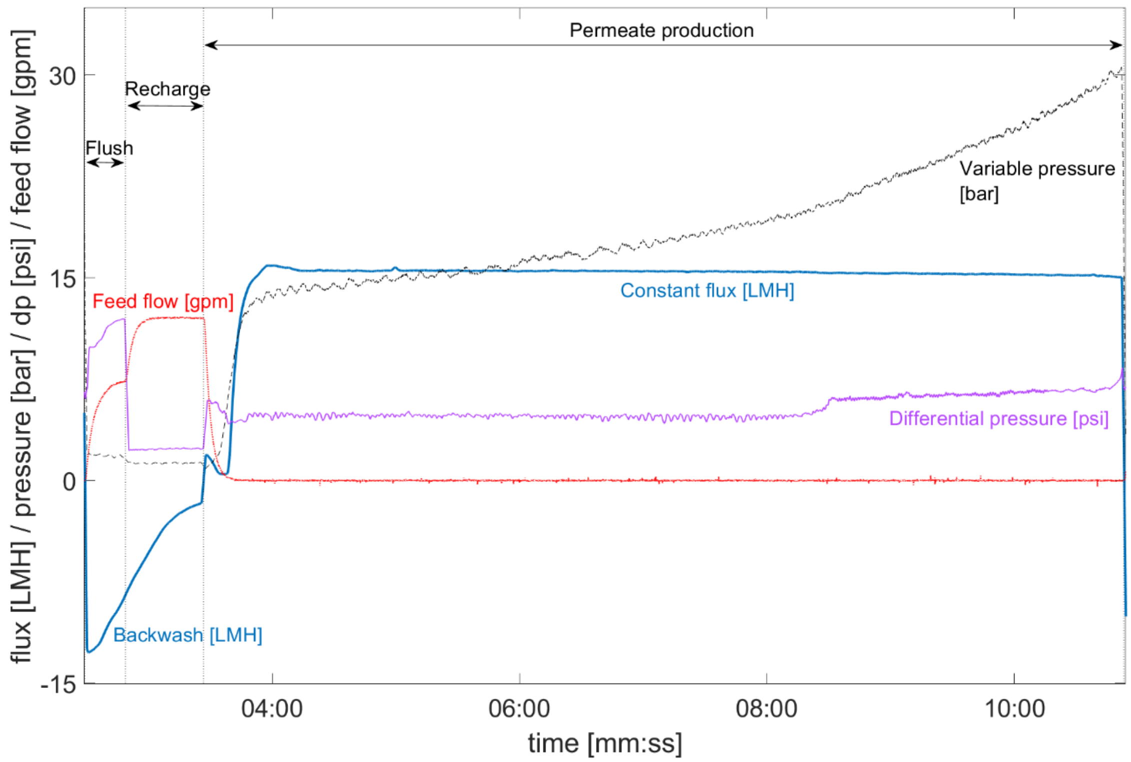

Figure 6: Sensor data from a single batch cycle. First, the system is flushed of brine from the previous permeate production cycle. New feed enters the system while permeate re-enters the de-pressurized system via osmosis. The flush phase is followed by the recharge phase – the bladder is emptied out and the system is filled with fresh feed. In this cycle it takes ~20 s for permeate production to ramp up once the high-pressure pump is turned on (10 s for pump to reach full speed and 10 s for the pressure to rise). We plan to reduce this ramp-up time in Arizona by turning the high pressure pump on near the end of the recharge phase. We monitor the system pressure and differential pressure across the bladder to determine when to end the permeate production phase and reset the system again.

Concentration of MODE RO concentrate at the Yuma Desalting plant showed similar results as seen in laboratory tests with NaCl. The system was operated for 6 h on feedwater (RO brine) with conductivity of approximately 9.0 mS/cm and pH of approximately 6 (no acid was added by our system). As shown in Figure 7, flux was consistent between batches, and pressure rose slightly each time we increased the system recovery over the course of the trial (at approximately 60 and 240 minutes). Product water with an average conductivity of 494 µS/cm was produced from the RO brine at a recovery ratio of 81.6%. Pale yellow crystals can be seen accumulating in the bottom of the brine tank, showing that the brine is supersaturated with one or more salts. The system power consumption (not including the roughly 70-Watt laptop used for control) was 500 W, for an SEC of 2.49 kWh/m^3.

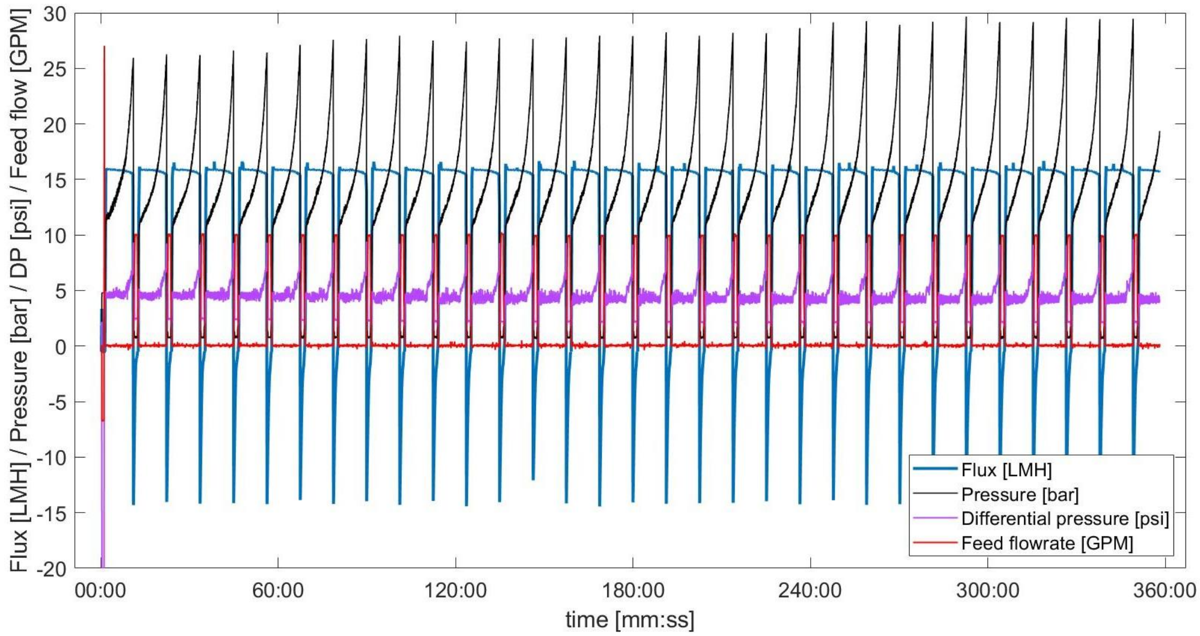

Figure 7: Six hours of data from the batch RO system treating Yuma Desalting Plant brine.

VI. OUTLOOK

While the pilot performed as expected with sodium chloride solutions in the lab and RO brine in initial field tests, the success of batch RO hinges on its ability to desalinate scaling-prone water long-term. Our presentation will include further data and lessons learned from the week-long demonstration of brine concentration at the Yuma Desalting Plant.

This demonstration of low-energy (<2.5 kWh/m^3), high-recovery (>80%) batch RO treatment of RO brine can improve the inland desalination and brine concentration industries. By leveraging batch RO's cyclical operation and demonstrating its effectiveness with Yuma's challenging RO concentrate, we are working to expand the capabilities of RO to include high-recovery desalination of scaling-prone water.

VII. CREDIT AUTHOR STATEMENT

Quantum J. Wei: Software, investigation, funding acquisition, writing – original draft, writing – review and editing. **Michael J. Plumley**: investigation. **Kei L. Chua**: investigation (bladder design). **Audrey R. Abraham**: investigation, writing – review and editing. **John H. Lienhard V**: funding acquisition, writing – review and editing. **Emily W. Tow**: Investigation (pilot system design), methodology, funding acquisition, writing – review and editing, project administration.

VIII. APPENDIX - PULSE FLOW RO DATA

During initial pilot testing we operated the system without powering on the circulation pump. This essentially turns the system into a pulse flow RO system, an RO process being commercialized by IDE Technologies. Data from two pulse flow RO cycles is shown below in Figure 8. In case of complete circulation pump failure, a batch RO system can operate as a pulse flow RO system, assuming there is still a pressurized feed source to flush and recharge the system.

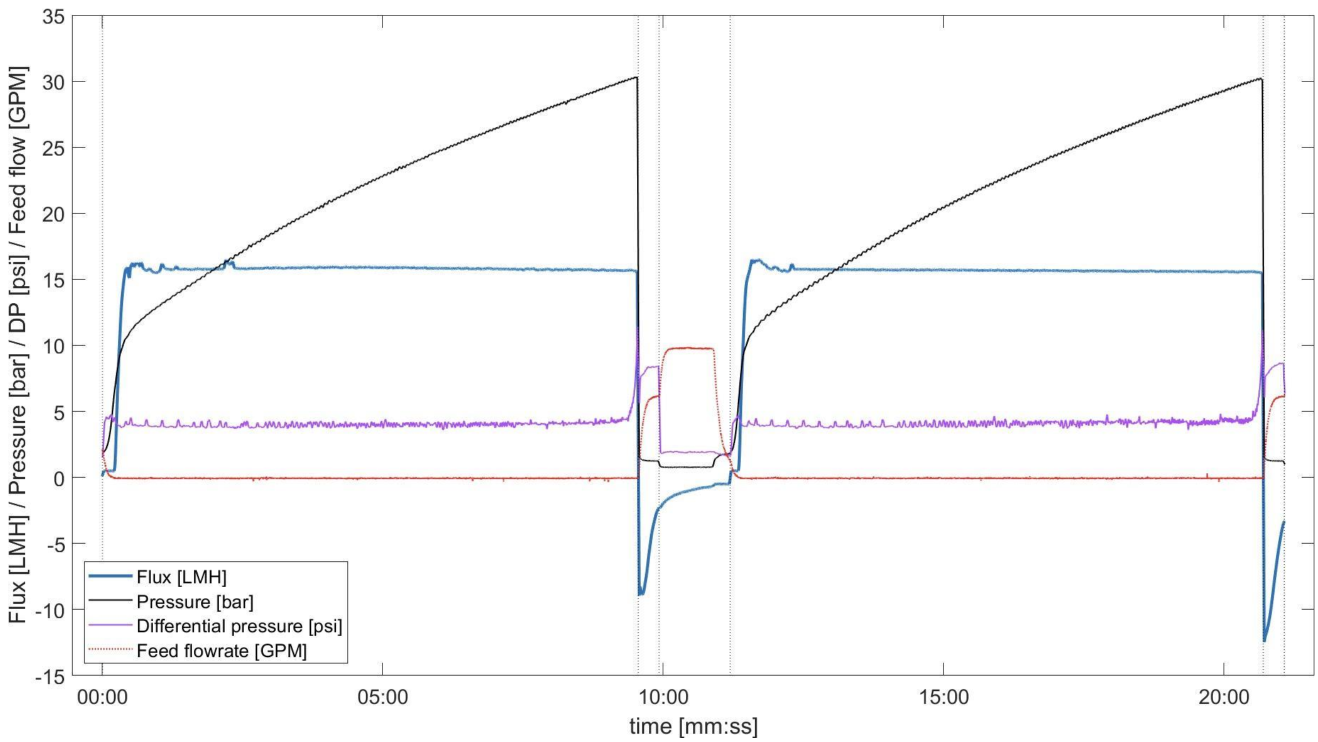

Figure 8: Two cycles worth of data from our pilot system operating as a pulse flow RO system (i.e. with no recirculation). The concentration in a pulse flow RO system varies approximately linearly with time, as opposed to sublinearly in batch RO (see Figure 6).

IX. REFERENCES

1. D.M. Warsinger, E.W. Tow, K.G. Nayar, L.A. Maswadeh, and J.H. Lienhard, "Energy Efficiency of Batch and Semi-batch (CCRO) Reverse Osmosis Desalination," *Water Research*, online 25 Sept. 2016, **106**:272-282, 1 Dec. 2016.

2. Q. J. Wei, C.I. Tucker, P.J. Wu, A.M. Trueworthy, E.W. Tow, J.H. Lienhard, "Impact of salt retention on true batch reverse osmosis energy consumption: experiments and model validation," *Desalination*, online 03 February 2020, 479:114177, 1 April 2020.

3. E. Hosseinipour, K. Park, L. Burlace, T. Naughton, and P. A. Davies, "A free-piston batch reverse osmosis (RO) system for brackish water desalination: Experimental study and model validation," *Desalination*, 527, 115524, 2022.

4. D.M. Warsinger, E.W. Tow, L.A. Maswadeh, G. Connors, J. Swaminathan, and J.H. Lienhard, "Inorganic fouling mitigation by salinity cycling in batch reverse osmosis," *Water Research*, online 5 Feb. 2018, **137**:384-394, 15 June 2018.

5. Q. J. Wei, "Can batch reverse osmosis make desalination more affordable and sustainable?" PhD Thesis, Massachusetts Institute of Technology, Cambridge MA, June 2021

6. J. Swaminathan, E.W. Tow, R.L. Stover, and J.H. Lienhard, "Practical aspects of design of batch reverse osmosis for energy efficient seawater desalination," *Desalination*, online 21 August 2019, 470:114097, 15 November 2019.

7. H. Gu, M. H. Plumlee, M. Boyd, M. Hwang, and J. C. Lozier, "Operational optimization of closed-circuit reverse osmosis (CCRO) pilot to recover concentrate at an advanced water purification facility for potable reuse," *Desalination*, 518, 115300, 2021

8. E.W. Tow, D.M. Warsinger, J. Swaminathan, A.M. Trueworthy, G.P. Thiel, S.M. Zubair, A.S. Myerson, and J.H. Lienhard, "Comparison of fouling propensity between reverse osmosis, forward osmosis, and membrane distillation," J. Membrane Sci., online 27 March 2018, 556: 352-364, 15 June 2018.