System development and testing of wind-powered reverse osmosis desalination for remote Pacific islands

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Abstract Reverse osmosis (RO) is one of the most feasible methods of desalination to produce a supplemental freshwater supply. Because traditional RO desalination is energy-intensive, it is not a viable solution for remote Pacific islands where electricity is also in short supply. The utilization of wind power holds promise as a solution to this problem, as most of these remote islands are subject to constant trade winds. RO desalination of brackish groundwater, which is available in many of these islands, requires low feed water pressure that can be delivered by wind power at a moderate wind speed. Testing of a prototype wind-powered RO desalination system constructed on Coconut Island, a small island off the windward coast of Oahu, Hawaii, indicated that at an average wind speed of 8.5 m/s, a freshwater flow of over 4000 L/d can be produced. This volume is sufficient to meet the freshwater needs of a typical remote island community.

Keywords Brackish water; reverse osmosis; system control; wind power

Introduction

The Pacific islands fall into two categories: volcanic islands and low coral islands or atolls. Perennial streams exist only in large volcanic islands where storage facilities are usually required to regulate the highly variable rainfall distributions. Due to the high porosity of the ground, a surface water supply is almost nonexistent in atoll islands.

The groundwater supply of large Pacific islands occurs as a basal water lens. Water in the transition zone of a basal water lens, which separates freshwater from the underlying seawater, is brackish. It is not considered a good water-supply source due to its high salinity. Over-pumping of coastal groundwater, which causes an expansion of the transition zone as well as a declination of the water table, reduces the freshwater supply in these islands (Liu et al., 1991). As for small atoll islands, the naturally recharged water usually mixes with the underlying saltwater, such that only brackish groundwater occurs (Peterson, 1997).

An inadequate supply of freshwater of acceptable quality has been one of the critical factors limiting sustainable development on many remote islands in the Pacific Ocean. Population increases and deforestation make the situation even worse. Alternative water supply methods must be developed, and desalination is one of the most attractive alternatives.

The salt content (or salinity) of water is usually expressed in terms of its total dissolved solids (TDS) concentration. Water is considered brackish when its TDS concentration is between 1,000 mg/L and 10,000 mg/L. The World Health Organization’s standard for salinity in the water supply is 500 mg/L of TDS, or about 2% that of seawater. Thus, without desalination, most of the water in a transition zone is not suitable to serve as a domestic water supply.

The reverse osmosis (RO) process is one of the most popular desalination methods commercially available (Liu and Park, in press). It is the reverse of the well known natural phenomenon called osmosis, which is when pure water is diffused through a semipermeable
membrane into a salt solution. The reverse osmosis process that causes water in a salt solution to move through a semipermeable membrane to the freshwater side is accomplished by applying to the salt solution a pressure in excess of the natural osmotic pressure. Seawater desalination by the reverse osmosis process is a fully developed technology, but it is often not economically feasible due to the great amount of energy needed to create and maintain the required feed water pressure.

Feron (1985) first investigated using wind energy to raise feed water pressure of a reverse osmosis desalination system. He studied the system performance by mathematical modeling under the following assumptions: (1) the system operation is intermittent, depending on the wind availability, and (2) the feed water pressure is variable, depending on the prevailing wind speed. The results derived by Feron (1985) were largely theoretical and were not verified with any experimental data.

A pilot-scale wind-powered RO system was later developed by Robinson et al. (1992) to meet the water-supply needs of remote communities in Australia. The design capacity of their system was relatively small, as they estimated that a typical remote community would need only 500 to 1,000 L/d of clean freshwater. A pressure vessel was included in their system to store the feed water under pressure. There was no control mechanism for the pressure vessel, and the system operation was intermittent.

In this research, a prototype wind-powered RO desalination system was designed, constructed, and tested. This research was planned and executed in order to find answers to the following questions: (1) Can a wind pump be used to generate and maintain a required feed water pressure for RO desalination at a moderate wind speed of 10 to 20 mph (4.5 to 9.0 m/s)? (2) Can continuous operation of the system be achieved by a data acquisition and control? and (3) How large a freshwater flow can this prototype system produce?

System development

A prototype wind-powered RO system was designed and constructed at an experimental site located on Coconut Island, Hawaii. Coconut Island is entirely owned by the University of Hawaii and is the home of its Hawaii Institute of Marine Biology. The system has four major components: a windmill/pump subsystem, a flow/pressure stabilizer subsystem, an RO subsystem, and a data acquisition and control subsystem (Figure 1).

Windmill/pump subsystem

The energy contained in the wind is its kinetic energy (KE). The basic equation for this energy is KE = \( \frac{1}{2} m V^2 \), where \( m \) is the mass of air and \( V \) is the wind speed. When the wind pushes on the rotors of a windmill, the blades capture this energy. The mass of air moving through a windmill in a unit of time can be calculated as \( m = \rho A V \). The power output of an ideal windmill is given by

\[
P_w = \frac{1}{2} \rho A V^3 = \left( \frac{\pi \rho}{8} \right) D^2 V^3
\]

where \( P_w \) = wind power (watts); \( \rho \) = air density (kg/m\(^3\)); and \( A \) = the cross-sectional area of the parcel of air (m\(^2\)). \( A = (\pi/4)D^2 \), where \( D \) is the diameter of the windmill rotor (m) and \( V \) = wind speed (m/s). At standard conditions, \( \rho = 1.3 \) mg/m\(^3\).

Eq. (1) indicates that the power produced by a windmill increases with the square of the diameter of the rotor and with the cube of the velocity of the wind. Eq. (1) is true only if the wind is completely stopped by the rotors. In reality, the wind is not completely stopped but only slowed down; there is also energy loss due to friction. The power output of a windmill is then given by
where \( C_p \) = power coefficient. \( C_p \) is about 0.30 to 0.35 with a good windmill design.

There are two basic windmill designs: (1) multivaned windmills and (2) high-speed, thin-blade windmills. Multivaned windmills were invented in the United States in the late 19th century and have continuously been modified and improved. Modern wind turbines for electricity generation are based on thin-blade designs to capture more energy from the wind.

A multivaned windmill was used in this study because (1) it converts wind power directly into the hydrologic power of feed water, and (2) it produces a large torque at start-up, which is when a pump requires the most torque. Modern thin-blade wind turbines have zero torque at start-up.

The windmill selected for this study uses a 9.0 m tall steel tower and has a blade diameter of 4.3 m. The wind pump attached to this windmill uses a 70 mm cylinder. The wind pump can be operated with a 250 mm or 300 mm stroke.

Flow/pressure stabilizer subsystem
A stabilizer was developed by this study to produce a feed water flow to the RO unit at a relatively uniform pressure and flow rate. This was necessary because the flow rate and water pressure generated by wind pumps are unstable due to the high variability of ambient wind and because the Dempster wind pump used by this study discharges water only during the downward movement of the pump piston.

The stabilizer developed is a hydro-pneumatic pressure tank, with an inside diameter of 0.56 m, an outside diameter of 0.57 m, and a height of 1.14 m. Its total volume is 0.3 m³, an amount sufficient to store the estimated maximum hourly flow. It was constructed with a conventional vertical pressure vessel with a cylindrical welded shell, flat circular ends, and a ring pedestal base. The shell is 0.005 m thick, and the heads, made of \textit{ASTMA A 36 steel}, are 0.006 m thick.

The stabilizer is precharged with air by injecting air under pressure into the empty stabilizer, before it is operated together with the wind pump. As water is delivered to the tank, the air in the tank is compressed, exerting pressure on the water. A diaphragm or bladder separates the air and water in the tank, to eliminate “water-logging” problems.
Prefilter and reverse osmosis subsystem

A pretreatment is applied to maximize the RO system’s efficiency and membrane life by minimizing fouling, scaling, and membrane degradation. The degree of pretreatment depends on the quality of the feed water, which to a large extent depends on the feed water source. In this study the brackish feed water required a simple pretreatment with a 5 µm cartridge microfilter.

Performance of the RO process is usually evaluated by the rejection rate (RR) and recovery rate (Y). The rejection rate indicates the amount of solute removed, or \( RR = (1 - C_p/C_f) \times 100\% \), where \( C_p \) is permeate concentration and \( C_f \) is the feed water concentration. The recovery rate indicates the amount of permeate discharge produced from a given feed water discharge, or \( Y = (Q_p/Q_f) \times 100\% \), where \( Q_p \) is permeate discharge and \( Q_f \) is feed water discharge. The amount of permeate discharge depends on membrane properties, solution temperature, applied pressure, and the solution’s osmotic pressure.

The amount of water produced by RO is a function of its membrane type, which includes its surface area and mass-transfer coefficient (also known as the water permeation coefficient), pressure differential, and the concentration of the feed water. The water flux is described by the equation:

\[
Q_p = A_m K (\Delta P - \Delta \pi) \tag{3}
\]

where \( A_m \) = membrane surface area (m²), \( K \) = water permeation coefficient (s/m), \( \Delta P \) = pressure differential between the feed and product water (kPa), and \( \Delta \pi \) = osmotic pressure difference between the feed water and product water, or permeate, (kPa). The water permeation coefficient, \( K \), depends on the nature of the RO membrane. Osmotic pressure can be calculated as (Reynolds and Richards, 1996)

\[
\Delta \pi = 1.64 \times 10^{-3} (C_f - C_p) \tag{4}
\]

where \( C_f \) = TDS concentration of feed water and \( C_p \) = TDS concentration of product water.

According to Eq. (4), osmotic pressure across a semi-permeable membrane, separating seawater with a TDS of 35,000 mg/L and freshwater with a TDS of 50 mg/L, is about 2,700 kPa. On the other hand, the osmotic pressure across a semipermeable membrane, separating brackish water with a TDS of 2,500 mg/L and freshwater with a TDS of 50 mg/L, is only about 190 kPa. Therefore, brackish water desalination would require smaller applied pressure than seawater desalination.

Efforts have been made to develop RO membranes that allow decreased operating pressure without sacrificing performance. An ultra-low-pressure RO membrane that can be operated at a feed water pressure in the range of 520 to 690 kPa was used by this study.

Data acquisition and control subsystem

A data acquisition and control mechanism – which consists of a Campbell Scientific CR10X datalogger and a pressure sensor, a solenoid valve and relay set, and a flow sensor and relief valve set – was designed and installed onto the wind-powered RO desalination system (Figure 2). The desirable operating pressure range for the RO used by this study is 75 to 105 psi (517 to 724 kPa). The solenoid valve is closed when the system operation starts. As the water is pumped into the stabilizer, water pressure in the stabilizer builds up. When the pressure reaches a pre-set value of 75 psi, the datalogger sends a signal through a relay to open the solenoid to let the water flow out of the stabilizer and into the prefilter and RO subsystem.

The rate of flow entering the pressure stabilizer depends on wind speed, which is highly
variable. As the prevailing wind picks up, the rate of flow entering the pressure stabilizer increases. When the water pressure in the stabilizer reaches the upper limit of 105 psi, the feedback control sends a signal to the relief valve to discharge the excess water from the system, while the system continues to operate. As the prevailing wind diminishes, the rate of flow entering the pressure stabilizer decreases. If this inflow is smaller than the outflow, the water pressure in the stabilizer declines. When the water pressure in the stabilizer declines to 75 psi, the feedback control cuts off the flow and the system operation is interrupted.

Field experiments
Field experiments were conducted in February and March 1999 at the study site on Coconut Island, Oahu, Hawaii. The average speed of wind during these experiments ranged from 4.5 to 10.3 m/s.

First, the wind pump and stabilizer subsystems were operated together to evaluate the pumping capacity of the system at varying wind speeds. During these experiments, the average pressure at the discharge end of the wind pump was controlled to stay within a small range of 560 to 670 kPa. It was found that the pumping capacity of the system increases linearly with average wind speed (Figure 3).

The performance of the data acquisition and control subsystem was then tested. Figure 4 shows the variations of the minimum and maximum water pressures in the stabilizer as monitored during the field experiment conducted in February 29, 1999, when the average wind speed was about 6 m/s. It shows that the data acquisition and control subsystem was able to control the water pressure in the stabilizer in a range of 75 to 105 psi (517 to 759 kPa) throughout the experiment.

The overall performance of the entire system is indicated by the results shown in Table 1. These results were observed during the experiment when the wind speed was 8.5 m/s and the pumping capacity was 25,700 L/d.

The flow of freshwater produced by this prototype system depends on the operating pressure. A freshwater flow of 3.2 L/min (0.85 gpm) can be produced under an operating pressure of 695 kPa, and a freshwater flow of 2.1 L/min (0.55 gpm) can be produced under an operating pressure of 520 kPa.
Brackish water with a TDS concentration that ranges up to 4,000 mg/L was desalinated successfully by this system. The salt rejection rates under varying experimental conditions were all higher than 90%. At an operating pressure of 520 kPa, the salt rejection rate for brackish water with a TDS concentration of 4,000 mg/L was 91.5%, or a product water TDS of 340 mg/L. For feed water with a TDS concentration of 2,000 mg/L and an operating pressure of 695 kPa, the salt rejection rate was 97.2%, with a product water TDS of 2439 mg/L. These results are summarized in Table 1.

Table 1 Results of field-testing of the overall system performance

<table>
<thead>
<tr>
<th>Model run</th>
<th>Feed water TDS (mg/L)</th>
<th>Stabilizer pressure (kPa)</th>
<th>Permeate flow (L/d)</th>
<th>Brine flow (L/d)</th>
<th>Brine TDS (mg/L)</th>
<th>Rejection rate (%)</th>
<th>Recovery rate (%)</th>
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<tr>
<td>1</td>
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<td>695</td>
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<td>2,439</td>
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<td>625</td>
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<td>91.5</td>
<td>3.7</td>
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</table>

Note: TDS = total dissolved solids
pressure of 695 kPa, the product water TDS was 60 mg/L. Note that both salinity levels of
the product water met the TDS standard of 500 mg/L recommended by the World Health
Organization. The recovery rate changes with the TDS concentration of feed water and the
operating pressure. The lowest recovery ratio of 3.7% occurred at a feed water TDS con-
centration of 4,000 mg/L and an operating pressure of 520 kPa; the highest ratio of 18.5%
occurred at a feed water TDS concentration of 2,000 mg/L and an operating pressure of
695 kPa.

Concluding remarks
A new technology for a wind-powered RO desalination system was developed to provide a
supplemental water supply for communities in remote islands and coastal regions where
both freshwater and electricity are in short supply. This system can be operated at a pre-
vailing wind speed that is as low as 4.5 m/s. At a moderate wind speed of 8.5 m/s, the wind-
powered pump can deliver continuously a brackish feed water flow of 25,000 L/d at a
pressure of 520 to 695 kPa. At a feed water TDS concentration of 2,000 mg/L, the system
can produce more than 3,000 L/d of freshwater. The rejection rate was over 96% and the
recovery rate was over 12%. The freshwater produced is sufficient to meet the water-supply
needs of a typical remote community. Note that a higher recovery rate or higher rate of
freshwater production can be achieved simply by using several RO units in series.

Modern thin-blade wind turbines have zero torque at start-up, when a pump requires the
most torque. Therefore, thin-blade wind turbines were not used in this project, even though
they are more efficient in absorbing wind energy. In continued technological development,
the use of a modern thin-blade wind turbine for the wind-powered RO desalination system
should be investigated by solving the start-up problem.

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