Enabling Renewable-Energy Driven Reverse Osmosis Desalination Using Integrated Compressed Gas Energy Storage—Bench-Scale Experiments and Modeling

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ABSTRACT

Growing fresh water needs have led to increasing interest in desalination using reverse osmosis (RO) membranes, but energy requirements are extreme so renewable sources are sought. Unfortunately, many renewable sources are intermittent and low-intensity while RO membranes typically operate with continuous, high-intensity power. This paper investigates a method to enable wind-energy driven RO using a compressed gas energy storage mechanism integrated directly into the RO process. Bench-scale proof-of-concept experiments were performed to test the energy storage device and mathematical modeling was carried out to predict the performance of the setup and to translate our bench-scale findings to conceptualize a full scale system.

Keywords: membranes, reverse osmosis, renewable energy, energy storage, modeling

1. INTRODUCTION

With a rapid depletion in fresh water reserves, seawater desalination has become a viable option to meet the increasing demand for drinking water across the world. RO membrane desalination is typically used for sewater desalination [1-3]. However, a substantial amount of electricity is consumed in membrane processes to overcome the osmotic pressure. With increasing fuel costs and an awareness to protect our environment from greenhouse gas emissions, there is a need to use renewable energy sources to drive the system [4].

Wind energy is considered to be a reliable source to drive RO desalination plants. However, the intermittent and unpredictable nature of wind poses a challenge in utilizing it as a reliable source of energy. It is therefore connected to a grid network or attached to an energy storage devise to counter the fluctuations in energy supply [5]. One such storage device is batteries [6, 7].

The present work investigates the use of a pressure vessel working as an energy storage device integrated into a conventional RO unit. A cylindrical vessel working on the principle of compressing gas acts as the energy storage device. The novel concept is to store energy inside the pressure vessel when wind energy is available and use it for desalination during the no-wind conditions. The bench-scale experimental setup consists of a pressure vessel incorporated within the RO unit [8] such that energy is stored when pump speed (input energy) is high and released when the pump speed decreases. Desalination continues for a time even after the pump is turned off because the system remains pressurized. Aside from the energy storage aspect, this approach also differs from conventional RO in terms of crossflow hydrodynamics. Crossflow is required to decrease concentration polarization (CP) in RO, but doing so requires energy input. In our system the crossflow can be easily decoupled from pressure because of the integrated pressure vessel, allowing us to optimize crossflow for CP reduction. Mathematical modeling is carried out to predict the performance of the setup and to translate our bench-scale findings to conceptualize a full scale system. Traditional RO modeling based on film theory is being modified to account for the fluctuating nature of the feed flows [9, 10].

2. CONCEPTUAL DESIGN

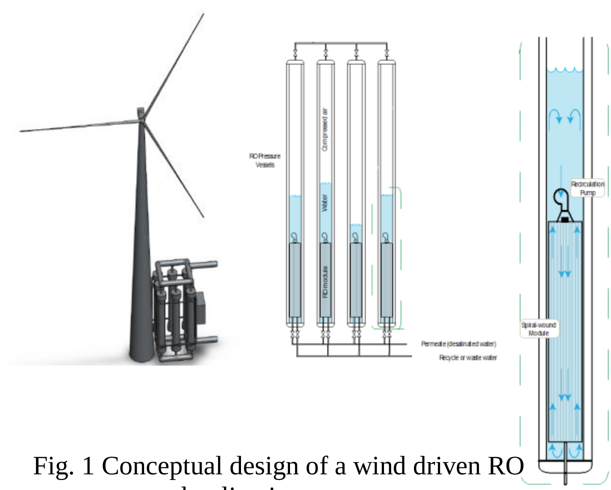

Fig. 1 Conceptual design of a wind driven RO desalination system

Fig. 1 shows a conceptual design of a propsed wind-RO desalination system. The wind turbine is directly connected to the pressure vessels each of which contain a RO membrane element. A small pump is installed in the vessel to provide crossflow. The wind turbine produces energy to drive a pump that pumps sea water into a pressure vessel pre-charged with air. Sea water is pumped until the pressure inside a vessel reaches 1000 psi. Pumping is stopped and desalination occurs inside the vessel by releasing the permeate. In the meantime, the pump fills the next pressure vessel in the same manner. Thus, the process of desalination is at different stages in each pressure vessel. The advantage of this method is that the wind energy is used fully to pump sea water into pressure vessels and desalination continues to occur when it is unavailable.

3. MATERIALS AND METHODS

3.1. Bench-scale Air-pressure Energy Storage Setup

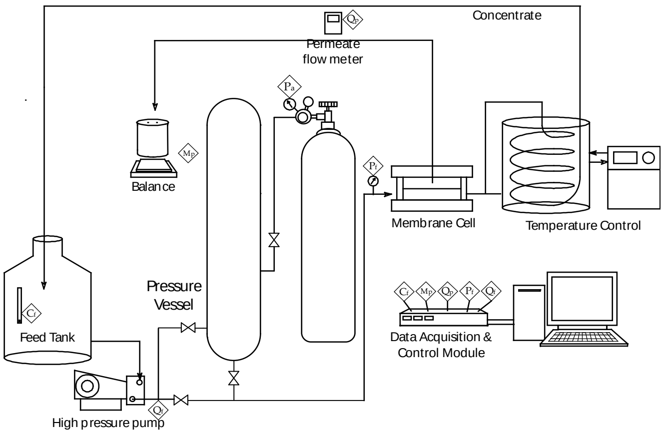

Fig. 2 Bench-scale setup of an integrated pressure vessel RO desalination system

The air-pressure energy storage device (APESD) setup is shown in Fig. 2. This setup was constructed such that by detaching the pressure vessel and the nitrogen cylinder the system can work as a conventional RO setup. The components of the APESD setup included membrane test cell, pump, motor, pressure gauges, cooling system, valves, balance, and data acquisition equipment, pressure vessel and a nitogen tank. The permeate conductivity was measured by allowing the permeate to flow over a small tube with the conductivity probe inserted into it. The permeate was then fed into a container placed over the balance for flux measurement. The pressure vessel served as the energy storage device made from stainless steel and had four openings. Three openings were attached each to the pump, membrane and nitrogen cylinder. The fourth opening served as an outlet to drain excess water from the vessel. Each opening had ball valves to control the flow of water. Nitrogen gas was used to pressurize the vessel. The data acquisition unit consisted of a personal computer with a data acquisition card capable of analog input and output. The software used for programming and signal interpretation was LabView, which featured feed and permeate conductivities, permeate flux, applied pressure, rejection, tank volume and temperature over time.

3.2. Membranes

Reverse osmosis membranes were obtained from two manufacturers: SW30HR from Filmtec, a wholly owned subsidiary of the Dow Chemical Company (Midland, Michigan), and SWC4 from Hydranautics a Nitto-Denko company (Oceanside, California). Coupons for experiments were cut and placed in DI water, then stored at 4 °C at least overnight and up to several weeks with DI water replaced regularly.

3.3. Salt Water

Salt water feed solution was prepared in the laboratory by mixing amorphous sodium chloride salt in deionized water. The concentrations used for testing were 0, 5, 15, 25 and 35 g/L. A 14 L fresh salt water solution was prepared for each experiment.

3.4. Experimental Methods

In the APESD setup, nitrogen gas was delivered into the vessel such that it exerted an initial pressure between 0 and 600 psi. Salt water was then continuously pumped into the vessel, bringing it to 1000 psi. The system was run at 1000 psi for 2 hours to obtain a nearly constant flux; this constituted the “steady state” portion of the experiment. The pressure was then decreased gradually to 700 psi, simulating batch operation. The APESD system was compared with the conventional setup by disabling the pressure vessel and nitrogen cylinder. In the conventional mode the system was run at steady state for 2 hours at a constant pressure of 1000 psi.

The system was cleaned by running DI water to avoid salt in the pump, pipes, vessel and the membrane test unit. Another DI water run was carried out to record the flux and pressure in order to calculate the permeability coefficient of the membrane. This coefficient is an intrinsic property of a membrane and is useful in calculating the concentration polarization factor.

To simulate a wind energy driven system, the pump speed was varied continuously and the flux and salt rejection were monitored for both the setups.

3.5. Modeling

A mathematical model was developed using Matlab to predict the concentration polarization, flux, permeate concentration, membrane rejection, air-to-water volume ratios in the pressure vessel and a full-scale design of the system. The model used input data collected from the bench-scale experiments. Traditional RO modeling based on film theory was modified to account for the fluctuating nature of the feed flows.

4. RESULTS AND DISCUSSIONS

4.1. Experimental Results

The system was tested to simulate an intermittant availability of wind power. This was achieved in the laboratory by shutting the pump supplying feed water to the RO unit to simulate a dead wind condition. Four different scenarios were compared: 1) conventional mode without crossflow during pump shut-off, 2) conventional mode with crossflow during pump shut-off, 3) APESD mode without crossflow during pump shut-off, and 4) APESD mode with crossflow during pump shut-off time. The initial conditions for the system were kept the same for each experiment. As expected, as soon as the pump was stopped, the pressure in the conventional setup dropped to 0 psi. On the contrary, in the APESD setup, the pressure was maintanied due to the energy stored as compressed air. Fig. 3 shows the flux curves for each mode. There was no flux during the pump shut off time in the conventional modes. In the APESD without crossflow a decaying flux curve was obtined due to the buildup of salts at the membrane surface. Whereas when there was continuous crossflow, the flux through the membrane remained fairly constant during the dead wind condition. The salt rejection was also highest for APESD with constant crossflow.

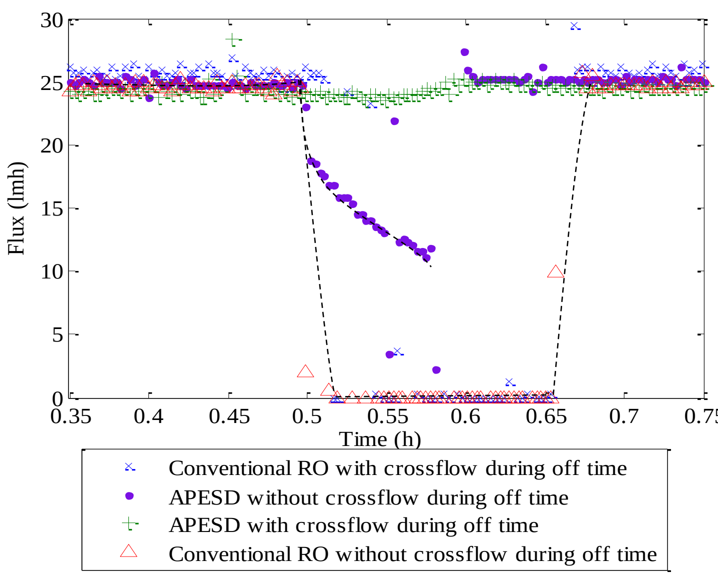

Fig. 3 Permeate flux for various RO operating conditions (Dotted lines are to guide the eyes)

4.2. Modeling Results

Film theory was used to predict the performance of the system. To reduce the concentration polarization, RO membranes are supplemented with feed spacers that increase turbulence at membrane surface. Since the film theory model assumes open flow channels [9], a correction factor, τ_f, was introduced to account for the complex hydrodynamics in a spacer-filled channel. This correction factor was assumed to take into account the variation in the channel height due to a porous spacer. The value of τ_f was assumed to be 0.5.

4.2.1. Predicting concentration polarization and permeate flux

Using an iterative method and by modifying film theory equations, the concentration polarization factor (f_{cp}) and permeate flux (v_w) were predicted for steady state and declining pressure conditions as [9],

$$f_{cp} = exp(^{v_w}/_k) \tag{1}$$

$$v_w = K_w(\Delta p - \Delta\pi_m) \tag{2}$$

Where, k is the mass transfer coefficient, K_w is the membrane permeability, Δp is the differential pressure and $\Delta\pi_m$ is the trans-membrane osmotic pressure. Fig. 4a shows the modeled and actual flux plot and corresponding concentration polarization factor in the steady state and declining pressure conditions

4.2.2. Predicting permeate volume and pressure decline across the membrane

Permeate volume (V_p) was determined from the predicted flux (v_w) and membrane area (A_m) as follows,

$$V_p = {}^{v_w}/_{A_m} \tag{3}$$

Using the ideal gas law ($P.V = n.R.T$) and change in permeate volume (ΔV_p), the pressure decline (ΔP) over time was determined by,

$$\Delta P = \frac{n.R.T}{\Delta V_p} \tag{4}$$

In Figs. 4b and 4c, the actual and the modeled permeate volume and the pressure profile suggest that the model fits well with the experimental results.

4.2.3. Predicting permeate concentration

The solute flux (v_s) through the membrane depends on the salt concentration at the membrane surface (C_m), permeate concentration (C_p) and the solute mass transfer coefficient (K_s). The permeate concentration was determined by calculating the solute flux as follows,

$$v_s = K_s(C_m - C_p) \tag{5}$$

Fig. 4d shows plot for modeled and actual permeate concentration. The initial drop in the actual concentration may be caused by membrane compaction.

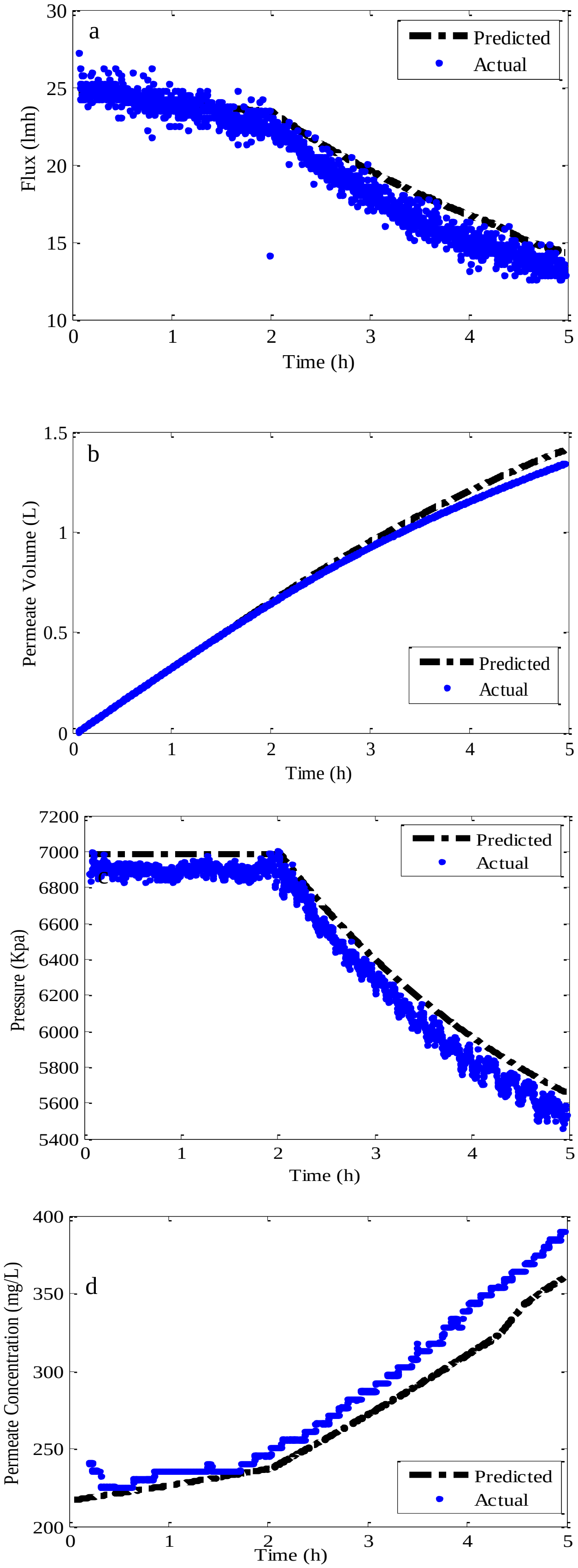

Fig. 4. Plots showing experimental and modeled flux(a), permeate volume(b), pressure (c) and permeate concentrations (d) for a staedy state and declining pressure condition

5. CONCLUSIONS

A conventional RO system was modified to enable the use of wind or other renewable sources of energy by integrating an energy storage device that has dual functions: it dampens the fluctuations caused due to variation in wind energy and it also stores energy that is used for desalination in a batch operation mode. From the experimental results it can be concluded the energy storage device provides a remarkable advantage over conventional RO. The four modes of operations compared described in the paper clearly indicate that by connecting an energy storage setup to the system, wind energy can be used to obtain a continuos desalination process with high performance characteristics. Further, the system was modeled to validate the experimental data. Equations from traditional film theory were modified to account for spacer filled channels and fluctuating flow. Plots suggest that these modifications enable adequate prediction of the system's performcace.

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