A desalination system with efficiency approaching the theoretical limits

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Abstract: The objective of this project is to design a new desalination system with energy efficiency approaching the theoretical thermodynamic limit even at high recovery ratio. The system uses reverse osmosis (RO) and a batch principle of operation to overcome the problem of concentration factor which prevents continuous-flow RO systems from ever achieving the theoretical limit except by using an infinite number of RO stages with inter-stage booster pumps. Batch operation comprises a cycle in 3 phases: pressurisation, purge and refill. To achieve maximum efficiency, no feed water is added to the pressure circuit during the pressurisation phase. Analysis shows that, compared to closed-circuit desalination, the new system should use 33% less energy at recovery=0.8. The system is powered by a positive displacement pump which may be driven by photovoltaic energy or by conventional energy. Energy recovery is inherent to the design. A prototype is being constructed and preliminary results will be presented from tests using brackish water. Future developments and applications of the system will be discussed.

Key words: solar, RO, brackish water, high recovery, high efficiency, sustainable development
Introduction

Efficient desalination systems are important for sustainable development. Access to improved drinking water has been included among the Millennium Development Goals, and thankfully the percentage of world population having such access increased from 76% in 1990 to 89% in 2012 (UN1). Nonetheless, this still leaves some 800 million people without access to clean water. The Millennium Development Goals, which officially run their term this year, are to be superseded by Sustainable Development Goals. According to Sachs2, overarching objectives of sustainable development should include economic prosperity and social inclusion for disadvantaged members of society. By boosting water supplies for drinking, cultivation of crops, and making water accessible to more people, desalination can contribute to the accomplishment of Sustainable Development Goals.

Nevertheless, desalination also presents difficulties as regards environmental sustainability – which is another important aspect of sustainable development. Among methods of supplying freshwater, it is among the most energy consumptive. It also produces harmful by-products of reject brine. Further, for inland applications especially, desalination can deplete groundwater sources. For these reasons it is required to: (1) reduce the energy consumption of desalination and to (2) increase the recovery of freshwater from the process.

These two requirements conflict. The energy usage of desalination depends on the free energy of mixing, and in turn on the osmotic pressure of the feedwater 3. The theoretical minimum specific energy consumption per m³ of freshwater (SEC) can, for dilute saline solutions, be conveniently expressed in terms of the osmotic pressure $P_{\text{osm}}$ and the recovery ratio $r$.

$$ SEC_{\text{ideal}} = \frac{1}{r} P_{\text{osm}} \ln \left( \frac{1}{1-r} \right) $$  

(Eq. 1)

The expression shows that the minimum SEC increases with osmotic pressure (which is approximately proportional to salt concentration) and with recovery ratio. (For concentrated solutions, Eq.1 becomes less accurate but these trends remain the same).

Detailed studies of real brackish water desalination plants have revealed that the SEC is actually many times higher than Eq.1 suggests 4,5. This is because there are many costs and considerations in designing and operating a water treatment plant, among which the energy of salt removal is just one consideration. Nevertheless, it is strategic to focus on energy reduction towards the theoretical minimum. The aims of this paper are to: (i) describe a desalination system which is capable in principle of achieving this minimum SEC; and (ii) report initial progress in constructing the prototype system.

Design rationale

In standard RO systems based on continuous flow an avoidable energy loss arises due to increase in concentration along the length of the membrane module. However much effort is given to the perfection of pumps, membrane materials and energy recovery devices, this loss remains unless the system is reconfigured to overcome the conflict requirements of: (a) exceeding the osmotic pressure at
all points in the module to ensure positive flux (b) exceeding it by only a minimal amount to avoid wasted energy consumption associated with excess pressure.

The conflict can be recognised as ‘contradiction’ in the terminology of TRIZ and is overcome by alternative strategies of spatial or temporal separation of functions.  

1. Spatial Separation: separate the system into consecutive modules each operating at optimised pressures simultaneously. Booster pumps are used between stages. For ideal performance, an infinite number of stages is theoretically required.

2. Temporal separation: only one stage is used but the pressure is varied with time to meet the osmotic pressure of the batch being processed. In principle ideal performance can be achieved in just one stage.

Researchers have already described batch RO systems as used in the second option, but for the most part these systems have focussed on a closed loop that is continually topped up with incoming pressured saline feedwater, to compensate for water passed through the RO membrane. As such these systems will not meet the theoretical minimum efficiency because the mixing of incoming saline water with more concentrated water in the loop is an irreversible process creating entropy of mixing and presenting a lost opportunity for energy recovery. Analysis of the batch system as described here suggests that, compared to closed-circuit desalination, the new system should use 33% less energy at recovery ratio of 0.8.

**Design concept of batch system**

Our concept consists in essence of a pressurised batch of fluid acting against a semi-permeable RO membrane. The pressure in the fluid is gradually increased to offset the increase in osmotic pressure. In principle this pressurisation can be achieved by a movement of a piston inside a cylinder (Figure 1). Once a certain amount of liquid has been extracted through the membrane, the liquid remaining in the cylinder is replaced by new feedwater. The discarded water fraction constitutes the reject brine from the process.

In practice it is not always convenient, however, to drive the process using a piston as shown in Figure 1. It may be more convenient to drive it using conventional pump. This is possible if a pump is used to drive pressurised feedwater against the reverse side of the piston. On the return stroke of the piston, the displaced liquid is then used to refill the cylinder for the start of the cycle. The corresponding sequence of operations is illustrated in Figure 2.
Figure 2: Arrangement and sequence of operation of the system: (a) pressurise, (b) purge, (c) refill.
Details of the design

Figure 3 shows a physical realisation of the schematic shown in Figure 2. An aluminium frame (dimensions 2.00 m high × 0.85m wide × 0.85 m deep) provided a stable platform for many of the test rig components. The bill of materials is included in Table 1 and the individual parts are now described in more detail.

![Prototype test rig](image)

**Figure 3:** Prototype test rig

<table>
<thead>
<tr>
<th>Table 1: Bill of Materials</th>
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<table>
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<tr>
<th>Components</th>
<th>Quantity</th>
<th>Components</th>
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</tr>
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<tbody>
<tr>
<td>4inch RO cylinder (Pressure exchange vessel)</td>
<td>1</td>
<td>PVC-U Union, 3/4 in x 3/4 in</td>
<td>10</td>
</tr>
<tr>
<td>2.5inch RO module</td>
<td>1</td>
<td>90° PVC-U Elbow, 3/4in x 3/4in</td>
<td>16</td>
</tr>
<tr>
<td>Bore hole pump (helical rotor type)</td>
<td>1</td>
<td>90° PVC-U Elbow, 1/2in x 1/2in</td>
<td>2</td>
</tr>
<tr>
<td>Recirculation Pump (central heating type)</td>
<td>1</td>
<td>PVC-U Reducer Bush, 3/4in x 1/2in</td>
<td>12</td>
</tr>
<tr>
<td>16bar Pressure gauge</td>
<td>2</td>
<td>PVC-U Manual ball valve 3/4in</td>
<td>5</td>
</tr>
<tr>
<td>Flow meter</td>
<td>2</td>
<td>PVC-U Manual ball valve 1/2in</td>
<td>2</td>
</tr>
<tr>
<td>HDPE rod (2000mm length; 110mm OD)</td>
<td>1</td>
<td>PVC-U Socket, 1/2 in Rp Female x 1/2 in Cement Male</td>
<td>5</td>
</tr>
<tr>
<td>PVC Pipe, 3/4 inch outer diameter</td>
<td>6m</td>
<td>Non Return Valve</td>
<td>2</td>
</tr>
<tr>
<td>PVC Pipe, 1/2 inch outer diameter</td>
<td>1m</td>
<td>PVC 3/4in Sockets</td>
<td>5</td>
</tr>
<tr>
<td>10 inch Water Filter Housing</td>
<td>1</td>
<td>3/4in Pipe clamps</td>
<td>30</td>
</tr>
<tr>
<td>PVC-U Equal Tee 3/4in x 3/4in</td>
<td>12</td>
<td>O-rings (ID: 91.44mm, CS:5.33mm)</td>
<td>6</td>
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<tr>
<td>PVC-U Equal Tee 1/2in x 1/2in</td>
<td>2</td>
<td>O-rings (ID: 7.59mm, CS:2.62mm)</td>
<td>2</td>
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<tr>
<td>PVC-U Union, 1/2in x 1/2in</td>
<td>5</td>
<td>O-rings (ID:16.6mm, CS:2.4mm)</td>
<td>2</td>
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</tbody>
</table>
Pressure exchange vessel and piston: A 4.0 inch diameter reverse osmosis pressure cylinder was repurposed to create a pressure exchange vessel, and house a cylindrical, high density polyethylene (HDPE) piston serving to isolate the batch of fluid undergoing reverse osmosis from that being used to drive the process.

![HDPE Piston](image)

*Figure 4: HDPE Piston*

In order to achieve different recovery ratios for the purpose of testing, three pistons of lengths 0.26 m, 0.62 m and 0.69 m were custom designed and manufactured. Figure 4 shows an example piston used, with various O-ring groove locations for flexibility.

Pressure differential sensor and electronics: A mechanical sensor was custom-built to prevent system over-pressureisation when the piston reached its end of travel. The assembly was specifically designed to electrically isolate the bore pump when the pressure differential across the pressure exchange vessel exceeded 1 bar. The sensor (Figure 5) principally comprised of a hollow tube with two hydraulic connections at either extremity; connected in parallel to the pressure exchange vessel. A plain, stainless steel rod, which had a piston at its centre, was connected to two angled switch plates at both ends.

When actuated, the piston and rod assembly moved along the tube in a direction dictated by the net pressure difference, until one of the switch plates contacted a push-to-break switch and stopped the pump. (See Figure 6 for the electric circuit). Two springs situated between the switch plates and sealing cap served two purposes: 1) to centralise the piston in the tube, and 2) control the actuation pressure.

![Pressure differential sensor](image)

*Figure 5: Pressure differential sensor*
A simple electronic circuit was developed in conjunction with the pressure differential sensor (Figure 6) consisting of:

- Main isolation switch – an on/off safety switch designed to initially start the bore pump and isolate the device in an emergency;
- Two pressure differential micro-switches (Push-to-break) – used to isolate the bore pump and prevent system over-pressurisation (actuated automatically when the pressure differential across the pressure exchange vessel exceeded 1 bar);
- Jog switch – a push-to-make switch used to override the two push-to-break switches (described above) and restart the system once the pressure differential sensor had been actuated;
- Recirculation Pump switch (On/Off) – used to start and stop the recirculation pump.

For simplicity, the test rig was designed to be primed and operated manually using only the described electronics system and a collection of manually-actuated ball valves. Later these may be replaced by electrically actuated valves.

**Recirculation Pump:** A small, repurposed, central heating pump served two purposes: 1) to recirculate the concentrate leaving the reverse osmosis module during pressurisation, and return it to the pressure exchange vessel, and 2) refill the pressure exchange vessel at the end of the pressurisation cycle.
Conclusions and further work

We have described a new type of RO system and built it using readily available components. It follows a batch principle which incorporates energy recovery and allows efficient operation without multi-staging. Recovery ratios up to 80% are anticipated. The system is suitable for use with PV panels and will be tested with a Solar Array Simulator initially. Brackish water solutions in the salinity range 2000–5000 ppm will be made up to simulate groundwater compositions reported in the literature. We will monitor water output and energy usage. Following monitoring of performance, the system will be improved and optimised. Due to possible uneven energy usage, an energy storage device like a battery or super-capacitor may be used in future designs to buffer the power supply from the PV panel. We hope to deploy the system in places of need where local artisans can carry out the construction to open-access plans published on-line, using locally sourced materials where possible. Nonetheless, certain components like the RO membranes and borehole pumps are likely require specialised suppliers. It is also possible to design the system for seawater desalination, but components will need to be selected to deal with the much higher pressures encountered.

Acknowledgements

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References

1 The Millennium Goals Report, UN, 2014.