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A compact hybrid batch/semi-batch reverse osmosis (HBSRO) system for high-recovery, low-energy desalination

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HIGHLIGHTS

- A new hybrid batch/semi-batch reverse osmosis (HBSRO) system.
- At high recovery, HBSRO has much smaller work exchange vessel than batch RO.
- Specific energy consumption of HBSRO is lower than that of batch RO at high recovery.
- HBSRO has high flexibility to adjust the recovery according to feed composition.
- HBSRO is a promising solution towards minimal liquid discharge.

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ABSTRACT

Batch reverse osmosis (RO) is a promising approach to high-recovery desalination. It has low energy consumption, but system size increases sharply with recovery because of the need for a large work exchange vessel. In this study, we propose a compact hybrid batch/semi-batch reverse osmosis (HBSRO) system incorporating aspects of each approach. HBSRO works in three phases, i.e. semi-batch pressurisation phase, batch pressurisation phase, and finally purge-and-refill phase. We analyse ideal and practical cases of HBSRO to gain understanding about the specific energy consumption (SEC) and size of the system. In the ideal analysis, HBSRO can halve the size of work exchange vessel while incurring just a 5% energy penalty compared to batch RO at all recoveries. In the practical case, accounting for non-idealities, HBSRO has lower SEC than batch RO at recovery over 0.9, because a smaller volume of work exchange vessel minimises the energy penalty of the purge-and-refill phase in HBSRO. The reduced volume not only makes HBSRO more practical, but also improves energy-efficiency through reduced losses. Thus, our study highlights that HBSRO is highly flexible, achieving high recovery, compact size, and low SEC – advantages that are especially important in minimal or zero liquid discharge applications.

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1. Introduction

Desalination harvests large fresh water resources from seawater and brackish water [1–3]. On-going increase in global desalination capacity is, however, raising concerns about its energy footprint [4–7]. Numerous studies have focused on how to improve the energy efficiency of desalination systems [5,6,8–13]. These studies can be categorised broadly as: (1) design of new desalination processes [11,12,14], (2) hybridization of conventional processes [10,15], and (3) retrofit in the existing processes [8,16]. Reverse osmosis (RO) is regarded as one of the most energy-efficient desalination technologies currently [5,6,17]. Most recently, constructed seawater and brackish water desalination plants use RO for this reason [5,18,19]. Nonetheless, the energy requirement to operate RO systems still exceeds the theoretical minimum; so the energy efficiency of the RO systems can in principle be further improved [4–6]. Recent studies regarding energy-efficient RO systems have been carried out corresponding to the above categories e.g. hybridization with nanofiltration [20,21] or pressure retarded osmosis [6,22–25], retrofit of energy recovery device (ERD) [8,26,27] or staged RO [8,9,28], and new RO configurations [13,29–32].

Another important trend is towards high-recovery desalination systems for the purpose of reducing ecological and environmental impacts [33,34]. Zero liquid discharge (ZLD) is a prominent option for the treatment of concentrated brine from desalination to avoid such impacts [35]. However, complete ZLD solutions are challenging because of high energy usage and cost [35–37]. Recently, minimal liquid discharge (MLD) has been proposed as an alternative to avoid excessive energy consumption and cost, while still retaining most of the ecological and environmental benefits of ZLD [38,39]. In MLD, efficient membrane-based desalination processes such as RO can be employed, unlike in ZLD which generally requires more energy-intensive thermal processes. Novel RO-based processes have been suggested for MLD, including low-salt-rejection reverse osmosis (LSRSO) [39], osmotically assisted RO (OARO) [38,40], and draw solution assisted RO (DSARO) [41]. However, these alternative processes are based on conventional continuous RO configurations, which have inherent efficiency limitations associated with the constant high feed pressure [4–6].

New configurations of batch RO and semi-batch RO (or closed-circuit desalination) have been proposed to improve the energy efficiency of RO [13,29]. Feed pressure in the RO systems is directly correlated to energy consumption, and the high energy efficiency in batch RO results from a gradual increase of pressure through the cycle of operation, such that the average feed pressure is relatively low [13,29–31,42]. Like batch RO, semi-batch RO also varies the feed pressure cyclically. However, semi-batch RO does not easily achieve an energy consumption lower than continuous two-stage RO, because the mixing effect in feed and concentrated brine streams upstream of the RO membrane modules generates entropy [6,13]. Therefore, the most prominent method for improving the energy efficiency of RO systems is batch RO, especially at high recovery as needed for MLD [4,29].

Several studies about batch RO have focused on filling the research gap between conceptual design and actual realisation. After the batch RO concept was proposed, two types of batch RO design, i.e. using a free-piston [31,43] or flexible bladder [30,44,45], were developed for practical realisation. Experimental validation of the batch RO system was carried out [30,31,43–45]; and non-ideal factors in batch RO were identified [43,46,47] and theoretically modelled [13,29,48,49]. Recent research has sought to extend the application of batch RO towards large-scale treatment of inland brackish water desalination [47] and full-scale system for seawater desalination [45,48]. These studies found that batch RO suffers the drawback of a large work exchange vessel (in the free-piston design) or large flexible bladder, when recovery over about 0.8 is required [45,47,48]. For example, a recent study showed that a pilot-scale, free-piston type batch RO system using a 1 m-long 8-inch RO module requires 64.6 L and 145 L of work exchange vessel to reach 0.8 and 0.9 recoveries respectively [47]. These volumes correspond to vessel lengths of 2 m and 4.5 m respectively if a 8-inch vessel is also used for the work exchanger. Such a large work exchanger not only raises the capital cost of the batch RO system, but also requires longer pipes which could increase salt retention and frictional pressure drops. It is desirable to reduce the size of the work exchange vessel in high-recovery batch RO for a practical and efficient design.

Semi-batch RO avoids this problem of large work exchange vessel. However, the semi-batch RO cannot avoid the problem of entropy generation [6,13]. The pros and cons of semi-batch RO are opposite to those of batch RO. Thus, these two approaches could be complementary in solving the problems of large work exchange vessel and energy minimisation. If a new hybrid batch RO/semi-batch RO (HBSRO) process were developed, it could be utilised for high-recovery desalination without high penalty of energy consumption (as occurs in semi-batch RO) and without large work exchange vessel (as needed in batch RO). In other words, the hybrid process could provide a compact and energy-efficient solution for MLD.

In this study, we introduce a HBSRO process to achieve high-recovery, energy-efficient desalination with a compact work exchange vessel. The structure of the paper is as follows. Section 2 introduces the concept and working principle of HBSRO based on a simplified and idealised representation. This is followed by a practical design example of the HBSRO using a free-piston and 8-inch spiral wound RO module. Mathematical models for HBSRO are developed using differential-algebraic equations (DAE). Models of semi-batch RO and batch RO are used for comparison with the HBSRO. Section 3 gives the results for the ideal and practical cases. Specific energy consumption (SEC) and reduced size of work exchange vessel in the HBSRO are calculated and compared with batch RO and semi-batch RO. A case study with a 8-inch pressure vessel is used to investigate practical implementation. Based on the results, operation strategies for HBSRO are recommended. Section 4 summarises the findings and general implications for HBSRO.

2. Process description and modelling

2.1. Rationale and working principles of HBSRO

HBSRO is conceptually represented by the membrane cell of Fig. 1. This stirred membrane illustrates, in an idealised manner, the basic working principles of batch RO, semi-batch RO, and HBSRO. A practical design of HBSRO will be introduced in Section 2.2. The HBSRO process integrates batch RO (Fig. 1a) and semi-batch RO (Fig. 1b) configurations in a single cycle. At the beginning of each cycle, semi-batch RO operation is employed in the HBSRO process (Fig. 1c). Solution is fed into the membrane cell at sufficient pressure to overcome osmotic pressure such that water permeates the RO membrane. The concentration inside the cell increases as salt from the incoming feed is added and retained during this semi-batch phase. When the concentration reaches a certain level, the operation switches from semi-batch phase to batch phase. In the batch phase, a piston in the membrane cell travels towards the membrane driven by a work input, while the water in the cell continues to permeate the membrane (Fig. 1d). After the piston reaches a certain intermediate position, the cell is purged of residual concentrated brine and finally refilled with fresh feed solution, thus completing the batch RO phase. Through these working principles, a single cycle of the HBSRO process is completed.

A membrane cell, though useful to explain the working principles, is not a practical approach to industrial batch and semi-batch RO because the membrane area is too small. Instead, a commercial RO module (such as spiral wound type) should be used, with the function of the stirrer provided by a recirculation pump. For batch RO, the function of the piston is provided externally to the membrane cell by a work exchange vessel as shown in Fig. 2 (A flexible bladder can also provide this same function) [30,45,47]. At the start of the batch RO cycle, the work exchange vessel (or flexible bladder) and the RO module contain feed solution. Upon pressurisation (by pushing the free-piston or supplying
feed water to the initially empty bladder), the feed solution permeates the RO membrane, such that the amount of permeate in each batch RO cycle is the same as the internal volume of the work exchange vessel (or flexible bladder) \[^{[30,45,47]}\]. Concentrated brine remains in the RO module, and has to be purged in preparation for the next cycle. The recovery of the batch RO equals the volume of the work exchange vessel (or flexible bladder) divided by the sum of the volumes of the RO module and the work exchange vessel (if neglecting the volume of connecting pipes) \[^{[47]}\]. Because the volume of the commercial RO module is fixed, the work exchange vessel (or flexible bladder) must have a very large internal volume to achieve high recovery.

In the HBSRO process, the required volume of the work exchange is reduced by including a semi-batch phase before the batch RO operation. The feed solution is fed from the outside of the HBSRO system during the semi-batch phase, not from the work exchange vessel, unlike in the conventional semi-batch RO. The energy penalty caused by the semi-batch RO operation is minimised due to the existence of the work exchange vessel. Unlike the conventional semi-batch RO configuration, the suggested HBSRO process includes the work exchange vessel. The total volume of the HBSRO process including RO module, work exchange vessel, and pipes is significantly larger than the volume of the conventional semi-batch RO process (only including RO module and pipes). Thus, the concentration increase in the HBSRO process during the semi-batch RO operation is slower than in conventional semi-batch RO, so the concentration difference between the incoming feed and the recirculated brine during the semi-batch phase is reduced. Thus, the entropy generation by mixing during the semi-batch phase is minimised. This is the most remarkable feature of the HBSRO process. Compared to the conventional batch RO, HBSRO allows a compact design with minimum energy penalty associated with the initial semi-batch RO phase.

Fig. 2 shows how the theoretical minimum pressure (osmotic pressure) progresses in semi-batch RO, batch RO, and HBSRO processes. The horizontal axis is the instantaneous recovery i.e. the volume of permeate recovered so far as fraction of the total feed volume over the cycle \[^{[13]}\]. The area below each curve represents SEC. The osmotic pressure of semi-batch RO increases linearly, while that of batch RO rises at an increasing rate \[^{[13,42]}\]. These time variations in pressure arise from the corresponding variations in internal volume, mass and concentration illustrated in Fig. 3. In the case of HBSRO, the linear pressure increase in the semi-batch phase has a small gradient thanks to the work exchange vessel. The large system volume, including the work exchange vessel, slows the increase of concentration in the system for the same permeate flow rate. Thus, the energy penalty in the HBSRO is minimised. During the subsequent batch phase, the HBSRO has the minimum thermodynamic energy consumption theoretically. As shown in Fig. 2, the energy penalty in the HBSRO is determined by the proportion of the semi-batch phase to the total operation time of the HBSRO. There is a trade-off between the energy penalty and the reduced volume of work exchange vessel, according to the switch point from semi-batch to batch operation, as will be discussed in Section 3.

### 2.2. Practical design model of the HBSRO process

To realise the HBSRO system in detail, we propose a configuration with a RO module, a work exchange vessel, two pumps, and four valves (Fig. 4). This resembles the existing free-piston batch RO design, which has three valves \[^{[47]}\], modified by the addition of a fourth valve. Other configurations are possible, but this one is favoured for its simplicity. A detailed analysis of this design will allow prediction of the HBSRO performance in practical (and not just ideal) cases.

In the initial semi-batch phase, the bypass and recirculation valves are open, while the feed and purge valves are closed, allowing feed water to bypass the work exchanger and permeate the RO membrane (Fig. 4). Meanwhile the recirculation pump provides low differential pressure as needed to overcome friction in the RO module and connecting pipes. The concentration inside the recirculation loop increases continuously while permeate is produced, and the pressure increases to maintain permeate flux against the rising osmotic pressure. Because the feed valve is closed, the feed flow does not act on the left side of the free-piston, which thus remains at its leftmost position throughout the semi-batch phase. Once a certain amount of fresh water is produced through the semi-batch phase (as will be discussed in Sections 3.1 and 3.2), operation switches to the batch pressurisation phase.

The batch pressurisation and purge-and-refill phases are the same as in our previous design \[^{[29,47,50]}\]. After the bypass valve is closed and the feed valve is opened, the batch pressurisation phase begins. The
Fig. 2. Theoretical rationale of the HBSRO compared with the semi-batch RO and the batch RO. The SEC of each process is determined by the area under the pressure vs. instantaneous recovery curve in each case.
pressurised feed solution pushes the free-piston rightwards, transferring pressure to the solution located to the right of the piston and causing this solution to flow into the RO module and permeate the membrane. When the free-piston reaches the extreme right position, the batch pressurisation phase ends. Then, the recirculation valve closes, and the purge and bypass valve open to start the batch purge-and-refill phase.

During the batch purge-and-refill phase, the solution at the left end of the work exchange vessel is pumped to the right end, returning the free-piston to the left. Meanwhile, the concentrated brine inside the recirculation loop is purged by the feed pump. In this phase, only small pressures from the feed and recirculation pumps are required, just enough to overcome friction inside the pipes and RO module. There is no permeate stream, as pressure is released by the purge valve. The end of purge-and-refill is triggered by a drop in concentration of the rejected brine. The purge and feed valves close, and the recirculation valve opens to restart the semi-batch phase of the next cycle. The cyclic operation of the HBSRO process is thus repeated indefinitely.

To maximise the benefit of the HBSRO process, it is important to determine carefully the point of switching from semi-batch to batch pressurisation phase. Also, non-ideal factors affecting the practical design should be considered. In the following sections, full mathematical modelling of the HBSRO process is developed.

### 2.3. Ideal modelling of batch, semi-batch, and HBSRO processes

#### 2.3.1. Ideal modelling of batch RO and semi-batch RO

Mathematical modelling of the semi-batch and batch RO systems has been carried out separately and then combined to represent the HBSRO system. For each of the three systems, both ideal and practical design cases are covered. The ideal case ignores losses, such as frictional pressure drop of cross flow in the RO module and pipes, and pore resistance across the RO membrane. In other words, the pressure required in the ideal cases is the same as the osmotic pressure of the recirculating solution. The area beneath the curve indicating SEC. The enclosed shaded area is the small energy penalty of HBSRO vs batch RO, and the secondary horizontal axis shows the volume saving in switching from hybrid to batch operation at $r_{sb}$.

The ideal SEC of conventional batch and semi-batch RO are given as [42]:

\[
SEC_{\text{BRO}} = \frac{\pi_{\text{feed}}}{r} \left( \frac{1}{1 - r} \right)
\]
\[ \text{SEC}_{\text{SBRO}} = \pi_{\text{feed}} \left[ 1 + \frac{r}{2(1-r)} \right] \]  

where \( \pi_{\text{feed}} \) is the osmotic pressure of feed stream and \( r \) is the recovery in each system. The subscripts \( \text{BRO} \) and \( \text{SBRO} \) denote batch RO and semi-batch RO, respectively.

### 2.3.2. Ideal modelling of HBSRO

In the HBSRO process, SEC is calculated by adding the energy consumptions of the three phases:

\[ \text{SEC}_{\text{HBSRO}} = E_{\text{sb}} + E_{\text{bp}} + E_{\text{br}} \]  

where \( E_{\text{sb}}, E_{\text{bp}}, \) and \( E_{\text{br}} \) are the energy consumptions of semi-batch, batch pressurisation, and batch purge-and-refill phases, respectively. The denominator above is the permeate volume, given by the sum of the required feed volumes \( V_{\text{sb}0} \) and \( V_{\text{b}0} \) of the semi-batch and the batch pressurisation phases respectively.

The energy consumption of the semi-batch phase is calculated using Eq. (2) as:

\[ E_{\text{sb}} = \frac{V_{\text{b}0} \pi_{\text{feed}}}{V_{\text{sb}0} + V_{\text{b}0}} \left[ 1 + \frac{r_{\text{sb}}}{2(1-r_{\text{sb}})} \right] \]  

The recovery in the semi-batch phase of the HBSRO process is defined as:

\[ r_{\text{sb}} = \frac{V_{\text{b}0}}{V_{\text{sb}0} + V_{\text{b}0} + V_{\text{m}}} \]  

where \( V_{\text{m}} \) is the volume inside the RO module, and \( r_{\text{sb}} \) is the recovery at the semi-batch phase of the HBSRO process. \( r_{\text{sb}} \) is larger than in conventional semi-batch RO because of the work exchange vessel.

Following Eq. (1), the energy consumption and recovery of the batch pressurisation phase of the HBSRO process are given as:

\[ E_{\text{bp}} = \frac{V_{\text{b}0} \pi_{\text{bp,feed}}}{r_{\text{bp}} \ln \left( \frac{1}{1 - r_{\text{bp}}} \right)} \]  

\[ r_{\text{bp}} = \frac{V_{\text{b}0}}{V_{\text{b}0} + V_{\text{m}}} \]  

\[ \pi_{\text{bp,feed}} = \pi_{\text{feed}} \left[ 1 + \frac{r_{\text{sb}}}{2(1-r_{\text{sb}})} \right] \ln \left( \frac{1}{1 - r_{\text{bp}}} \right) \]  

where \( \pi_{\text{bp,feed}} \) is the osmotic pressure of feed solution at the batch pressurisation phase and \( r_{\text{bp}} \) is the recovery at the batch pressurisation phase. Because the batch pressurisation phase begins after finishing the semi-batch phase, \( \pi_{\text{bp,feed}} \) is higher than \( \pi_{\text{feed}} \). The increased osmotic pressure of the feed solution is expressed using Eq. (8). By combining Eqs. (6) and (8), \( E_{\text{bp}} \) is calculated as:

\[ E_{\text{bp}} = \frac{V_{\text{b}0} \pi_{\text{bp,feed}}}{r_{\text{bp}} (1 - r_{\text{bp}}) \ln \left( \frac{1}{1 - r_{\text{bp}}} \right)} \]  

During the batch purge-and-refill phase, the feed and recirculation pumps supply the pressure required to overcome the pressure drops in the RO module and pipes. However, in this ideal case, the pressure drops are neglected; thus \( E_{\text{br}} = 0 \).

Then, SEC in the HBSRO process is obtained by combining Eqs. (3),...
(4), and (9):

$$SEC_{HBSRO} = \frac{V_{\text{sb}} \pi_{\text{rec}} \left[ 1 + \frac{r_{\text{sb}}}{V_{\text{sb}}} \right] + \frac{V_{\text{sb}} \pi_{\text{rec}}}{\eta_{\text{rec}}} \ln \left( 1 - r_{\text{sb}} \right)}{V_{\text{sb}} + V_{\text{sb}}}$$  \hspace{1cm} (10)

Using Eqs. (A3), (A6), and (A7) in Supporting Information Appendix A, Eq. (10) is rearranged as:

$$SEC_{HBSRO} = \frac{\pi_{\text{rec}}}{\eta_{\text{rec}}} \left[ \frac{r - r_{\text{sb}}}{2} \left( \frac{1}{1 - r_{\text{sb}}} + 1 - r_{\text{sb}} \right) + \frac{1}{r_{\text{sb}} - 1} \right]$$  \hspace{1cm} (11)

$$V_{\text{sb}}$$ is given by Eqs. (A6) and (A7):

$$V_{\text{sb}} = V_{\text{sb}} \frac{r - r_{\text{sb}}}{r_{\text{sb}}(1 - r)}$$  \hspace{1cm} (12)

Thus, SEC of the HBSRO process can be expressed as a function of the overall recovery ($r$) and the recovery in the batch pressurisation phase ($r_{\text{bp}}$). Eqs. (11) and (12) show the energy and design characteristics of the HBSRO process, allowing comparison with conventional batch RO and semi-batch RO. The extreme cases of the HBSRO process are the same as the batch RO and semi-batch RO cases: putting $r = r_{\text{bp}} = r_{\text{sb}} = 0$ in Eqs. (11) and (12), gives the equations of semi-batch RO, with $V_{\text{sb}}$ becoming zero. Therefore, the characteristics of HBSRO are between those of batch and semi-batch RO, such that HBSRO can be tuned by varying the switch point, $r_{\text{bp}}$.

### 2.4. Practical modelling of batch, semi-batch, and HBSRO processes

In the practical case, non-ideal correction factors including concentration polarisation, salt retention factor, longitudinal concentration gradient, pore friction across the RO membrane, flow friction factors along the RO module and pipes, and pump inefficiency must be included to provide a realistic assessment of the SEC of each RO configuration.

#### 2.4.1. Non-ideal analysis of HBSRO

As in the ideal case, Eq. (3) gives the SEC; however, the energy terms in the numerator must be increased to account for losses in the non-ideal case. To estimate the practical energy consumption of the HBSRO, non-ideal correction factors including concentration polarisation, salt retention factor, longitudinal concentration gradient, pore friction across the RO membrane, and flow friction factors along the RO module and pipes should be included. Then, the expressions for each energy term in Eq. (3) are [47]:

$$E_{\text{fb}} = \frac{1}{\eta_{\text{feed}}} \int_{t_{\text{in}}}^{t_{\text{fb}}} \frac{P_{\text{feed}} Q_{\text{feed}}}{V_{\text{feed}}} \Delta t + \frac{1}{\eta_{\text{rec}}} \int_{t_{\text{in}}}^{t_{\text{fb}}} \frac{P_{\text{rec}} Q_{\text{rec}}}{V_{\text{rec}}} \Delta t$$  \hspace{1cm} (13)

$$E_{\text{bp}} = \frac{1}{\eta_{\text{feed}}} \int_{t_{\text{in}}}^{t_{\text{bp}}} \frac{P_{\text{feed}} Q_{\text{feed}}}{V_{\text{feed}}} \Delta t + \frac{1}{\eta_{\text{rec}}} \int_{t_{\text{in}}}^{t_{\text{bp}}} \frac{P_{\text{rec}} Q_{\text{rec}}}{V_{\text{rec}}} \Delta t$$  \hspace{1cm} (14)

$$E_{\text{sb}} = \frac{P_{\text{feed}}(V_{n} + V_{\text{pipe}})}{\eta_{\text{feed}}} + \frac{P_{\text{rec}} V_{n}}{\eta_{\text{rec}}}$$  \hspace{1cm} (15)

where $\eta_{\text{feed}}$ and $\eta_{\text{rec}}$ are the feed and the recirculation pump efficiencies respectively, $P_{\text{feed}}$ and $P_{\text{rec}}$ are the pressures applied by the feed and the recirculation pumps respectively, $Q_{\text{feed}}$ and $Q_{\text{rec}}$ are the feed and the recirculation flow rates, $t_{\text{fb}}$ and $t_{\text{bp}}$ are the durations of the semi-batch phase and the batch pressurisation phases respectively, and $V_{\text{pipe}}$ is the pipe volume of the purge region as described in Fig. S1 in Appendix B (Supporting Information). $Q_{\text{feed}}$ is held constant to maximise efficiency [51]. $Q_{\text{rec}}$ in Eqs. (13) and (14) will be represented as a recirculation flow rate ($\alpha$) divided by $Q_{\text{feed}}$ during the pressurisation phases (first and second phases). It should be noted that, in the final purge-and-refill phase, $Q_{\text{rec}}$ is increased to $Q_{\text{rec}} V_{\text{sb}}/(V_{n} + V_{\text{pipe}})$ to finish the purge and the refill simultaneously [47].

Durations $t_{\text{fb}}$ and $t_{\text{bp}}$ can be obtained from $Q_{\text{feed}}$ and the feed volumes required in each phase ($V_{\text{fb}}$ and $V_{\text{bp}}$). $V_{\text{fb}}$ and $V_{\text{bp}}$ are calculated using Eqs. (A4) and (A5) in Appendix A. However, these equations should be modified to consider the pipe volume in the practical design model (detailed information is described in Appendix B and Fig. S1). Then, $t_{\text{fb}}$ and $t_{\text{bp}}$ are expressed as follows:

$$t_{\text{fb}} = \frac{V_{n} + V_{\text{pipe}}}{Q_{\text{feed}}} \left( \frac{r_{\text{fb}} - r_{\text{bp}}}{1 - r_{\text{bp}} - r_{\text{fb}}} \right)$$  \hspace{1cm} (16)

$$t_{\text{bp}} = \frac{V_{n} + V_{\text{pipe}}}{Q_{\text{feed}}} \frac{r_{\text{bp}}}{1 - r_{\text{bp}}}$$  \hspace{1cm} (17)

Because $Q_{\text{feed}}$ is constant, $V_{\text{fb}}$ and $V_{\text{bp}}$ are given by $t_{\text{fb}} Q_{\text{feed}}$ and $t_{\text{bp}} Q_{\text{feed}}$, respectively.

$P_{\text{feed}}$ in semi-batch phase and batch pressurisation phase (Eqs. (13) and (14)) is calculated from the average osmotic pressure of the solution filled in the RO module, concentration polarisation factor, pore friction across the RO membrane, and RO membrane friction factor [47]. Note that because of the concentration dynamics in these kinds of batch RO systems (including semi-batch RO, batch RO, and HBSRO), input and output concentrations at time $t$ are not simply related by module recovery and concentration factor as they are in continuous RO.

$$P_{\text{feed}}(t) = C_{p} \left[ \frac{\pi_{\text{in}}(t) + \pi_{\text{out}}(t)}{2} \right] \frac{J_{w}}{A} \frac{\Delta P_{w}}{2}$$  \hspace{1cm} (18)

where, $C_{p}$ is the concentration polarisation factor, $\pi_{\text{in}}$ and $\pi_{\text{out}}$ are the osmotic pressures of inlet and outlet streams in the RO module, $J_{w}$ is the average water flux in the RO module, $A$ is the water permeability of the RO membrane, and $\Delta P_{w}$ is the pressure drop inside the RO module. Note that the arithmetic average of the osmotic pressure in the RO module can be justified due to the short length of the RO module (less than three 8-inch spiral wound modules in series) [47,52]. If the total length of RO modules is longer, this averaging approach may no longer be accurate. In future work, a more detailed numerical approach will be developed to cover all cases. The osmotic pressure of the solution is obtained from the van’t Hoff equation as follows [10,53]:

$$\pi = i C$$  \hspace{1cm} (19)

where, $i$ is the ionisation number, $C$ is the concentration, $R$ is the gas constant, and $T$ is the temperature. We developed dynamic modelling equations, based on algebraic-differential equations, to estimate the concentrations in HBSRO (Appendix B, Supporting Information), conventional semi-batch RO and batch RO (Appendix C, Supporting Information). The effects of salt retention factor and longitudinal concentration gradient on the solution concentration are included in the modelling equations. Then, $C_{\text{in}}$ and $C_{\text{out}}$ as needed to determine the osmotic pressures in Eq. (18), are calculated numerically by solving the equations in Appendices B and C.

Concentration polarisation is calculated in the conventional manner by the Sherwood analogy. $C_{p}$ denotes the osmotic pressure of the solution at the membrane surface over the osmotic pressure of the bulk solution.

$$C_{p} = \frac{\pi_{\text{in}}}{\pi_{\text{b}}} = \exp \left( \frac{J_{w}}{k} \right)$$  \hspace{1cm} (20)

where $J_{w}$ is a design input variable. Because the permeate water production rate ($Q_{\text{perm}}$) is equal to $Q_{\text{feed}}$ in the pressurisation phase, $J_{w}$ is equal to $Q_{\text{feed}}$ divided by the RO membrane area ($A_{mn}$). $k$ is the mass transfer coefficient, which is obtained from Sherwood number as follows [10,17,54]:

$$k = Sh \frac{D}{d_{p}}$$  \hspace{1cm} (21)

$$Sh = 0.2 Re^{0.57} Sc^{0.4}$$  \hspace{1cm} (22)
\[ Re = \frac{\rho v d_h}{\mu} \]  
\[ Sc = \frac{\mu}{\rho D} \]  

\[ \Delta P_m \] is the hydraulic diameter which is equal to half the feed channel height \[ [54] \], \( D \) is the diffusion coefficient, \( v \) is the cross-flow linear velocity in the RO module, \( \rho \) and \( \mu \) are the solution density and viscosity, respectively. \( v \) is obtained from an average velocity in the RO module. Because the inlet (Q_{m,in}) and outlet (Q_{m,out}) feed flow rate in the RO module is expressed by recirculation flow rate ratio \( (\alpha) \) as shown in Appendix B and Fig. S1, \( v \) is obtained as follows;

\[ v = \frac{(\alpha + 1)Q_{m,in} + \alpha Q_{m,out}}{2d_hw} \]  

where \( w \) is the membrane width.

\[ \Delta P_m \] can be expressed by using Hagen-Poiseuille equation as follows \([47]\);

\[ \Delta P_m = \frac{f_m \mu L}{d_h} \]  

where \( f_m \) is the friction factor in the RO module, which is determined from the experimental data in literature \([47,55]\), and \( L \) is the membrane module length.

\( P_{feed} \) in Eq. (15) and \( P_{recirc} \) in Eqs. (13)–(15) are obtained from the frictional pressure loss calculation. In our previous work, we calculated these pressure drops using resistance coefficient method including Darby’s 3-K method and Moody diagram \([47]\). The results revealed that the pressure drop in the pipes is almost similar to the pressure drop in the RO module (7.75 kPa for pipes and fitting compared to 8.91 kPa for the RO module). Also, the energy consumption required to overcome these pressure drops is less than 5% of the overall SEC. Thus, in this study, we assumed that the pressure drop in the pipes is the same as the frictional pressure loss in the RO module to avoid undue complexity in the energy calculation model. This is a reasonable assumption because the pressure drops in the pipes of HBSRO, batch RO, and semi-batch RO will be calculated and compared in Section 3 on the same basis. In the semi-batch and batch pressurisation phases, \( P_{recirc} \) in semi-batch and batch pressurisation phases is attributed to the frictional loss in the RO module and pipes. Thus, in the semi-batch and batch pressurisation phases, \( P_{recirc} \) is calculated as twice \( \Delta P_m \). In the batch purge-and-refill phase, \( P_{feed} \) is caused by the pressure drops in the RO module and short pipes in the region of \( V_{pipe,R} \) (Fig. S2, Supporting Information). However, the pressure drop in the short pipes is neglected for simplicity. \( P_{recirc} \) in the batch purge-and-refill phase is attributed to the pressure drop in the pipes, so \( P_{recirc} \) is approximately the same to \( \Delta P_m \). Then, \( P_{feed} \) in Eq. (15) and \( P_{recirc} \) in Eqs. (13)–(15) are listed in Eqs. (27)–(29).

\[ P_{feed} \cong \Delta P_m \] (in batch purge – and – refill phase)  

\[ P_{recirc} \cong 2 \Delta P_m \] (in semi – batch and batch pressurisation phases)  

\[ P_{recirc} \cong \Delta P_m \] (in batch purge – and – refill phases)  

Note that \( v \) for calculation of \( \Delta P_m \) is different in each situation. In Eqs. (28) and (29), \( Q_{recirc} \) is different as mentioned above. Thus, \( v \) and \( \Delta P_m \) should be calculated based on each \( Q_{recirc} \).

The differential equations in the Appendices were solved using DAE solver ‘ode15s’ in MATLAB R2017a. The integral in Eqs. (13)–(15) was calculated by using a trapezoidal rule.

### 2.4.2. Non-ideal analysis of batch RO

To compare the HBSRO with the conventional batch RO and semi-batch RO on the same basis, a consistent approach was taken to the practical design and modelling. SEC of the batch RO is expressed as follows:

\[ SEC_{BRO} = \frac{E_{br} + E_{rec}}{V_{in}} \]  

\[ E_{br} = \frac{1}{\eta_{feed}} \int_{0}^{\epsilon_{br}} P_{feed} Q_{feed} dt + \frac{1}{\eta_{recirc}} \int_{0}^{\epsilon_{br}} P_{recirc} Q_{recirc} dt \]  

\[ E_{rec} = \frac{P_{feed} (V_{br} + V_{pipe,R}) \eta_{feed}}{\eta_{recirc}} + \frac{P_{recirc} V_{in}}{\eta_{recirc}} \]  

\[ t_{bp} \] is obtained by the same approach as in Eq. (17), but \( r \) is used instead of \( t_{bp} \) as follows;

\[ t_{bp} = \frac{V_{br} + V_{pipe,R}}{\eta_{recirc} \left( \frac{r}{1-r} \right)} \]  

Then, \( V_{in} \) is calculated as \( t_{bp} Q_{feed} \). Eqs. (18)–(29) are utilised to calculate SEC_{BRO}, \( C_{in,in} \) and \( C_{in,out} \) in the batch RO are obtained by solving Eqs. (B12), (B14), and (C1) numerically (in Supporting Information).

### 2.4.3. Non-ideal analysis of semi-batch RO

To simulate the conventional semi-batch RO and calculate SEC_{SBRO}; the energy modelling equations are developed as follows:

\[ SEC_{SBRO} = \frac{E_{sb} + E_{rec}}{V_{in}} \]  

\[ E_{sb} = \frac{1}{\eta_{feed}} \int_{0}^{\epsilon_{sb}} P_{feed} Q_{feed} dt + \frac{1}{\eta_{recirc}} \int_{0}^{\epsilon_{sb}} P_{recirc} Q_{recirc} dt \]  

\[ E_{rec} = \frac{P_{feed} (V_{sb} + V_{pipe,R}) \eta_{feed}}{\eta_{recirc}} \]  

\[ t_{sb} \] is obtained in Eq. (C7) from Supporting Information. \( E_{br} \) is the energy consumption for purge and refill in the semi-batch RO. Unlike the batch RO or HBSRO, there is no retained region during the purge phase in the semi-batch RO, and only feed pump drives to purge the concentrated brine and refill the new feed solution in the system volume \( (V_{in} + V_{pipe,R}) \). Then, Eqs. (18)–(29) are also utilised to calculate SEC_{SBRO}; \( C_{in,in} \) and \( C_{in,out} \) in the semi-batch RO are obtained by solving Eqs. (C2), (C4), and (C8) numerically.

### 3. Results and discussion

The modelling assumes dilute solutions, such that the osmotic pressure is proportional to the salt concentration. This is valid for many sources of feed water at low and moderate concentrations, including most sources of brackish groundwater. The feed stream is assumed to be NaCl aqueous solution with concentration of 3 kg/m³ and temperature of 25 °C, representing brackish water. The modelling is based on a system using a single 8-inch RO module. These assumptions provide a consistent basis for comparison within this study and with earlier works \([47]\).

#### 3.1. Energy and feasibility analysis of HBSRO in the ideal case

The results of SEC and second law efficiency depending on the total recovery of the hybrid process, \( r \), and the recovery of the batch phase alone, \( t_{bp} \), are shown in Fig. 5a and b. The second law efficiency is calculated as \( SEC_{BRO}/SEC_{SBRO} \), because SEC_{BRO} in the ideal case is the theoretical minimum energy of separation. As mentioned in Section 2.3, \( r_{bp} \) is varied from 0 (pure semi-batch) to \( r \) (pure batch operation). SEC decreases with increasing \( r_{bp} \) (Fig. 5a). As previous studies reported, the SEC of batch RO and semi-batch RO are the same at \( r = 0 \), but diverge as recovery increases with batch RO becoming advantageous (Fig. 5a and b) \([13,42,49]\). In the HBSRO process, however, it should be noted that we can select an energy efficiency by adjusting \( r_{bp} \). As \( r_{bp} \) decreases, SEC increases, while the size of the work exchanger decreases. Thus, the
The HBSRO process is flexible in allowing us to choose the desired trade-off between energy efficiency and design compactness. The benefit of the HBSRO process is shown in more detail in Fig. 5 c and d. With the conventional batch RO at $r = 0.95$, the SEC is 0.2079 kWh/m$^3$ (second law efficiency = 1) and the required volume of work exchange vessel ($V_{bo}$) is 275.7 L. If the HBSRO process is used at the same overall recovery ($r = 0.95$) and $r_{bp}$ selected as 0.87, the $V_{bo}$ is reduced to 97.1 L and the SEC is increased to 0.2184 kWh/m$^3$ (second law efficiency = 0.9517). Thus, $V_{bo}$ is three times smaller, with just a 5% energy penalty. Fig. 5d shows that, while keeping second law efficiency in the range 0.9–1, in the range $r = 0.75–0.95$ HBSRO has much smaller $V_{bo}$ than the simple batch RO system, while it is also substantially more energy-efficient than the semi-batch RO system.

### 3.2. Energy and feasibility analysis of HBSRO in the practical case

The practical feasibility of the HBSRO, including non-ideal factors, is assessed with the help of the mathematical modelling equations of Section 2.4 (and Appendices B and C in Supporting Information). The simulation conditions and design parameters used in this study are summarised in Table 1. The BWRO membrane module in this study is a high-permeability type (DuPont XLE-440) with maximum operating pressure of 4136 kPa. Water flux can be calculated by $Q_{feed} \cdot r / A_m$, and the water flux is maintained during the productive operation time (pressurisation phase) in the batch RO, semi-batch RO, and HBSRO. The water flux at each recovery is fixed regardless of the process configuration thus allowing a fair comparison. Diffusion coefficient, density, viscosity, and ionisation number of NaCl solution are obtained from the

| Name                              | Value (unit) | Name                              | Value (unit) |
|-----------------------------------|--------------|-----------------------------------|--------------|
| Feed salinity ($C_{feed}$)        | 3 (kg/m$^3$) | Feed temperature ($T_{feed}$)     | 298.15 K     |
| Feed flow rate ($Q_{feed}$)       | $2.5 \times 10^{-4}$ (m$^3$/s) | Pipe volume ($V_{pipe}$)          | 1.708 (L)    |
| Pipe volume in purged region ($V_{pipe,p}$) | 0.285 (L) | Pipe volume in retained region ($V_{pipe,r}$) | 1.423 (L) |
| Pipe diameter                      | 2.692 $\times 10^{-2}$ (m) | Recirculation flow rate ratio ($\alpha$) | 3 (--)      |
| Volume of RO module ($V_m$)       | 15.8 (L)     | RO membrane area ($A_m$)          | 40.8 (m$^2$) |
| Longitudinal dispersion factor ($\lambda$) | 0.08 (--)  | RO module width ($w$)             | 40 (m)       |
| RO module length ($L$)             | 1.02 (m)     | Hydraulic diameter of RO module ($d_k$) | $2.31 \times 10^{-11}$ (m/Pa/s) |
| Water permeability ($A$)           | $2.31 \times 10^{-11}$ (m/Pa/s) | Feed pump efficiency ($\eta_{feed}$) | 0.7 (--)    |
| Friction factor in the RO module ($f_m$) | 0.08 (--)    | Recirculation pump efficiency ($\eta_{recir}$) | 0.5 (--)    |

Fig. 5. SEC and second law efficiency for desalination of feed solution at salinity of 3 kg/m$^3$. (a) SEC depending on $r$ and $r_{bp}$, (b) second law efficiency depending on $r$ and $r_{bp}$, (c) SEC depending on $V_{bo}$ in the HBSRO process, and (d) second law efficiency depending on $V_{bo}$ in the HBSRO process.
literature [17,47,56,57]. It is initially assumed that batch RO, semi-batch RO, and HBSRO have the same length of pipes, while the pipe bore was fixed at $0.0269$ m, so $V_{\text{pipe}}$ is the same in each case.

The results are shown in Fig. 6. To compare the HBSRO with the conventional batch RO and semi-batch RO processes, Fig. 6a gives the SEC breakdown for each process at $r = 0.8$. Note that the pressurisation phase in HBSRO includes both the semi-batch and batch pressurisation phases. The practical SEC of each process is $0.3865$ kWh/m$^3$ (batch RO), $0.4862$ kWh/m$^3$ (semi-batch RO), and $0.3880$ kWh/m$^3$ (HBSRO with $0.5 \times V_{b0}$ meaning that the work exchanger size is half that in the pure batch system), respectively. Semi-batch RO requires the highest SEC for brackish water desalination due to the additional entropy generation by

![Energy analysis and feasibility assessment results of HBSRO in the practical non-ideal case.](image)

(a) SEC breakdown with $3$ kg/m$^3$ of $C_{\text{feed}}$ and $0.8$ of recovery for batch RO, semi-batch RO, and HBSRO with $0.5 \times V_{b0}$ which means that the HBSRO has a half of work exchanger volume compared to the batch RO. SEC of the ideal case is overlaid to represent the increased inefficiency owing to the non-ideal correction factors. (b) SEC depending on the recovery ($r$) in batch RO, semi-batch RO, and HBSRO with $0.5 \times V_{b0}$. (c) SEC depending on $r$ in HBSRO with different volume of $V_{b0}$. SEC of Batch RO represents the case of HBSRO with $1.0 \times V_{b0}$. (d) SEC difference between the batch RO and HBSRO with $0.5 \times V_{b0}$. (e) $P_{\text{feed}}$ of batch RO, semi-batch RO, and HBSRO with $0.5 \times V_{b0}$ in a single operation cycle (at $r = 0.9$). Osmotic pressure is also displayed to show the theoretical minimum pressure in each process. In the HBSRO, the time of change from the semi-batch phase to the batch pressurisation phase is shown by the text box ‘switch’. (f) The required volume of and the corresponding length of 8-inch commercial work exchange vessel in the cases of batch RO ($V_{b0}$), HBSRO with $0.5 \times V_{b0}$, and HBSRO with $0.3 \times V_{b0}$.

Fig. 6. Energy analysis and feasibility assessment results of HBSRO in the practical non-ideal case.
continuous mixing as mentioned in the Introduction.

The semi-batch phase of HBSRO consumes additional energy such that total SEC for pressurisation is higher at 0.3863 kWh/m³ compared to only 0.3806 kWh/m³ for batch (r = 0.8). However, the overall SEC of the two processes is almost equal, because the SEC of the purge-and-refill phase (negliged in the ideal case) in batch RO is higher than in HBSRO due to the larger V₀₀ in the former. Large V₀₀ means energy is spent in transferring rapidly a large volume of feed solution from one end to the other of the work exchange vessel. At reduced transfer flow rate, the elapsed time of the purge-and-refill phase would be longer and the production rate would be compromised. In HBSRO, V₀₀ can be adjusted depending on the requirements. The energy penalty in the pressurisation phase is modest and offset by the lower flow rate of the purge-and-refill phase. This advantage becomes significant at increasing recovery as shown in Fig. 6b. At recovery over 0.89, SEC of HBSRO with 0.5 × V₀₀ becomes lower than that of batch RO. The results reveal that HBSRO can improve the practicality of the design, by reducing the size of work exchange vessel significantly while maintaining the high energy efficiency of the batch RO for high-recovery desalination and brine concentration.

Given the current energy and environmental concerns, the importance of energy-efficient desalination and of MDL or ZLD systems with high recovery has been emphasized repeatedly [7,13,35,36,39,58]. The HBSRO has the potential to be an energy-efficient desalination system at high recovery has been emphasized repeatedly [7, 13, 35, 36, 39, 58]. The required length of the 8-inch pressure vessel for a work exchange vessel as shown in Fig. 7a and b. At r = 0.8, the required length of the 8-inch pressure vessel is 4.75 m (HBSRO with 0.5 × V₀₀), and 2.85 m (HBSRO with 0.3 × V₀₀). As discussed in Fig. 6c, the energy penalty caused by the initial semi-batch operation phase is minor.

3.3. Case study to assess the feasibility of the HBSRO by changing the length of work exchange vessel and the membrane water permeability

As discussed in Section 3.2, a large volume V₀₀ is required for batch RO at high recovery. The utilisation of a commercial pressure vessel for the work exchanger requires excessive length. In Section 3.2, the elongated pipes needed by such a long work exchange vessel were not considered. To assess the practical feasibility of the HBSRO with a commercial pressure vessel, we investigate the effect of elongated pipes on SEC with a baseline design of batch RO (developed in our previous study [47]). The baseline design used a 8-inch RO module and 9.5-inch pressure vessel for a work exchange vessel as shown in Fig. 7a and b. At r = 0.8, the required volume and length of the 9.5-inch work exchange vessel are 64.2 L and 1.4 m, respectively [47]. In this section, we assumed that the length of work exchange vessel in the batch RO would be elongated from 2.0 m to 6.7 m corresponding to the increased r (0.85–0.95) (Fig. 7a). Meanwhile, the length of work exchange vessel in the HBSRO is fixed at 1.4 m regardless of r (Fig. 7b). The parameters of pipes in Table 1 were obtained from the pipeline diagram of the base batch RO system at r = 0.81 [47]. Thus, we assumed that the length of the elongated pipes is proportional to the volume of V₀₀ of the batch RO at r = 0.8 (64.2 L). We also assumed that the pressure drop Precp in the elongated pipes increases in proportion to length.

The results are shown in Fig. 7c. As the recovery increases, the pipes...
become very long to connect the elongated work exchange vessel, so energy consumption in the purge-and-refill phase is increased by the large pressure drop in the long pipes. The pipe pressure drop in batch RO and HBSRO are also compared in Fig. 7c. As the recovery increases, the increased \( V_{50} \) needs a higher flow rate of the recirculation pump in the purge-and-refill phase. Also, the length of pipes is elongated depending on \( V_{50} \) at high recovery. The higher flow rate and longer pipes increase the pressure drop almost exponentially, as shown in Fig. 7c. The large pressure drop requires high \( P_{\text{recir}} \) in the purge-and-refill phase. This is not a desirable situation, causing additional inefficiency in the batch RO.

However, SEC in the HBSRO is less than that of the batch RO at high recovery (over 0.85) owing to the shorter length of the pipes and the smaller volume of work exchange vessel. Furthermore, Fig. 7c shows that HBSRO can increase the recovery without increasing the size of
work exchange vessel. Note that it may be possible to avoid the elongated pipe length by using multiple vessels in a parallel arrangement as in [50]. However, multiple work exchangers also tend to increase the complexity of pipework introducing further possible salt retention and flow balancing issues.

To investigate the potential of HBSRO with development of membrane technology, SEC of batch RO and HBSRO were calculated by increasing membrane water permeability up to three times above today’s typical values. Fig. 7d shows that HBSRO can achieve SEC lower than 0.6 kWh/m³ at 0.95 recovery and 0.45 kWh/m³ at 0.9 recovery with improved membrane technology. The SEC of brackish water RO is normally around 0.5–1.5 kWh/m³, and the recovery is usually less than 0.8 [3,60,61]. According to these results, HBSRO is a good candidate for desalination systems with high recovery and high energy efficiency, and the potential will grow as RO membrane technology advances.

3.4. Recommended operating strategy for effective utilisation of the HBSRO

The HBSRO is a flexible system which can accommodate different volumes \( V_{b0} \) by changing the operation time of the semi-batch phase. There is flexibility to adjust the operation time of the semi-batch RO; and flexibility in the design specification of HBSRO to achieve a compact system. As shown in Fig. 8, \( V_{b0} \) depends on the switch point. At low recovery (Fig. 8a), HBSRO can reduce the operation time of the semi-batch phase to minimise the energy penalty in the semi-batch operation. At high recovery (Fig. 8b), the HBSRO can reduce the required volume of the work exchange vessel by extending the semi-batch phase. Despite the energy penalty in the semi-batch phase, HBSRO is more energy-efficient than batch RO due to the small \( V_{b0} \). This flexibility in design and operation is an important advantage of HBSRO compared to batch RO. Furthermore, the reduced size of work exchange vessel may be beneficial for technoeconomic analysis at large-scale system compared to batch RO. A technoeconomic analysis should be conducted in future work.

4. Conclusions

In this study, we have proposed a novel hybrid batch/semi-batch RO (HBSRO) to reduce the size of work exchange vessel at high recovery. A theoretical analysis of the ideal case has been conducted to assess the ideal performance of HBSRO compared to existing batch RO and semi-batch RO. We have also put forward a practical design for the HBSRO using a free-piston and 8-inch spiral wound RO module. It operates in three phases: semi-batch, batch pressurisation, and purge-and-refill phase. A mathematical model for simulating the performance of the HBSRO has been developed using algebraic-differential equations. The performance of the HBSRO has been investigated for desalination of brackish water at a concentration of 3 kg/m³ NaCl aqueous solution.

- HBSRO can be implemented simply by installing a single additional control valve in the batch RO configuration (alternatively a 3-port valve may be used in place of the bypass and feed valves, so that the number of valves is kept to three).
- In the ideal analysis, HBSRO reduces the volume of work exchange vessel significantly (by more than half) with just a minor energy penalty (less than 5%) compared to batch RO at all recoveries.
- In a practical design working above recovery of 0.9, HBSRO with work exchanger volume half that of batch RO gives slightly lower SEC than batch RO due to energy-saving in the purge-and-refill phase.
- At \( r = 0.95 \), batch RO would need a very large work exchange vessel (305 L) requiring a length of approximately 9.5 m (8-inch vessel) and 6.7 m (9.5-inch vessel). By using HBSRO, the volume of work exchange vessel can be just a half or a third that in pure batch RO. This reduced volume makes the HBSRO system more compact and practical.
- HBSRO is a flexible system in which the operation time of the initial semi-batch phase can be adjusted to satisfy given requirements. For low recovery, a short semi-batch phase is desirable to minimise the energy penalty. On the other hand, a longer semi-batch phase is preferred for high recovery desalination to reduce \( V_{b0} \) and energy loss during the purge-and-refill phase.

Fig. 8. Schematic illustrations of recommended operation strategy in the HBSRO for (a) low recovery and (b) high recovery desalination systems. A shorter batch phase corresponds to a smaller volume \( V_{b0} \) of work exchange vessel.
Therefore, HBSRO can provide a much more compact desalination system than batch RO without losing the high energy-efficiency of batch RO at recovery over about 0.9, suggesting that HBSRO has potential to be implemented in high-recovery desalination for MLD and ZLD. In addition, HBSRO has flexibility to adjust recovery and system size. In conclusion, HBSRO is a high-recovery, compact, and low-energy consumption system.

CRediT authorship contribution statement

Kiho Park: Conceptualization, Methodology, Formal Analysis, Original Draft, Review and Editing.
Philip A. Davies: Conceptualization, Validation, Review and Editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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