Modified operation of a small scale energy recovery device for seawater reverse osmosis

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ABSTRACT

The Clark pump reciprocating pressure intensifier is a well established mechanism for highly efficient brine stream energy recovery in small scale seawater reverse osmosis (SWRO) desalination systems. This article describes operation of a modified Clark pump in which the roles of the two pairs of chambers are reversed and the general arrangement of the complete RO system is substantially altered. In particular, the low-pressure motorised pump that feeds into the standard Clark pump is replaced by a high-pressure motorised pump that sits in parallel with it. A conceptual comparison of the original and modified arrangements is presented, followed by a discussion of the practical modifications made to a standard Clark pump in order to test the concept. The initial tests were successful and results indicating specific energies in the range 3.5–4.5 kWh/m^3 are presented.

Keywords: Clark pump; Energy recovery; Reverse osmosis; RO

1. Introduction

Efficient and reliable brine-stream energy recovery is critical to the efficient operation of reverse osmosis desalination systems, particularly those operating from seawater. Early systems often employed Pelton wheels, which are simple and robust. In recent decades, RO system efficiencies and flexibility have been further improved through the development of FEDCO's HPB™ Hydraulic Pressure Booster [1], ERI's PX® Pressure Exchanger® [2] and Calder's DWEER™ [3].

Unfortunately, none of the above technologies are well suited to very small RO systems (below 50 m^3/day) and such systems are often built without any brine-stream energy recovery. This minimises the capital costs but is woefully inefficient in terms of energy consumption.

In small systems where energy efficiency is important – those powered by photovoltaics (PV) for example – brine-stream energy recovery is again critical. Recognising this in the 1980s, Keefer developed and demonstrated an energy-recovery mechanism built into a reciprocating pump (between the crank and the pistons) [4]. In the 1990s, Dulas demonstrated use of a Danfoss axial-piston motor [5]. More recently, Kunczynski has used axial-piston motors extensively in his long-term demonstrations of PV-powered seawater reverse osmosis [6].

Meanwhile, and initially for the marine yachting market, Clark Permar developed the Clark pump in association with Spectra Watermakers Inc [7]. Independent testing of the Clark pump recorded water-to-water efficiencies of up to 97%, which is outstanding
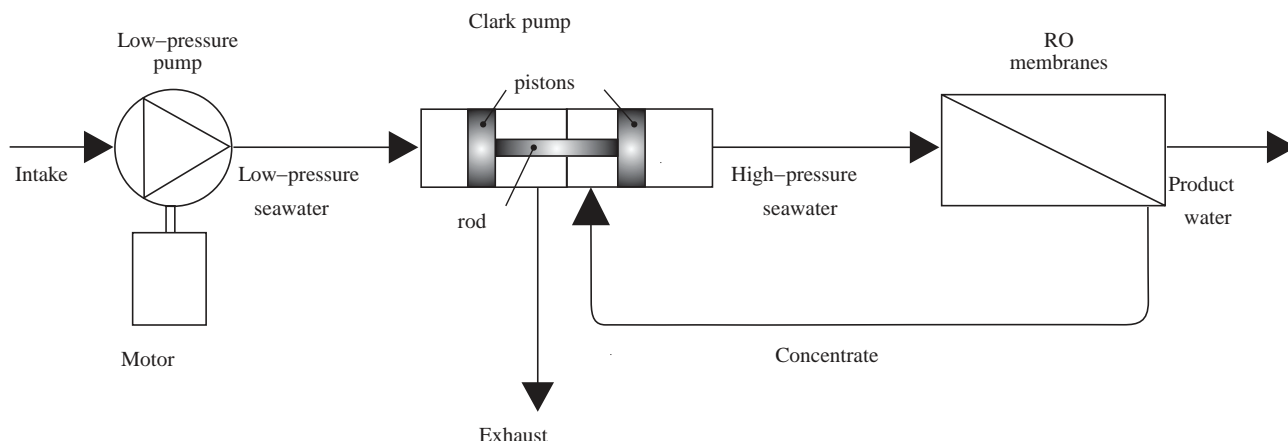
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Fig. 1. Basic configuration of a standard Clark pump (reciprocation valve gear not shown).

[8]. The Clark pump is a positive displacement pressure intensifier, which eliminates the need for a motorised high-pressure pump: unlike all the other energy recovery devices mentioned above, the Clark pump can operate with just a low-pressure feed pump, as shown in Fig. 1. In many ways this is good, but it also presents a challenge in that the efficiency of low-pressure pumps such as centrifugal, diaphragm and Moineau pumps is generally lower than high-pressure piston and plunger pumps.

This article describes the development and demonstration of a modified Clark pump in a seawater RO system driven only by a high-pressure pump.

2. The Clark pump

The basic configuration of the standard Clark pump is illustrated in Fig. 1. The two pistons are connected by a rod and this assembly is driven to the right by the forces of both the low-pressure feed and the concentrate. Thus, the high-pressure seawater is driven into the membranes and the exhaust (de-pressurised concentrate) is discharged. At the end of the stroke, a set of valves (not shown in the figure) act to swap round the four connections such that the piston assembly reciprocates.

The motorised pump carries the whole of the feed water flow and raises it to a modest pressure, typically around 5 bar in seawater applications. The Clark pump then raises this to around 50 bar by virtue of the energy recovered from the concentrate. The presence of the rod creates a difference between the effective areas of the two sides of each piston. The ratio of these areas determines the ratio of flows entering and leaving the Clark pump, and consequently the recovery ratio in the membranes.

Performance data for a desalination system configured as per Fig. 1 have been reported by Spectra Watermakers [9]. Their figures indicate a specific energy consumption (SEC) of 3.2 kWh/m^3 at 25 °C (see calculation below), which is remarkable for a system producing less than 1 m^3/d.

$$\text{SEC} = \frac{\text{motor voltage} \times \text{motor current}}{\text{Permeate flow}}$$
$$= \frac{1.25\text{V} \times 8\text{A}}{31.4\frac{\text{L}}{\text{h}}} = 3.2\frac{\text{Wh}}{\text{L}} = 3.2\frac{\text{kWh}}{\text{m}^3}$$

3. Alternative configurations

A second motorised pump may be added in parallel with the Clark pump and can be used to increase and control the recovery ratio. Such a system was implemented at CREST and operated briefly from a photovoltaic array without batteries [8]. Two observations arising from this work were the overall complexity of the system and that, while the high-pressure (plunger) pump achieved efficiencies around 80%, the efficiency of the low-pressure (Moineau) pump was sometimes as low as 40%. This led to consideration of eliminating the low-pressure pump.

Various configurations were considered, including using cylinders of different diameters, having the rod protruding through the ends of the device (to allow an area ratio of unity) or having no rod at all (similar to the DWEER™). Computer simulations were used to investigate the flow and pressure relationships arising from the different area ratios. Taking the standard Clark pump with an area ratio of 10:9 (greater than unity) as a base case, it became apparent that a device with a ratio of less than unity would be interesting. In
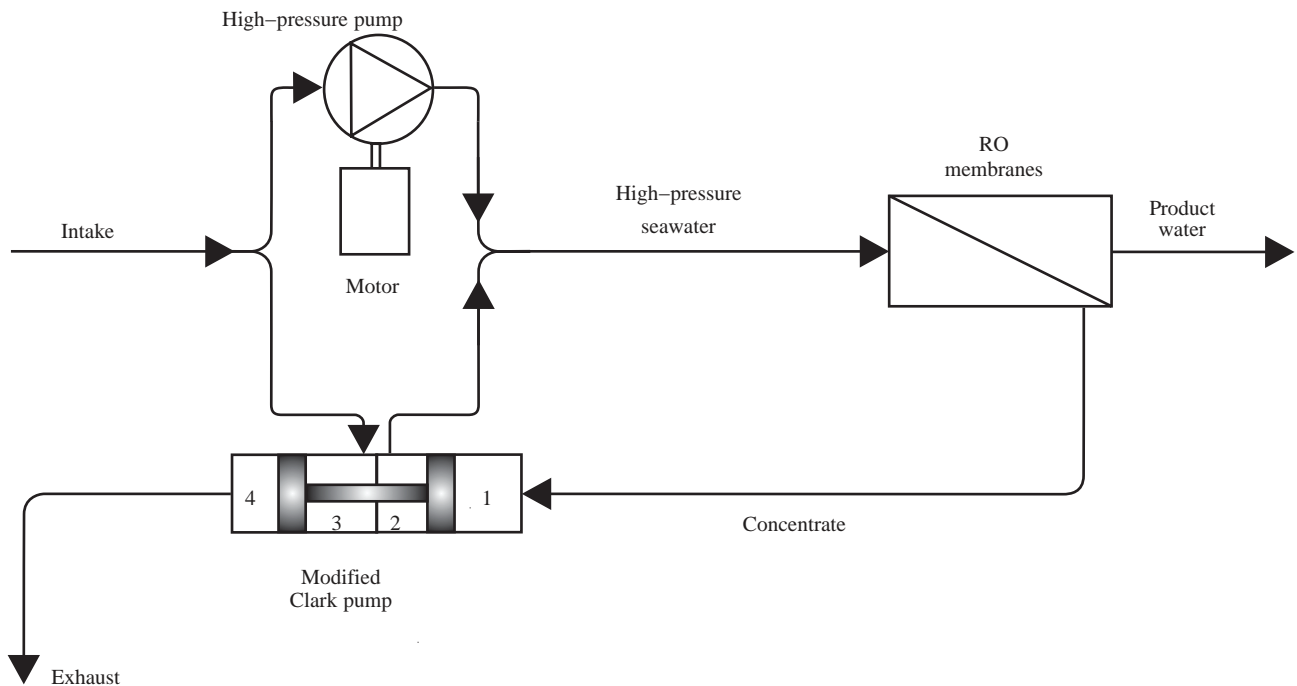
Fig. 2. Modified arrangement (reciprocation valve gear not shown).

particular, it promised to draw water in without need of a low-pressure pump. Achieving an area ratio of less than unity requires a device very like the Clark pump, but with the roles of the two pairs of chambers reversed.

4. The modified Clark pump

The configuration of a system using a modified Clark pump is shown in Fig. 2. Here, seawater flows in from the left through a common intake, which is split between the modified Clark pump and the high-pressure pump. These two pumps operate in parallel, each pressurising a portion of the flow. Their high-pressure outputs are then combined prior to entering the RO membranes; after these, the concentrate flows into the modified Clark pump.

In the modified Clark pump, the concentrate is the energy input; it flows into chamber 1, pushing the pistons and rod to the left. Most of the energy in the concentrate is used to pressurise the seawater in chamber 2; the rest of the energy is used to draw seawater into chamber 3, and to push the exhaust from the previous stroke out of chamber 4.

At the end of the stroke, a spool valve (described later) swaps over the connections, directing the concentrate to chamber 4 and allowing the exhaust to flow out of chamber 1, so that the pistons and rod reverse

direction. Check valves allow the roles of chambers 2 and 3 to swap over accordingly.

The arrangement in Fig. 2 is essentially the same as that being considered by Matt Folley for wave powered applications [10].

5. Comparison to the Clark pump

Comparing the modified arrangement of Fig. 2 against the standard Clark pump arrangement of Fig. 1, four observations may be made:

First, while the standard configuration uses a low-pressure pump, the modified configuration requires a high-pressure one. High-pressure pumps are capable of higher efficiencies and hence, offer good potential to improve the overall specific energy consumption of the system. This is discussed later in section 6.

Second, with the concentrate being applied to the larger side of the piston (the side without the rod), pressure intensification is achieved directly. This is unlike the standard Clark pump, where additional energy from the low-pressure feed is required to intensify the pressure.

Third, the flow of high-pressure seawater from the modified Clark pump is less than the flow of concentrate into it. Thus, the high-pressure motorised pump is essential in order to make up the difference and provide the product flow. This is unlike the standard Clark
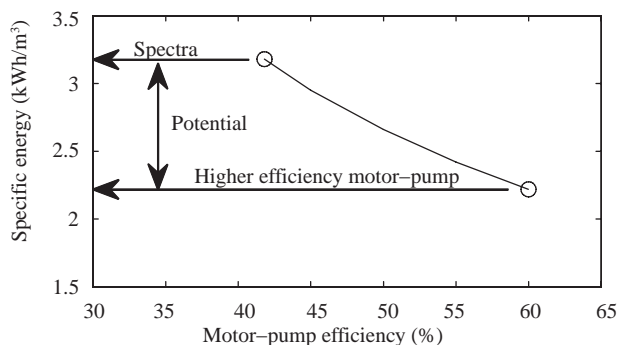
Fig. 3. Potential for specific energy reduction.

pump, where the additional high-pressure motorised pump is optional.

Fourth, having the high-pressure pump flow contributing to the membranes feed in addition to the modified Clark pump's flow means that the recovery ratio is not dictated by the geometry of the device.

6. Expected performance

In the system presented in Fig. 1 (standard Clark pump configuration), the low-pressure pump is the only source of motive power. The Spectra Watermakers implementation of this configuration, mentioned above, uses a motorised diaphragm pump with an overall efficiency of 42%. If this efficiency could be improved to 60% (motor and pump together), the specific energy consumption of the system would be improved from 3.2 kWh/m^3 to 2.2 kWh/m^3 with all other parameters remaining equal (see Fig. 3).

The implementation of a modified Clark pump in the configuration of Fig. 2 uses a high-pressure pump. Thus, assuming that a modified Clark pump could achieve device efficiencies comparable to those of the standard Clark pump, its use has the potential to yield reduced specific energy consumptions like those shown in Fig. 3. This is a consequence solely of the reduced losses in the motorised pump and assumes the same operating point of the membranes.

7. Modifying the Clark pump

Readers familiar with the standard Clark pump will appreciate that putting it to service in the modified arrangement of Fig. 2 is more than just a matter of re-plumbing the external connections: it requires that the reciprocation valve gear illustrated in Fig. 4 be reconfigured as per Fig. 5.

Fortunately, the spool valve (change-over valve at top of Fig. 4) is contained in the top block of the
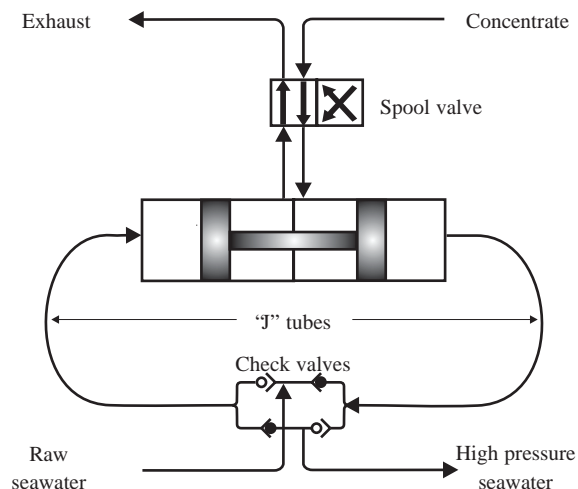

Fig. 4. Reciprocation valve gear configuration in the standard Clark pump.

standard Clark pump and can readily be detached from the main block [11]. Similarly the four check valves at the bottom of Fig. 4 can readily be accessed by removal of the stainless-steel "J" tubes. Thus, it was possible to effectively separate the valve gear from the main body of the Clark pump and then to use four flexible hoses to reconfigure it as indicated in Fig. 5. The photograph in Fig. 6 shows the flexible stainless-steel braided hoses used. Also apparent in this photograph are the small nylon tubes that carry the control flows connecting the main block to the spool valve.

The photograph in Fig. 6 shows just four control tubes, but it was found that a fifth connection was needed in order to operate the spool valve. In the standard Clark pump this supply is fed from the low-
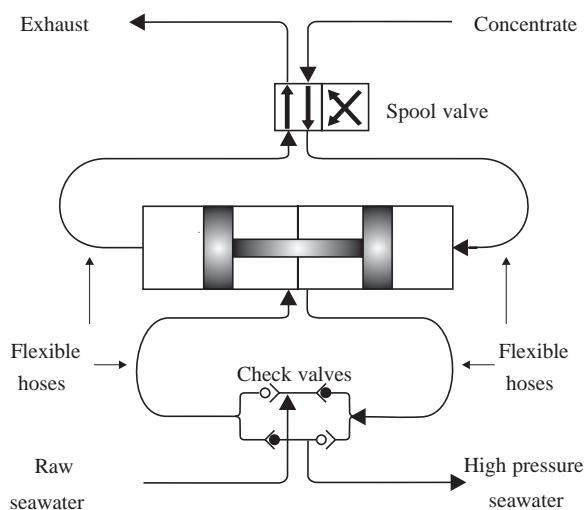

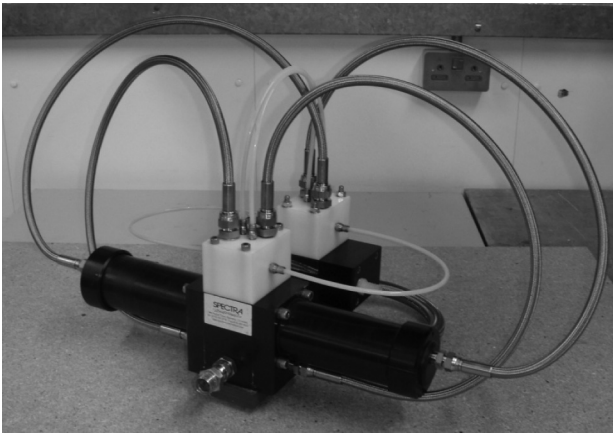Fig. 5. Required reconfiguration of the reciprocation valve gear.

Fig. 6. The modified Clark pump.

pressure stream (3–5 bar), but in the modified arrangement this stream is at negative pressure, drawing water in, and thus unable to operate the spool valve. For the purpose of the trial, the required control feed was supplied from mains water.

With the spool valve now operational, the modified Clark pump began reciprocating but refused to provide any pressure intensification; it also exhibited erratic flows during the strokes. Investigation revealed that the pistons were not actually fixed to the rod. In the

standard Clark pump, the water pressures always serve to push the pistons towards the rod, and thus they do not need to be attached. However, in the modified arrangement the two pistons were moving independently. A new rod was manufactured and the pistons fixed to it, which solved this issue and the pump began operation as expected.

8. Prototype test arrangement

The modified Clark pump was tested in a closed loop configuration as shown in Fig. 7. The system was fed from a tank which was replenished by both the permeate (product water) and the depressurised concentrate (exhaust).

The testing was conducted using a straight NaCl solution and the concentration in the tank and hence the intake was held close to 32,000 mg/L. The water temperature was close to 25 °C. A data acquisition system logged flows (F) and pressure (P) as indicated in Fig. 7.

The speed of the high-pressure pump was controlled by means of an inverter (variable-speed drive) to allow testing over a range of operational conditions. The shaft speed was also logged together with the electrical input power to the inverter.
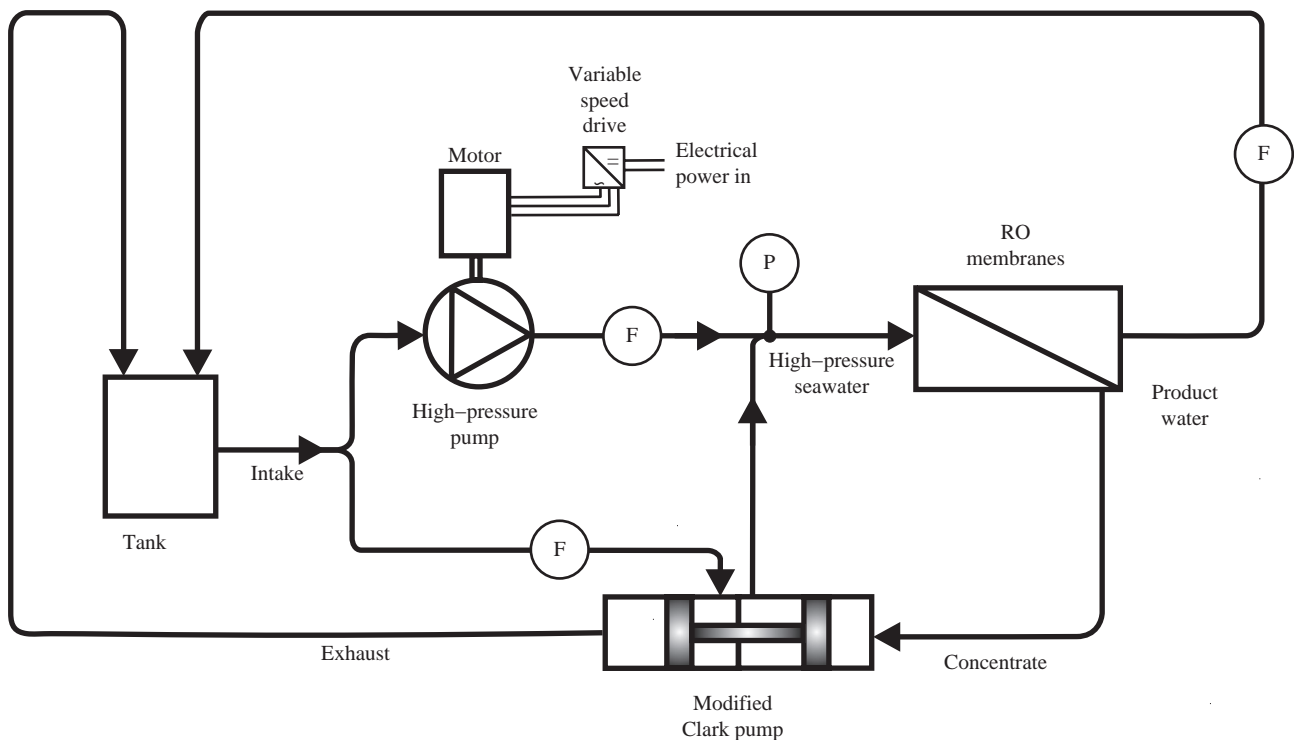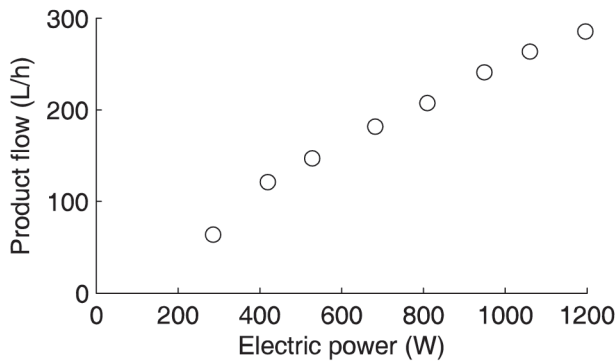

Fig. 7. Prototype test arrangement.

Fig. 8. Product flow.

Fig. 10. RO membrane feed pressure.

9. Results

Once stable operation at full speed was established, the motor speed was reduced in steps and the system allowed to stabilise so that data could be logged and averaged over one full minute of stable operation at each of eight speeds. This range of speeds corresponds to a range of electrical input powers from 286 W to 1196 W and this is used as the x-axis in the graphs (Figs. 8 and 9).

The product flow is shown in Fig. 8 and indicates that the system can operate usefully over a very wide range of electrical input power. Moreover, the product flow is almost linear with electrical power, which indicates that system efficiency is roughly constant over this range of operation. The specific energy shown in Fig. 9 confirms this and ranges from 3.5 to 4.5 kWh/m^3. While these values are respectable for such a small system, they are considerably higher than the expected values discussed earlier. This is partly because the prototype test rig was assembled purely to demonstrate the concept; the components used were second-hand and not in any way optimised. In particular, the membranes were six years old and have not been maintained; also the motor and pump are considerably oversized. However,
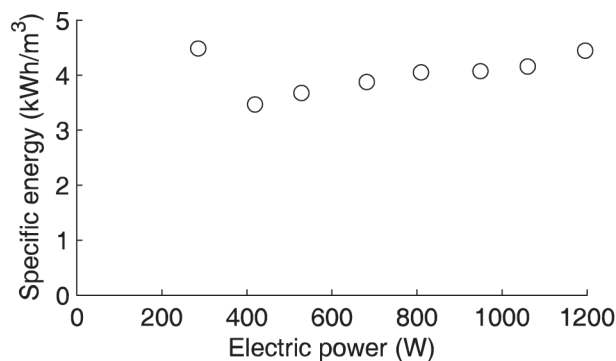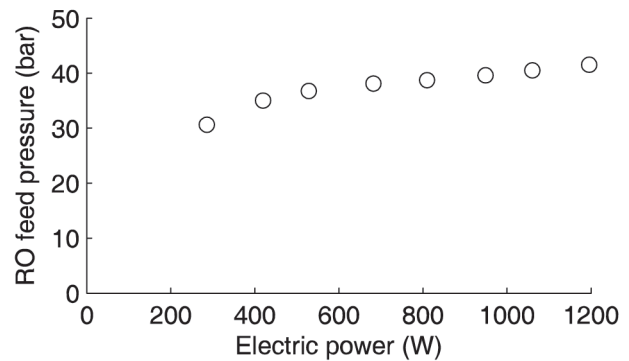
the main shortfall in system performance is due to the crude nature of the modifications made to the Clark pump, as discussed later.

The RO membranes feed pressure and recovery ratio are shown in Figs. 10 and 11 respectively. Both these characteristics are slightly flatter than anticipated and may indicate an internal leak between chambers in the modified Clark pump. The new rod to which the pistons were attached was a few hundredths of mm thinner than the original, which could give rise to such a leak. Unfortunately, the data collected during the tests are not sufficient to reach a definite conclusion in this respect and more tests will be necessary.

Also apparent during the testing was that the operation of the modified Clark pump was not as smooth as the standard configuration. Significant pressure pulses were observed at the end of each stroke and, even during the stroke, the pressures and flows were not constant. Factors causing this behaviour could include: the internal leakage mentioned above, the pistons now being firmly attached to the rod and the disruption to the reciprocation timing caused by the reconfiguration of the valve gear. These factors could also result in considerable energy losses and contribute to the higher specific energies observed.
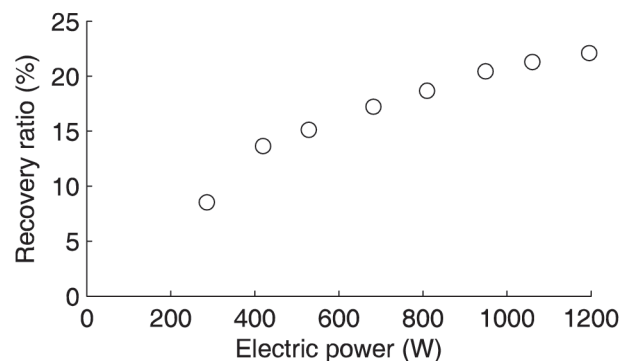

Fig. 9. Specific energy.
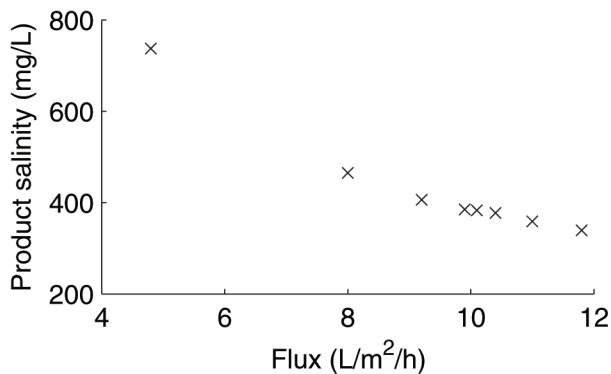

Fig. 11. Recovery ratio.

Fig. 12. Expected product quality. Values from ROPRO.

Samples of the feed and product waters were taken only while the system was running at full speed. Their concentrations were subsequently measured using a laboratory conductivity meter, which indicated 31,700 mg/L and 740 mg/L respectively. The latter is unacceptably high and is likely to be a consequence of the membranes age and their poor maintenance. A product salinity of around 340 mg/L is obtained with Koch's software ROPRO[®] [12] for the same pressure and recovery ratio and suggests that replacing the membranes with fresh ones would solve this problem.

Fig. 12 presents the expected product salinity calculated with ROPRO[®] for the rest of the measured data points. The figure shows that product salinities consistently below 500 mg/L could be expected, except at very low flux when the slightly higher concentration will have little impact on average product quality.

10. Future work

The successful operation of the modified Clark pump reported above illustrates that the concept works, but also that there are a number of issues to be addressed.

- The presence and extent of internal leaks needs investigation and solution.
- The smooth operation of the pump must be restored. The irregular flows and pressures observed during each stroke may be due to poor timing of the reciprocation valve gear operation. The long flexible tubes and hoses used to reconfigure the pump for the test may also be affecting this timing and a closely coupled configuration should be sought.
- An internal source must be found for the small supply of water required to actuate the spool valve.

(Mains water was used in the testing described above.)
- The firm attachment of the pistons to the rod may have increased friction within the pump and should be investigated.
- Once the modified Clark pump itself has been optimised, the other components in the system should be selected to minimise overall specific energy consumption.

11. Conclusions

A seawater reverse osmosis system with brine-stream energy recovery and driven by only a high-pressure pump has been demonstrated. It is a simple arrangement but differs from all standard commercially available schemes that the authors are familiar with. Whilst the hydraulic arrangement is simple, its operation is perhaps less intuitive than other schemes and it is reassuring to see it work stably over a wide range of input power and hence flow.

The specific energy figures achieved (3.5–$4.5\,kWh/m^3$) are not outstanding but are respectable for an initial prototype. None of the components have yet been optimised and there is good potential for significant efficiency improvements throughout.

Assuming that the modified Clark pump could be optimised to achieve efficiencies similar to the standard model, and observing that high-pressure plunger and axial-piston pumps have very high efficiencies, the configuration presented in this article has potential to significantly lower the specific energy consumption of small-scale seawater RO.

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