BATCH REVERSE OSMOSIS: EXPERIMENTAL RESULTS, MODEL VALIDATION, AND DESIGN IMPLICATIONS

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Abstract

In theory, batch reverse osmosis (RO) systems can achieve the lowest practical energy consumption by varying feed pressure over time. However, few batch RO systems have been built and operated. We have tested a bench-scale prototype of a true batch RO system using a bladder and a 2.5” (6.35 cm) spiral wound membrane element. Some practical issues in implementing batch RO include system start-up time, system depressurization, osmotic backwash during the reset phases, and lower permeate quality. This study is the first to validate batch models by measuring the hydraulic work of both the high pressure pump and the circulation pump. The experimental measurements agree well with the model (error $\leq$ 3%) after accounting for concentration polarization. We used the validated model to calculate the energy savings of true batch systems at higher salinities and recovery ratios. We find that the energy savings achievable by true batch systems are less than previously thought, but still significant at relatively high recoveries. At 50% recovery of seawater feed, a batch RO plant could save 15% of the energy consumed by a continuous RO plant while still maintaining the same effective flux. Further studies should identify the additional costs associated with batch RO in order to identify the operating conditions where batch RO will be an economically favorable option compared to conventional continuous RO.

Motivation

Reverse osmosis (RO) desalination can help to ensure secure water resources, but the process remains costly. From 2007-2017, global desalination capacity nearly doubled, from 47 to 92 million m^3/day, with RO accounting for two thirds of total installed capacity (Virgili et al., 2018). The total volume of treated water now accounts for around half a percent of global freshwater consumption (Hoekstra and Mekonnen, 2012). As a growing part of the world's sustainable water supply, RO must be made cheaper.

The cost of desalinated water is primarily driven by capital expenditures and energy consumption. In a seawater reverse osmosis (SWRO) plant, electrical energy costs account for more than 1/3 of the total cost. RO energy consumption has fallen dramatically since the 1970s, from 20 kWh/m^3 to roughly 3.5 kWh/m^3 in today's large-scale plants as a result of improvements in membrane permeability, pump efficiency, and energy recovery device efficiency. RO energy consumption can never fall below the thermodynamic least work of separation, which is about 1 kWh/m^3 for 50% recovery of seawater feed (Fritzmann et al., 2007. Lienhard et al., 2016). Practically speaking, RO energy consumption will not reach the thermodynamic limit but may be further reduced through improvement in system design (Lienhard et al., 2017).

Background

RO is typically implemented as a continuous process. Continuous RO is not the most energy efficient RO configuration. In continuous RO, the brine osmotic pressure at the end of the system is greater than the feed osmotic pressure at the feed inlet. Although the feed osmotic pressure may be relatively low, the entire feed stream must be pressurized to overcome the brine osmotic pressure at the system exit. The continuous RO system is **unbalanced**: freshwater production at the front of the system may be 5-7 times greater than at the back of the system due to large variations in net driving force (Fritzmann et al., 2007). A more thermodynamically balanced system could potentially produce the same amount of freshwater using less energy (Thiel et al., 2014). One way to improve balance is to operate RO as a batch process rather than the conventional continuous process.

The batch RO process saves energy because the feed pressure varies over time (Liu et al., 2011). During each batch cycle, a fixed volume of feedwater is gradually concentrated. As the osmotic pressure of the feed increases, the feed pressure increases as needed to produce the desired permeate flow. Once the desired amount of freshwater is recovered, the system is flushed of brine and refilled with new feedwater. Batch RO saves energy in a manner similar to multi-stage continuous RO, but the stages exist in time rather than space so only one high pressure pump is required in batch RO. However, permeate production in batch RO is not constant because the system must be reset every cycle.

Batch RO designs

In a true (or ideal) batch system, the hydraulic circuit connecting the feed tank to the membrane module must stay pressurized throughout the permeate production phase (Warsinger et al., 2016). This is not straightforward to implement because it requires a high-pressure, variable-volume tank to accommodate the hydraulic circuit's shrinking volume as permeate leaves the system. True batch systems can use a rigid piston or a flexible bladder, as shown in Figure 1. During the permeate production phase, the bladder increases in volume as make-up fluid (e.g., water) is pumped into it. Permeate leaves the system through the RO membrane in an equal volume. A circulation pump provides a cross-flow velocity to reduce concentration polarization (CP). After the desired permeate is produced, the remaining brine is flushed and new feed is introduced to reset the system.

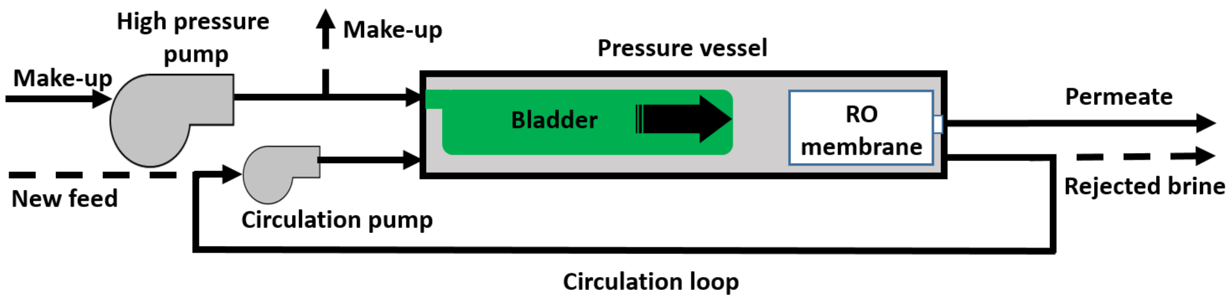

Figure 1. Schematic diagram of a true batch system using a bladder. Make-up fluid is pumped into the bladder to produce permeate. Dashed lines indicate flows during reset phases.

Some authors have proposed a simpler implementation of batch RO using already available energy recovery devices (ERDs). In this design, an ERD is placed between the feed tank and the membrane module. Energy is recovered from the high-pressure retentate leaving the membrane module to pressurize incoming feed. This enables the use of a low pressure tank, reducing system complexity. However, even with highly efficient ERDs (e.g., 96%), much of the potential energy savings are lost as feedwater passes through the ERDs multiple times per batch cycle (Warsinger et al., 2016).

A double-acting batch RO system would increase the energy savings of batch RO at the expense of increased complexity and cost (Davies et al., 2016a. Werber et al., 2017). In a double-acting system, there are two feed tanks. While the system is recovering permeate from the first feed tank during the batch phase, the second feed tank is being filled with new feedwater. By the end of the batch phase, the second feed tank is ready to undergo permeate production. This significantly reduces the reset time, although continuous permeate production may not be achieved: a double-acting batch system (as described in existing literature) must halt permeate production while flushing out residual brine.

Previous work

Davies et al. (2016b) implemented a true batch system using a rigid piston. They measured the hydraulic work done by the high pressure pump and showed performance lower than the theoretical minimum for single-stage continuous RO with an ERD. However, they did not measure the circulation pump work, which prior literature shows to have a non-negligible impact on energy consumption (Warsinger et al., 2016).

Prior comparisons of batch RO and continuous RO energy consumption assumed that both systems operate at the same feed salinity and recovery ratio. Werber et al. (2017) kept system flux in their comparison, whereas Warsinger et al. (2016) kept the pressure pinch fixed. We believe that both these studies slightly overestimate the potential energy savings of a batch RO system.

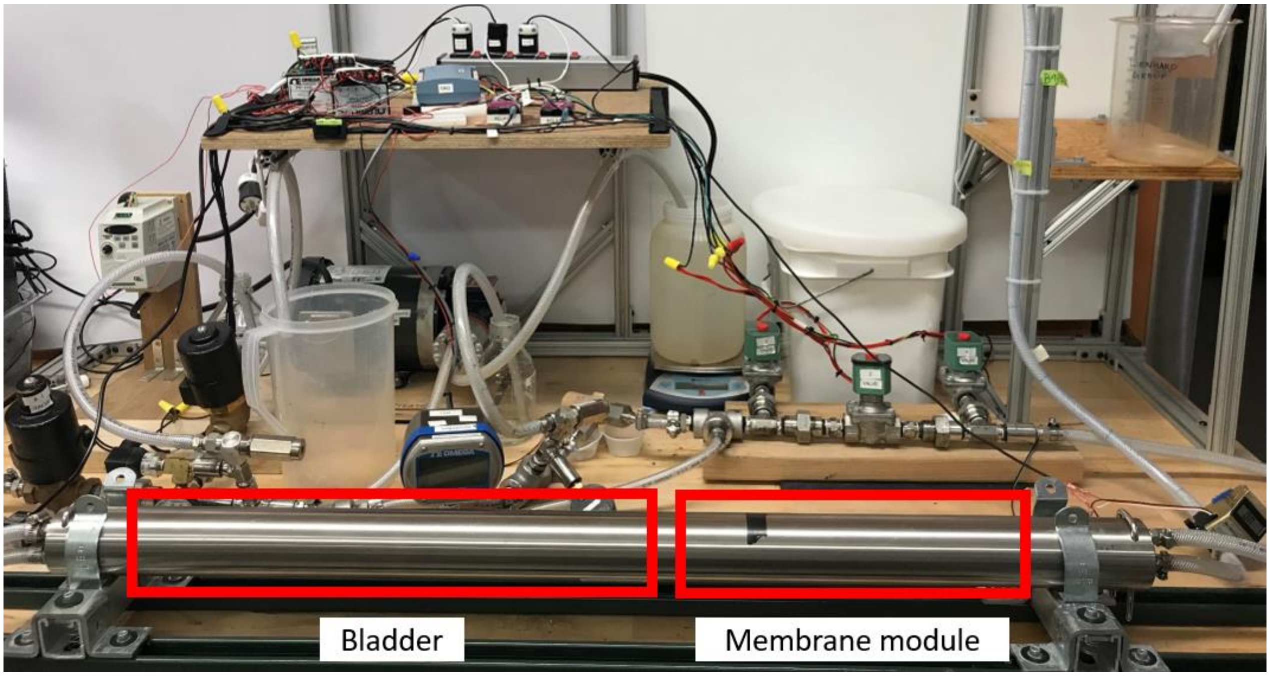

Figure 2. Batch RO bench-scale prototype. The prototype uses a commercially-available 2.5" diameter spiral wound membrane element (Hydranautics ESPA-2514).

Our work
In this study, we tested a bench-scale prototype (shown in Figure 2) of a true batch RO system using a bladder and a 2.5" (6.35 cm) spiral wound membrane element. This is the first study to validate batch models by measuring the hydraulic work of both the high pressure pump and the circulation pump. We used the validated model to calculate the energy savings of true batch systems at higher salinities and recovery ratios. The energy savings achievable by true batch systems are less than previously thought, but still significant at high recoveries. We find that true batch systems can indeed reduce the energy consumption of RO under appropriate conditions.

Design Implications

This section will explore under what conditions a batch RO plant can be presented as an energy-saving alternative to a continuous RO plant. While the batch RO process is theoretically more energy efficient than the continuous RO process, in practice intermittent permeate production and residual brine will have significant effects on the revenue and performance of a batch RO plant. In general, the energy savings of batch RO will be realized only at relatively high recovery ratios.

We calculated continuous RO energy consumption using a previously validated model, which accounts for concentration polarization (Wei et al., 2017). Batch RO energy consumption was calculated using our newly-validated batch RO model (see next section). Feedwater was modeled as an aqeuous NaCl solution for all systems. Other system parameters are shown in Table 1.

Table 1. Parameters used in energetic analysis of seawater and brackish reverse osmosis.

Parameter	**Value**	
Membrane permeability	3	L/m^2-h-bar
Membrane area	30.6	m^2
Pump efficiency	0.8	
ERD efficiency	0.98	
Circulation pressure drop	0.1	bar
Feed channel velocity	20	cm/s
System volume	120	L
Circulation pump flowrate	140	L/min

In this comparison, the batch RO plant must match the effective flux (daily permeate production per unit membrane area) of the continuous RO plant. We compare the energy consumption of a batch seawater RO (SWRO) plant to a continuous SWRO plant in Figure 3. Batch RO does not always consume less energy than continuous RO. This finding is contrary to previous literature, as indicated by the dotted line. At an effective flux of 15 LMH, a batch SWRO plant only begins to save energy at recovery ratios above 25%. The savings increase as recovery ratio increases, with the batch plant achieving 15% energy savings at a recovery ratio of 50%. It thus follows that a batch SWRO plant only becomes an energy saving alternative to a continuous SWRO plant when run at recovery ratios well above 26%.

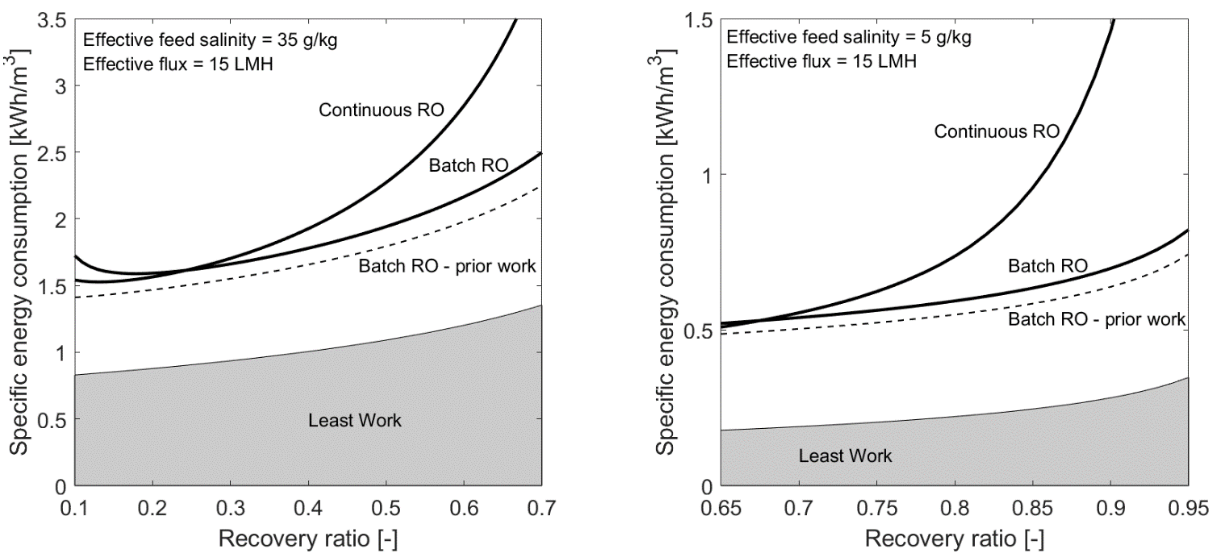

Figure 3 and 4. Specific energy consumption of seawater and brackish RO processes versus recovery ratio. Feed modeled as 35 g/kg and 5 g/kg NaCl solution. At an effective flux of 15 LMH, a batch SWRO plant saves energy at recovery ratios above 25% and a batch BWRO plant saves energy at recovery ratios above 67%. Prior work did not account for the disparity in operating and effective conditions (Warsinger et al., 2016). The least work of separation is shown in gray.

We show similar findings for a batch brackish RO (BWRO) plant, as shown in Figure 4. The batch BWRO plant begins saving energy at a recovery ratio of 67% and achieves energy savings of 20% by 80% recovery. Some BWRO plants are multi-stage continuous plants (not shown here), so batch RO would also have to out-perform those plants.

The results presented here are highly influenced by the circulation pump flowrate during the reset phases. At lower flowrates, the batch RO energy curve will shift upwards as it takes longer to reset the system. At higher flowrates, the batch RO energy curve will shift downwards. Here, we assume that the circulation pump operates at the same flowrate during the reset phases as during the batch phase. While it is possible to operate the circulation pump at higher flowrates, we choose to be conservative in this analysis. We note that the system start-up time will also tend to shift the batch RO energy curves up, as discussed in the next section.

The performance of a double-acting batch RO system would lie somewhere in between the energy consumption that we have calculated in this work and the energy consumption calculated in previous work.

Effective versus operating conditions

Unlike a continuous RO plant, a batch RO system that runs continuously has effective conditions that differ from its operating conditions. Previous comparisons between batch and continuous RO used the effective conditions to calculate batch energy consumption. The results are different if the operating conditions are used instead. Effective conditions correspond directly with overall plant revenues and expenses whereas operating conditions are tied to the system performance (e.g., energy consumption).

For example, in the case of system flux, since a continuous RO plant continuously produces permeate, its operating flux is the same as its effective flux. But since a batch RO plant only produces permeate during the batch phase, its effective flux is only a proportion of the operating flux, namely, the proportion of the duration of the batch phase to the duration of the total cycle (Swaminathan et al., 2017). These differences are represented in the equation below, where t_{total}, the duration of the total cycle, is defined as the sum of the duration of the batch phase and the reset phases:

$$J_{\mathrm{sys,eff}} = J_{\mathrm{sys,op}} \frac{t_{batch}}{t_{total}}$$

$$t_{total} = t_{batch} + t_{reset}$$

Thus, in order to match the effective flux of a continuous system, a batch system must operate at a higher operating flux, consequently consuming more energy than if the batch system were operating at the effective flux. The effective flux of a batch system may also be depressed due to the system start-up time, as discussed in the next section.

Figure 5 indicates the progression of the operating to effective flux ratio recovery ratio towards 1 as recovery ratio increases. The operating flux was calculated using the above equations and the parameters in Table 1. This progression supports the increase in energy consumption of batch RO at lower recoveries as it shows that a batch SWRO plant at a recovery of 30% must operate at a flux as high as 18 LMH in order to achieve an effective flux of 15 LMH. Notably a batch SWRO plant can still save significant energy compared to a continuous RO plant, despite the fact that it must operate at a higher flux, even at high recoveries. A batch SWRO plant achieves a 15% energy savings at 50% recovery even though it must operate at 16.8 LMH to achieve an effective flux of 15 LMH.

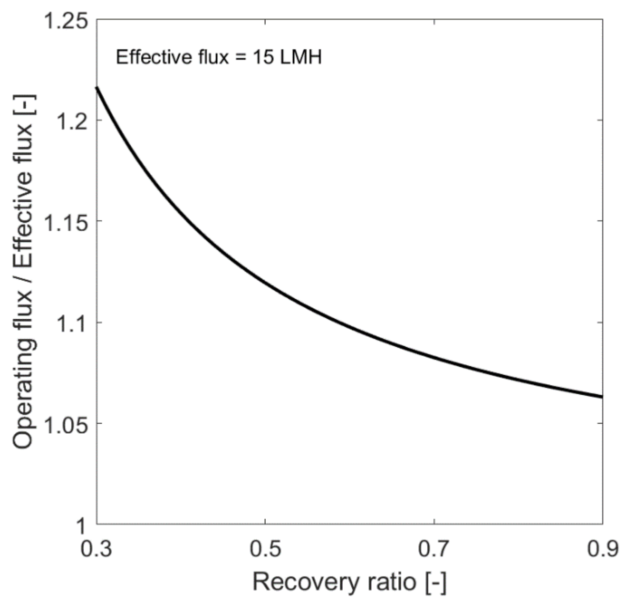

Figure 5. The ratio of batch operating flux to effective flux at various recovery ratios. At lower recovery ratios, the reset time accounts for a significant portion of the total cycle time so a batch system must operate at much higher flux in order to achieve the effective flux.

The operating feed salinity of a batch RO system will always be greater than the effective feed salinity due to residual brine left in the system after each flush phase. The degree to which the operating feed salinity is elevated is determined by the duration of the flush phase and was measured empirically on the bench-scale prototype.

Model Validation

Previous studies have modeled realistic batch RO systems, accounting for factors including membrane permeability, frictional losses, pump and ERD efficiencies, and concentration polarization (Swaminathan et al., 2017). We compared the energy consumption of our batch RO prototype to the predictions of a batch RO model over a range of recovery ratios, fluxes, and feed salinities. The experimental results agree well with the model predictions. This is the first time that models of batch RO energy consumption have been validated with experimental results, greatly increasing the utility of previous models. While our batch RO prototype is currently limited to operating pressures under 10 bar, we anticipate that the validated model can be used to predict batch RO performance over a wider range of operating conditions.

Overall results
The overall specific energy consumption (SEC) of our batch RO prototype agrees with the model predictions. Figure 6 shows measured and predicted SEC for a number of tests over a range of feed salinities (2-5 g/kg), fluxes (10-20 LMH) and recoveries (30-55%). The largest error of 3.1% occurs at the lowest recovery ratio (30%) due in part to the short test duration. Errors are lower at

higher feed salinities and recoveries. Our prototype is currently limited to operating pressures under 10 bar and recovery ratios under 55%. Beyond these limited conditions, we expect that the model will slightly overestimate batch RO energy consumption due to overestimates in the high pressure pump work, as discussed below.

These results represent the hydraulic work done by the high pressure pump and the circulation pump. Pump efficiency is not accounted for in these results since it is assumed that actual batch RO plants will use higher efficiency pumps than the small pumps in our bench-scale apparatus. Energy consumption of the prototype is calculated from pressure and flow measurements. For these model predictions, we modified a previous model (Warsinger et al., 2016) to include the effects of concentration polarization.

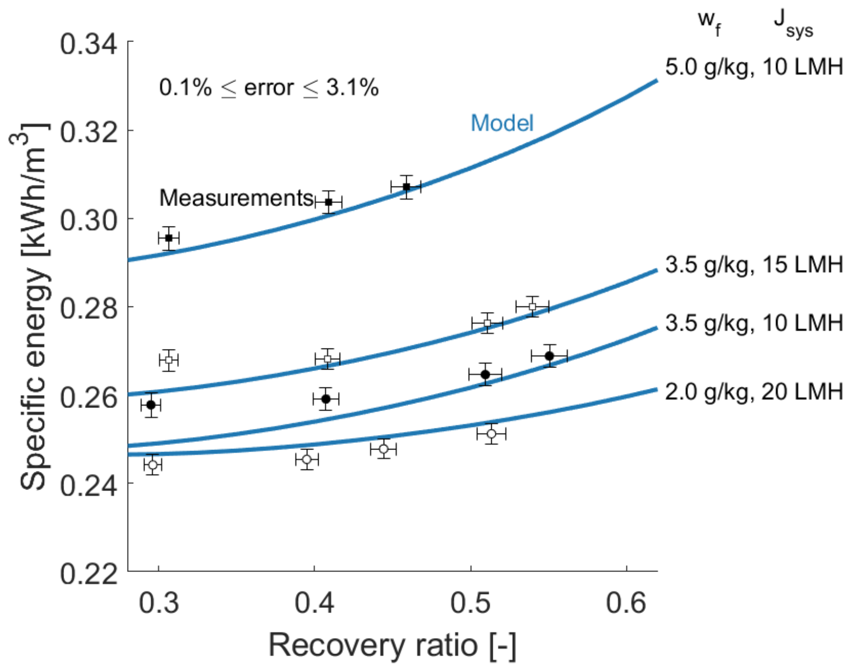

Figure 6: Measured and predicted specific energy consumption versus recovery ratio for various combinations of feed salinities and fluxes. The experimental results agree with the model predictions within 3.1%. Error bars represent 95% confidence intervals.

Sources of error

Energy consumption in batch RO is composed of two components: the high pressure pump work and the circulation pump work. The model assumes that the batch RO system instantly produces permeate at the desired flux, whereas in reality it takes time for the system to ramp up to the desired flux, as discussed in the next section. This leads to underestimates in the circulation pump work and overestimates in the high pressure pump work. In these tests, the error in circulation pump work ranges between 7-15% while the error in high pressure pump work ranges between 1-4.5%. While the percent error in circulation pump work is greater, the high pressure pump work is a larger proportion of the total work. The errors of the two components of work partially offset each other, reducing the overall error. We expect the overall error to be dominated by the high pressure pump error at higher feed salinities and recovery ratios.

As shown in Figure 7, the circulation pump work is underestimated in all tests. The model assumes permeate is immediately produced at the desired permeate flux. In reality, some time is required to reach steady-state operation so the circulation pump operates for a longer duration than is predicted. This source of error becomes less significant at higher feed salinities and recovery ratios as high pressure pump work and cycle times increase.

The circulation pump power is relatively constant throughout the batch RO cycle, so the circulation pump work scales with cycle time. The two tests shown in Figure 10 have similar cycle times (734 and 752 seconds), so the circulation pump works are similar. In the test with a higher feed salinity (5 g/kg) the proportion of work done by the circulation pump diminishes as the high pressure pump work increases, so the overall error is lower.

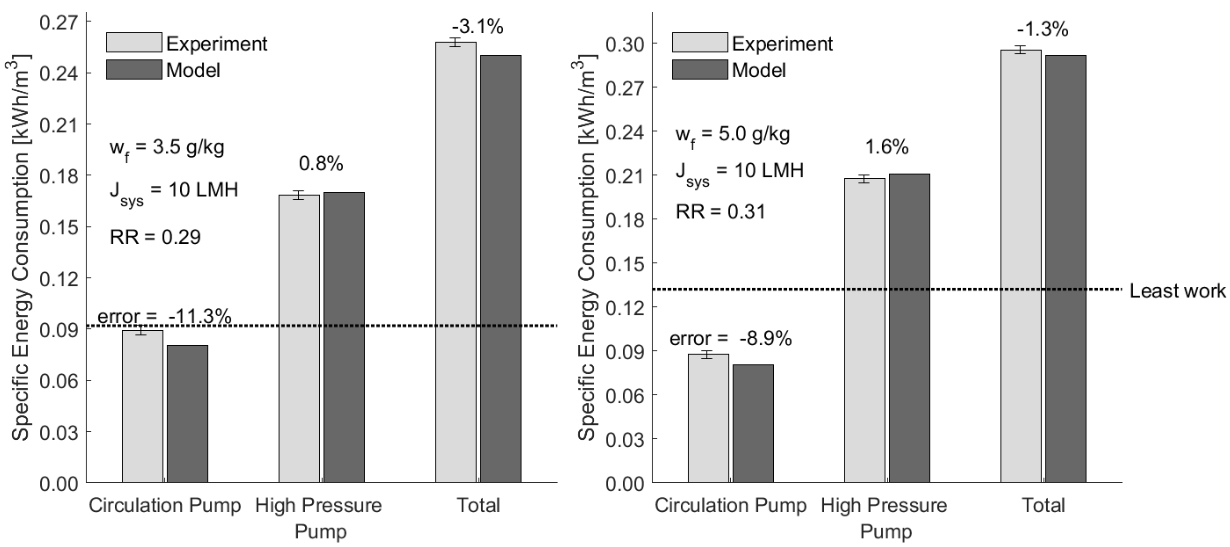

Figure 7. The energy consumption of the circulation pump and high pressure pump are compared to model predictions. The circulation pump operates while the system is starting up, so its work contribution is underestimated. At higher feed salinities, this error becomes smaller compared to the total work. Error bars represent 95% confidence intervals.

This source of error also decreases as cycle time increases, since the system start-up time represents a smaller proportion of the total cycle time. Cycle time increases as recovery ratio increases or as flux decreases. In Table 2, we see that the circulation pump error generally decreases at higher recovery ratios and lower fluxes. Since batch RO saves energy at higher feed salinities and recovery ratios than the conditions shown here, we expect that the error in high pressure pump work will dominate the overall error at practical operating conditions.

As shown in Figure 8, the high pressure pump is overestimated in part because the model assumes that all permeate production occurs at the nominal flux (20 LMH). In reality, the permeate flux ramps up 0 to 20 LMH gradually. Since the prototype is operating at lower flux during the start-up time, the measured high pressure pump work is lower than predicted. The largest overestimate in high pressure pump work occurs for the tests at 20 LMH, which correspond to the tests with the highest flux and shortest cycle times.

Table 2. Error in circulation pump work for various tests. The error generally decreases as cycle time increases, whether due to higher recovery ratio or lower flux.

Increasing cycle time →

	High flux – 15 LMH			
Recovery ratio [-]	31	41	51	54
$\text{Error}_{\text{circ}}$ [%]	14	12	10	10
	Low flux – 10 LMH			
Recovery ratio [-]	29	41	51	55
$\text{Error}_{\text{circ}}$ [%]	11	8	7	8

Increasing cycle time ↓

The model also overestimates the feed pressure needed to achieve the desired flux. Warsinger et al. (2016) modeled batch RO by setting a constant pinch at the end of the membrane module for each time step. The pinch is the difference between the feed gauge pressure P_f and osmotic pressure Π_f and is related to the permeate flux J_v by the membrane permeability, A:

$$J_v = A\left(P_f - \Pi_f\right)$$

The salinity of the feed increases in the direction of flow along the membrane module as water leaves to the permeate side. The feed salinity, and hence osmotic pressure, will be at its maximum at the end of the module. Since the feed pressure is mostly constant along the module, the permeate flux will decrease along the module as the osmotic pressure increases. The model thus overestimates the feed pressure required because the specified pinch is defined as that needed to achieve the *average* flux, not the *minimum* permeate flux that occurs at the end of the module. This source of error will become more significant as the spatial variance in feed salinity throughout the membrane module increases, whether due to higher flux or longer membrane trains.

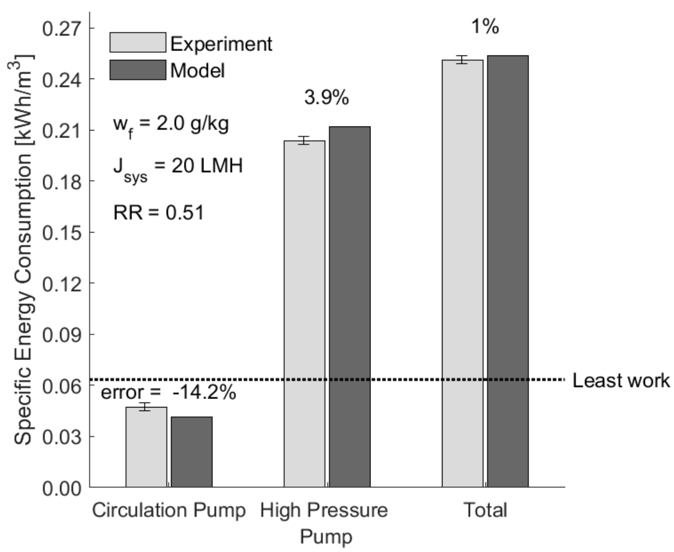

Figure 8: The energy consumption of the circulation pump and high pressure pump are compared to model predictions. The model overestimates high pressure pump work in part because the prototype operates at lower fluxes during system start-up. Error bars represent 95% confidence intervals.

Experimental Results

In this section we share some data and findings from our experience operating the batch RO system. Operation of a batch RO system is more complex than a continuous RO system, due to the transient nature of the system. The batch cycle is composed of three phases: batch, flush and recharge. First, the desired amount of permeate is produced during the batch phase. During the flush phase, the circulation pump introduces new feed into the system while residual brine exits the system. Finally, during the recharge phase, the circulation pump introduces more feed into the system and pushes make-up fluid out of the bladder. At the end of the recharge phase, the system is filled with fresh feed and the bladder is empty so that the next batch phase can commence.

We used National Instruments LabVIEW to automate transitions between the batch, flush, and recharge phases as well as to measure the feed pressure, permeate flow rate, circulation loop pressure, and circulation loop flow rate. We show data from one full batch cycle in Figure 9. The batch phase takes place from the beginning of the test and lasts just over ten minutes. The high pressure pump was switched on at the beginning of the batch phase, but it takes about a minute for the feed pressure to rise and for the permeate flux to reach the desired level (10.3 LMH), possibly due to residual air in the system. The circulation pump operates at a steady pressure and flow throughout the batch phase and during the system start-up. This system start-up is one source of error discussed in the previous section. Designers of batch systems should seek to minimize the start-up time since relatively little permeate is produced during this period.

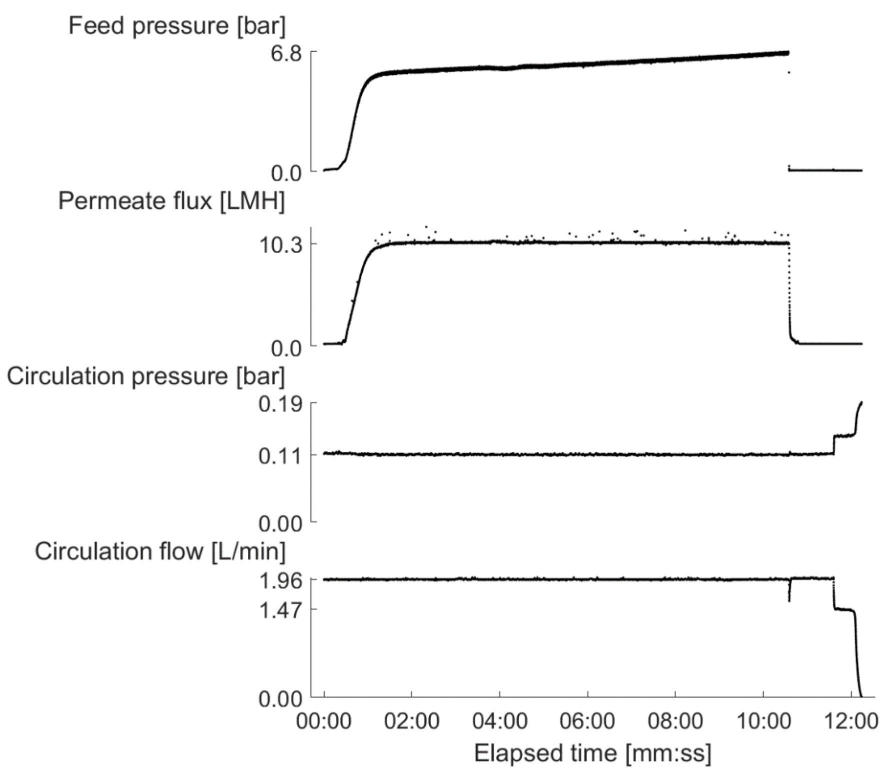

Figure 9: Pressure and flow data throughout one batch cycle of the batch RO prototype.

Once the desired amount of permeate is produced, the high pressure pump is switched off. The beginning of the flush phase is marked by a sudden depressurization as the circulation loop is exposed to the atmosphere. No permeate is produced during the flush phase and feed pressure is atmospheric. The circulation loop pressure and flow rate are approximately the same as during the batch phase.

Once the system has been flushed as desired, we switch to the recharge phase. The beginning of the recharge phase is marked by an increase in circulation pressure and a decrease in circulation flow. The circulation pump is pushing make-up fluid out of the bladder so the flow resistance is increased relative to the batch and flush phases. The recharge phase ends when the bladder is empty: the circulation pressure rises and the flow falls to zero.

Osmotic backwash occurs during the flush and recharge phases and will slightly depress the effective recovery of a batch RO system. For example, a batch RO system may produce 1 liter of permeate during the batch phase but some of that permeate will be lost to osmotic backwash as it passes through the membrane back into the feed since there is no pressure to stop (or reverse) the flow. The permeate outlet must be designed with this osmotic backwash in mind to avoid entrainment of air into the permeate tube and membrane module.

Salt passage across the membrane during the flush and recharge phases will lead to decreased permeate quality, especially at low recovery ratios and for the first batch cycle as shown in Table 3. The permeate concentration at the very beginning of each batch phase is high due to the salt passage during the preceding flush and recharge phases. As the batch phase continues, more fresh permeate is produced and the overall permeate concentration decreases. Similarly, the permeate concentration is relatively high the first time a batch system is run due to salt passage preceding start-up. The permeate concentration immediately improves for the second batch cycle and is maintained at a high level (97% rejection) afterwards. Davies et al. (2016b) observed similar results. We do not yet know how this phenomenon will affect permeate quality at higher salinities.

Table 3. Permeate conductivity for tests at various feed salinities and recoveries. Permeate quality is poor at low recoveries due to salt passage during the flush and recharge phases.

Cycle number [-]	Feed salinity [g/kg]	Recovery Ratio [-]	Permeate Conductivity [μS/cm]	Salt Rejection [-]
1	2	0.30	641	0.87
1	2	0.55	419	0.94
1	3	0.53	589	0.94
2	3	0.53	266	0.97
3-5	3	0.53	265-276	0.97

Conclusions

In this work we have validated models of batch RO energy consumption and revised previous estimates of energy savings achievable with a batch system. We have demonstrated the successful operation of a true batch system and shown that this configuration can indeed reduce energy consumption. Batch RO saves energy compared to a continuous system, but will also cost more to implement due to its increased complexity. Future work should identify the additional costs associated with batch RO in order to identify the operating conditions where batch RO will be an economically favorable option compared to conventional continuous RO.

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