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Batch Reverse Osmosis (RO) for High-Recovery and High-Efficiency Desalination of Brackish Groundwater

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Abstract: The demand for groundwater desalination is increasing with depletion of natural freshwater resources, over extraction, rising sea levels in coastal areas, and salinization. Groundwater desalination should achieve high recovery to minimise wastage, but conventional desalination for brackish groundwater incurs high specific energy consumption (SEC) at high recovery. Batch Reverse Osmosis (batch-RO) is designed to overcome this problem by providing both high recovery and high efficiency. It normally operates in three phases: pressurisation, purge and refill. A prototype batch-RO system has built almost entirely from off-the-shelf parts. It uses a double-acting configuration to eliminate the need for a separate refill phase. Laboratory tests have shown low hydraulic SEC of 0.2 kWh/m^3 but the overall electrical SEC is about 10 times higher due to losses. Further work to overcome the losses and reduce SEC to <1 kWh/m^3 is discussed.

Key words:

INTRODUCTION

Thedemand for desalination of brackish groundwater is increasing for several reasons. One reason is thedepletion of natural freshwater resources, which is making the need to access marginal brackish resources more pressing. Anotheris the tendency for groundwater to become increasingly salinized due to over-extraction and seawater intrusion. Rising sea level due to climate change is also contributing to this problem. Particularly in coastal regions, wells that were previously considered fresh are becoming saline. The coastal regions of Bangladesh provide a salient example of this [1]. Another example is the Upper Floridan Aquifer [2] where salinization has been exacerbated by low rainfall. Desalination of brackish water was reported to see a 29% increase in contracted capacity in the first half of 2017 [3].

Whereas desalination of brackish groundwater provides essential freshwater in the affected areas, groundwater resources are finite and should not be wasted. This means that is essential to maximise the recovery ratio from the desalination process. High recovery means that most of the extracted water is usefully converted to freshwater with only a smallfraction wasted in the brine reject stream. Unfortunately, current desalination technology incurs a high energy penalty when run at high recovery. The specific energy consumption (SEC) increases markedly at recoveries above 50%, rising well above that theoretically possible [4].

Batch-RO desalination has attracted interest as a highly efficient technique for desalination at high recovery [4-8]. Compared to continuous flow desalination without any energy recovery, batch-ROis about 3 times more efficient at 80% recovery. And it is about 1.5 times more efficient than its closest rival, semi-batch RO desalination[4]. However, batch-RO is a relatively undeveloped process with many of its theoretical and practical aspects still at an early stage of study. This paper therefore sets out to make contributions towards the mature development of this technology.

Batch-RO has been defined as a RO process where pressure is varied with time, rather than spatially in the system [4]. It is similar to semi-batch RO, also called closed-circuitRO, in that both processes maintain nearly uniform salinities internally by recirculation of a batch of water. The salinity increases gradually until reaching a maximum. Semi-batch RO, however, allows the incoming

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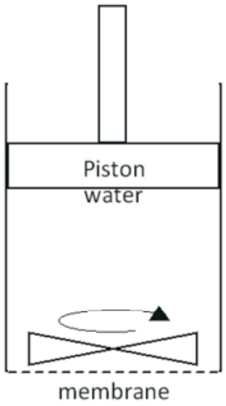
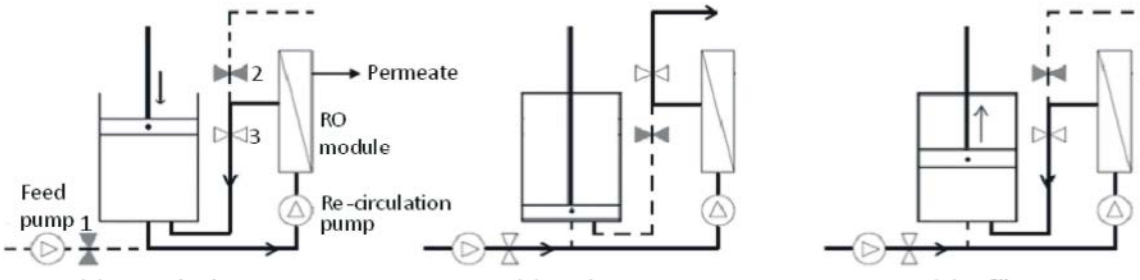


Fig. 1: Basic batch-RO system in the form of a stirred membrane cell.



(1) Pressurisation (2) Purging (3) Refill

Fig. 2: Batch-RO system intended for large output, with the RO module separate to the batch vessel to provide more area of membrane. The three phases of operation are shown [4].

feedwater to mix continuously with the batch of water already in the system. This mixing constitutes a thermodynamic irreversibility, which prevents the system from achieving the ideal maximum efficiency, whereas batch RO avoids this mixing [4, 7].

A drawback of both batch and semi-batch processes is the need to include additional vessels to hold the batch of saline water under pressure. In the case of the batch system, a means of displacing the water (without allowing it mix with the incoming feed) is also required. In this paper, we describe an approach to the construction of the batch system using standard RO pressure vessels which, being manufactured in large quantities, are relatively inexpensive. We show how batch systems can be constructed using mostly off-the-shelf components. Preliminary experimental results are presented and seen to be promising. Based on the experience so far, we indicate the further research needed to realise the full potential of the batch-RO concept.

Concept and Design Evolution: The basic concept of the batch RO process is well known in many small-scale laboratory membrane rigs. In its most basic form it consists of a stirred vessel, whose base is the RO membrane, and a piston to displace the water through the membrane (Figure 1). Sometimes compressed air is used to provide the action of the piston. This kind of device is not designed for large output or efficient operation, as the membrane area is very limited. Figure 2 shows an arrangement that provides a large output by incorporation of a separate membrane vessel with a low-pressure pump to recirculate the water. Thus, the recirculation fulfils the function of stirring i.e. to maintain homogeneity. Systems like this have been constructed using Rankine cycle engines to drive the piston [9]. The Rankine cycle takes its primary energy from a heat source. In this article, however, we will discuss systems that are electrically powered by means of a more conventional pump.

Generally, these batch systems operate cyclically in three phases: (1) a pressurisation phase yielding freshwater; (2) a purge phase to remove the residue of concentrated saline water (i.e. brine); and (3) a refill phase to replace it with a new batch of freshwater, allowing the cycle to start again. To allow an electrical pump to drive the system, the rodded piston of Figure 2 is replaced by a free piston as shown in Figure 3. The pump supplies

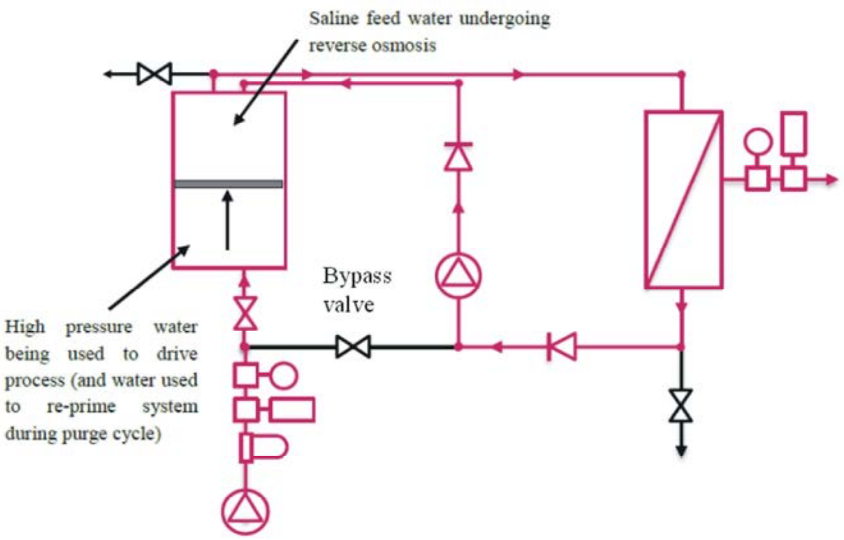


Fig. 3: Batch-RO system including a free piston, suitable for use with an electrically-driven pump, shown during the pressurisation phase of the cycle [5].

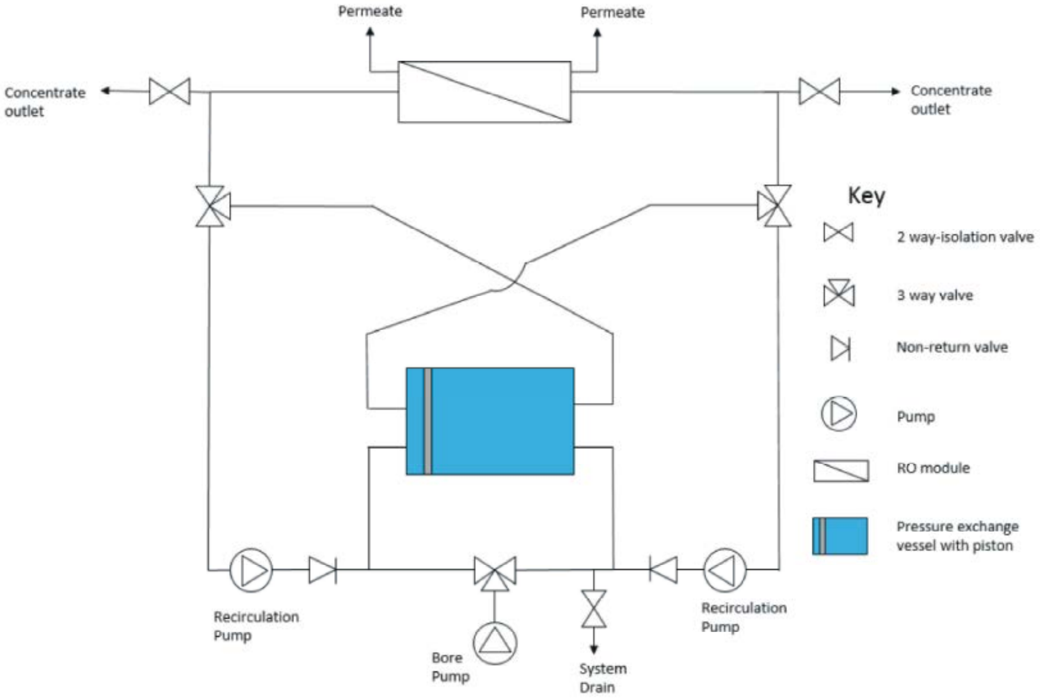


Fig. 4: Double acting batch-RO system with four phases of operation [6].

feed water to the upstream side of the piston, displacing water from the downstream side, for supply to the membrane – thus achieving the pressurisation phase. An arrangement of valves allows for purging by directing the feed water directly to the membrane module, bypassing the piston, for release through a separate purge valve. The convenient way to achieve the final refill stage is by using the low-pressure pump to displace water from the upstream to the downstream side of the piston, causing it to return to its initial position (i.e. at the bottom in Figure 3).

A drawback of the batch RO arrangement shown in Figure 2, is that only the first phase results in production of freshwater. Undesirably, the second and third phases correspond to 'wasted' time with no output.A design that reduces this downtime is shown in Figure 4 – the so called double-acting system. This design operates in a cycle of four phases i.e. pressurisation, purge, followed by (in the reverse direction) a second pressurisation, and then a second purge. There is no separate refill phase, as this is accomplished simultaneously with the pressurisation in each case. A putative secondary advantage of this design is that the continual reversal of flow helps to dislodge debris and thus minimise fouling inside the membrane module.

Experimental: Preliminary experiments have been carried out with a double-acting batch-RO system in the laboratory.

MATERIALS AND METHODS

The double-acting system was constructed using two 4x40-inch GRP pressure vessels (WaveCyber) connected by PVC pipework rated at 16 bar (Figure 5). The free piston was machined from high density polyethylene (HDPE) and fitted with an O-ring seal. The valves were of pressure-assisted solenoid type, controlled from a programmable logic controller (PLC). Pressure sensors (Telemecanique) were also connected to the PLC to measure the pressure at either side of the piston. When the piston reached an end of travel during pressurisation, the pressure rose higher on the feedside – triggering the start of the purge. The purge phase was timed to deliver a set volume of water, as determined by the analysis of reference [10]. An aluminium frame supported the system above the ground.

The high-pressure feed pump was a helical rotor type (GrundfosSQFlex 0.6-2) immersed in a 570 litre tank.At the beginning of the experiment, the tank was filled with tap water and sodium chloride added to achieve a set concentration (i.e. 1500 or 2000 ppm). About 3 g of sodium meta-bisulphite was also added to neutralise chlorine in the tap water. Experiments were conducted at 20 deg.C.

In operation, measurements were taken using measuring cylinders of permeate and purge volumes vs. time. Pressure was also recorded. Average concentrations of the solutions were determined using a conductivity meter. This allowed the amount of hydraulic pumping energy delivered to the rig to be calculated by integration of feed pump pressure against volume delivered. The electrical power and energy suppliedto the different components was also measured. Further experimental details may be found in reference [11].

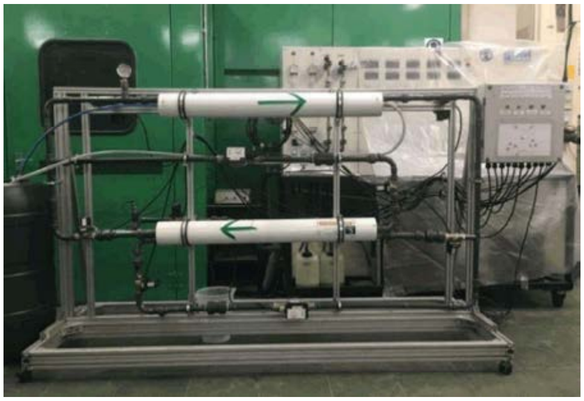


Fig. 5: Experimental double-acting batch RO system at Aston University.

Table 1: Summarised results from the double-acting batch RO system.

	Feed salinity	
	1500 ppm	2000 ppm
Recovery	70%	70%
SEC electrical (kWh/m^3)	1.76	2.62
SEC hydraulic (kWh/m^3)	0.21	0.19
Rejection	89%	81%
Output (m^3/day)	1.95	1.32

RESULTS

Figure 6 shows an example of the measured pressure vs. time and the theoretical osmotic pressure, which is substantially lower.

The results from the experiments conducted at different salinities are summarised in Table 1 below.

DISCUSSION AND CONCLUSIONS

The rather high difference between the electrical and hydraulic SEC is explained with the help of aSankey diagram (Figure 7).

Off the total power input of 143 W to the system, only 16.7 W ends up as hydraulic power at the pump. The losses were caused by several factors:

- Inefficient operation of the feedpump due to the low flow rate used, being well below the optimum duty of the pump. The pump was estimated to be working at about 20% efficiency only.
- Significant power consumption by the solenoid valves (17% of total power input).
- Significant power consumption by the recirculation pump (28% of total power input).

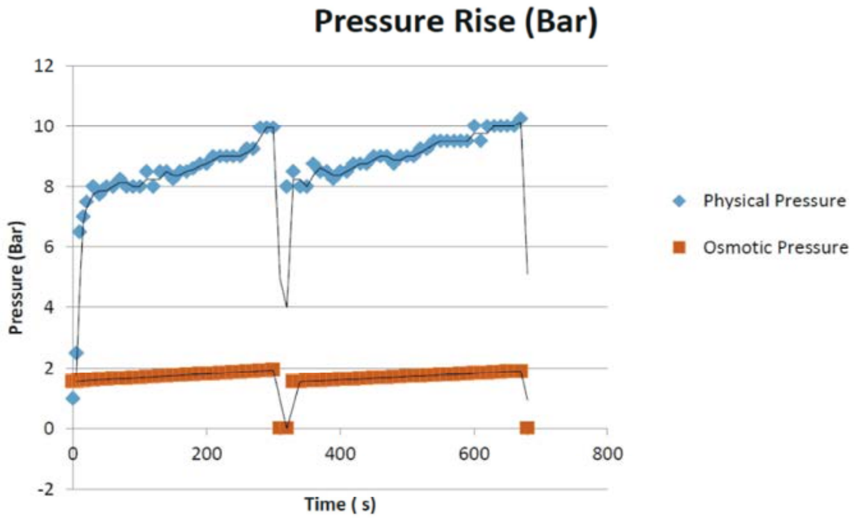


Fig. 6: Pressure vs time with 2000 ppm feed solution.

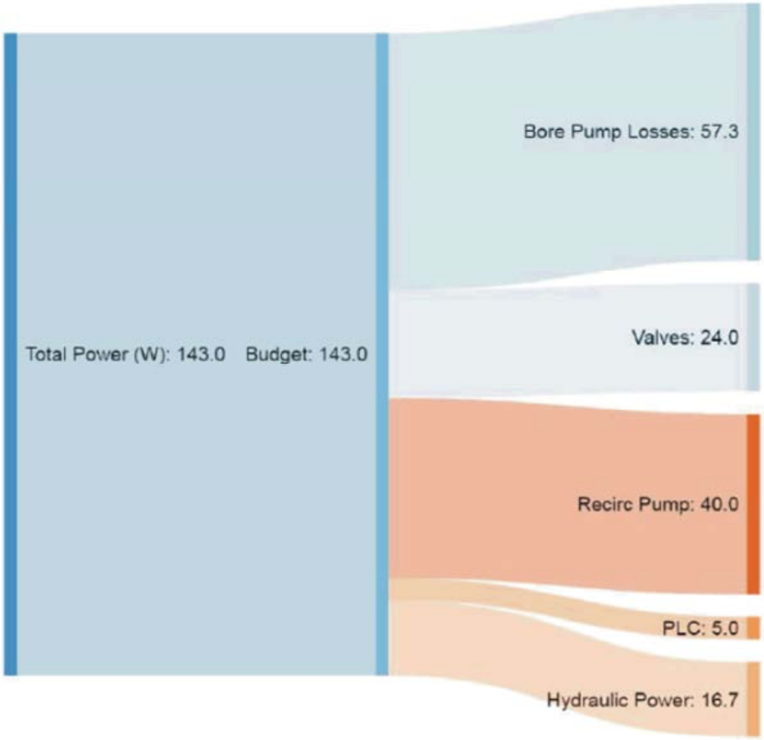


Fig. 7: Sankey diagram of power usage at 1500 ppm.

To achieve better SEC in future, it will be important to select a more efficient feed pump or run the feed pump at more efficient conditions. In practice, the low overall output of the system meant that it was difficult to find a more efficient pump. Instead, better pump efficiency can be achieved by scaling up the whole system. This will also reduce the percentage power consumption of the solenoid valves. Both pumps and valves benefit from efficiencies of scale. Therefore, the current work is focussing on developing a new version of the rig that will be larger in output. The design is also being simplified to reduce the number of valves, as practical experienced showed that valves add significant complexity and cost – as well as consuming power. With these improvements it is anticipated to achieve an electrical SEC below 1 kWh/m^3 and aiming for 0.5 kWh/m^3.

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