Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control

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Abstract

A prototype wind-powered reverse osmosis desalination system was constructed and tested on Coconut Island off the northern coast of Oahu, Hawaii, for brackish water desalination. The system has four major subsystems: a multi-vaned windmill/pump, a flow/pressure stabilizer, a reverse osmosis module, and a control mechanism. The feedback control mechanism, developed by this study, allowed this prototype system to be operated satisfactorily under mild ambient wind of 5 m/s or less. No auxiliary power source was needed. The system operational data showed that at an average wind speed of 5 m/s, brackish feedwater at a total dissolved solids concentration of 3000 mg/l and at a flow rate of 13 l/min could be processed by this system. The average rejection rate of this prototype system was 97\% and the average recovery ratio was 20\%. The energy efficiency of the system was measured at 35\%, which is comparable to the typical energy efficiency of well-operated multi-vaned windmills. Generally, the system’s energy efficiency decreases as wind speed increases.

Keywords: Brackish water; Reverse osmosis; Wind power; System control; Energy efficiency

1. Introduction

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

The groundwater supply in the Pacific islands generally occurs only in large volcanic islands as a basal water lens where freshwater floats on top of seawater. Water in the transition zone, which
separates freshwater from seawater in this water lens, is brackish. The high salinity of the brackish water makes this groundwater supply unsuitable as a freshwater source. Over-pumping of coastal groundwater, which causes an expansion of the transition zone as well as a declination of the water table, often causes more freshwater to become brackish [1]. As for small atoll islands, rainfall readily mixes with the underlying saltwater, such that only brackish groundwater occurs [2].

The salinity of water is usually expressed in terms of its total dissolved solids (TDS) concentration. Seawater has a TDS of 25,000 mg/l or more. Water is considered brackish when its TDS concentration is between 1000 mg/l and 10,000 mg/l. The World Health Organization's drinking water standard for salinity is less than 500 mg/l of TDS, or about 2% seawater [3]. Thus, without desalination, most of the brackish water that occurs under small atoll islands and in a transition zone under large volcanic islands is not suitable to serve as a domestic water supply.

As supplies of good-quality groundwater and surface water are not adequate, an alternative water supply must be developed for many atoll islands in the Pacific Ocean. Desalination is recognized as one of the most attractive methods to develop alternative supplies.

In this study, a prototype wind-powered reverse osmosis (RO) brackish water desalination system was constructed and tested on Coconut Island off the windward coast of Oahu, Hawaii. The objective is to develop an alternative water supply for small Pacific islands by utilizing readily available brackish water and constant trade winds.

2. Rationale for system selection

2.1. RO and brackish water desalination

Water desalination is a process that separates feed water into two streams: a freshwater stream with a TDS concentration much less than that of the feed water and a brine stream with a TDS concentration higher than that of the feedwater. The separation can be achieved by (1) thermal processes such as multistage flash distillation and freezing and (2) membrane processes such as RO and electrodialysis [4]. In the US, RO is used by most large-scale desalination facilities.

When a salt solution is separated from pure water by a semi-permeable membrane, water tends to diffuse through the membrane into the salt solution. This is the well-known natural phenomenon called osmosis. The RO process that causes water in a salt solution to move through a semi-permeable membrane to the freshwater side can be accomplished by applying pressure in excess of the natural osmotic pressure to the salt solution. The osmotic pressure difference between feed water and product water (or permeate) can be calculated by the following equation [5]:

\[
\Delta \pi = 0.078 (TDS_{\text{feed}} - TDS_{\text{product}})
\]

where \( \Delta \pi \) = osmotic pressure.

Based on Eq. (1), the osmotic pressure of seawater at a TDS concentration of 35,000 mg/l is about 2700 kPa (395 psi). Use of brackish water as feed water for the RO desalination process would give a smaller \( \Delta \pi \). Thus, brackish water desalination would require smaller applied pressure than seawater desalination. The osmotic pressure of brackish water at a TDS concentration of 3000 mg/l is only about 230 kPa (30 psi).

2.2. Natural energy and desalination

The use of natural energy to power desalination systems has been studied. Some background information on these studies as well as our study is presented below.

Ocean thermal energy conversion (OTEC) uses the ocean's natural thermal gradient between
surface water and water at a depth of 1000 m or more to drive a power-producing cycle. In an open-cycle OTEC system, warm seawater is “flash”-evaporated in a vacuum chamber to produce steam. The steam expands through a turbine that is coupled to a generator to produce electricity. The steam exiting the turbine is condensed to freshwater by cold deep ocean water [6]. Therefore, freshwater is a by-product of electricity generation. OTEC is a well-established technology. However, no commercial OTEC plants have been built due to the high cost of construction and deployment.

An ocean wave-powered RO desalination system that consists of a wave pump and an RO module was successfully developed and tested at two Caribbean locations by researchers at the University of Delaware [7]. This system is small in scale and is feasible where ocean water is shallow and under constant wave action.

The potential use of solar energy for water desalination has been studied extensively. In reality, all forms of renewable energy except tidal power are solar energy. Solar energy desalination is generally the collecting of solar thermal energy that is used for desalination directly in solar stills or that is converted to electricity first and then used in either thermal or membrane processes for desalination. A solar-powered RO system was found to be the most cost-effective, based on a study of five solar desalination systems supplying freshwater for remote arid areas of Saudi Arabia [8]. For large-scale desalination, a hybrid multi-effect distillation and RO system was found to be cost-effective [9]. As a stand-alone power system, wind was found to be more cost-effective than photovoltaic (PV) and hybrid wind/PV systems [10].

Feron [11] investigated the direct use of wind energy in an RO desalination system. He evaluated the system performance by mathematical modeling analysis under the following assumptions: (1) the system operation is intermittent, depending on wind availability, and (2) the feed water pressure is variable, depending on the prevailing wind speed. Results derived by Feron [11] were largely theoretical and were not verified with experimental data.

A small-scale wind-powered RO system was later tested by Robinson et al. [12]. Freshwater production by their system was only 0.5 to 1.0 m³/d, which is the estimated volume needed by a typical remote community in Australia. A pressure vessel to store the feedwater under pressure was included in their system. There was no feedback control mechanism for the system operation, and when the available wind power was low, a small diesel or portable gasoline pump was used.

Cost analysis of a wind-assisted RO system for desalinating brackish groundwater in Jordan was conducted by Habali and Saleh [13]. The high-pressure pump of the system was powered by either a diesel engine or a wind-energy converter. There was no actual field testing of the system. Instead, the analysis was based on measured wind speed distribution and power curves of the wind-energy converter in Jordan. The study found that it would cost less to desalinate brackish water with a wind-assisted RO system than with a conventional diesel-powered RO system.

An analytical study of utilizing wind power for RO desalination was conducted by Kiranousdis et al. [14]. Generalized design curves for process structural and operation variables were derived. The study indicated that the unit cost of freshwater production by a conventional RO plant can be reduced up to 20% for regions with an average wind speed of 5 m/s or higher.

Our study focuses on a wind-powered RO brackish water desalination system that can provide an alternative water supply for small Pacific islands. This system was selected (1) because of its cost-effectiveness and
(2) because brackish water and trade winds are two of the most important natural resources in small Pacific islands.

3. System development

A traditional wind-powered RO desalination system consists of a high-pressure pump, an RO module, and pretreatment and posttreatment units. As wind speed is highly variable, the flow rate and water pressure of the feedwater generated by a wind pump would also be highly variable. Therefore, adding a flow/pressure stabilizer and a feedback control mechanism to adjust the flow rate and water pressure according to the variable wind speed would make the system more efficient.

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 four major subsystems of the system are a windmill/pump subsystem, an RO and pretreatment subsystem, a flow/pressure stabilizer subsystem, and a data acquisition and control subsystem (Fig. 1).

3.1. Windmill/pump subsystem

There are two basic windmill designs: (1) multi-vaned windmills and (2) high-speed, thin-blade windmills. Multi-vaned windmills were invented in the US in the late 19th century and have continuously been modified and improved. Modern wind turbines for electricity generation are based on thin-blade designs in order to capture more energy from the wind. Since a pump requires the most torque at start-up, a multi-vaned windmill that produces a large torque at start-up was selected over a thin-blade windmill that has zero torque at start-up. The Dempster multi-vaned windmill used in this study has a 9.0-m-tall steel tower and 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.

3.2. RO and pretreatment subsystem

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

\[ Q_p = A_m K (\Delta P - \Delta \pi) \]

where \( A_m \) = membrane surface area (m\(^2\)); \( K \) = water permeation coefficient (s/m), which depends on the nature of the RO membrane, \( \Delta P \) = pressure differential between the feedwater and product water (kPa) and \( \Delta \pi \) = osmotic pressure difference between the feed water and permeate (kPa).

One of the major advancements in membrane technology for brackish water desalination is the development of ultra-low-pressure membranes [15]. A Filmtec ultra-low-pressure RO membrane that can be operated at a feed water pressure
ranging from 520 to 690 kPa was used by our prototype system. Typical operating pressure for traditional low-pressure brackish water desalination has been 1200 to 1900 kPa [15]. The lower operating pressure for an ultra-low-pressure membrane results in lower energy consumption. More important, the energy can be easily generated and maintained by a wind pump.

A pretreatment is applied to maximize the RO system 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 feedwater source. In general, well water requires very simple pretreatment, such as acid injection and microfiltration [16]. On the other hand, pretreatment of surface water usually requires additional steps such as polymer addition, clarification, and microfiltration or ultrafiltration. The brackish water used in this study was a mixture of tap water and pure sodium chlorides. A microfilter operated at the same feedwater pressure was used as the pretreatment unit.

3.3. Flow pressure stabilizer subsystem

The stabilizer used by this project is a hydro-pneumatic pressure tank, with an inside diameter of 0.562 m (22 1/8"), an outside diameter of 0.572 m (22 1/2"), and a height of 1.143 m (45"'). Its total volume is 0.3 m³ (75 gal), 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 (3/16") thick, and the heads, made of ASTM A 36 steel, are 0.006 m (1/4") thick. The stabilizer is precharged with air by injecting air under pressure into the empty tank 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. To eliminate "water-logging" problems, a

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**Fig. 2. Flow chart of the simple data acquisition and control mechanism.**

diaphragm or a bladder separates the air and water in the tank.

3.4. Data acquisition and control subsystem

The feedback control is accomplished by a simple data acquisition and control device and a feedback flow/pressure control device. The data acquisition and control device consists of a Campbell Scientific CR10X datalogger, a pressure sensor, a solenoid valve and relay set, and a flow sensor and relieve valve set (Fig. 2). The desirable operating pressure range for the RO used by this study is 517 to 724 kPa (75 to 105 psi). The solenoid valve is closed when the system operation starts. As water is pumped into the stabilizer, water pressure in the stabilizer builds up. When the pressure reaches a pre-set value of 517 kPa, the data logger 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
The feedback control is made of three parallel sets of solenoid/throttle valves (Fig. 3). Signals of water pressure in the stabilizer are sent through the pressure sensor to the data logger. The data logger evaluates these signals and then sends a command to open one or more sets of solenoid/throttle valves. Only one solenoid valve opens when the water pressure is between 517 and 586 kPa. Two solenoid valves open when the water pressure is between 586 and 655 kPa. Three solenoid valves open when the water pressure is between 655 and 724 kPa. This control mechanism allows the system to operate continuously and efficiently.

4. Field experiments

Field experiments were conducted on July 7 and 13, 1999, at the experimental station on Coconut Island, Hawaii. The prevailing wind during these experiments was mild with an average speed of about 5 m/s. Wind speed was relatively uniform on July 7 but highly variable on July 13 (Figs. 4a and 5a). Between 11:00 am and 12:30 pm on July 13, the average wind speed was below 2 m/s. TDS concentration of the feed water was 3500 mg/l for the July 7 experiment and 2700 mg/l for the July 13 experiment.

4.1. System performance

Figs. 4b and 5b show the variations of the average water pressure in the stabilizer during the July 7 and 13 experiments, respectively. Water pressure was monitored by the sensor on top of the stabilizer (Fig. 1). The pressure sensor recorded the minimum, maximum, and average water pressure every second and sent a signal to the data logger. The control subsystem developed by this study was able to control the water pressure at a rather constant value of 650 kPa throughout the experiments, even though the wind speed varied significantly.
Average rates of feedwater flow are shown in Figs. 4c and 5c. During the July 7 experiment, the average feed water flow rate of about 13 l/min was maintained. During the July 13 experiment, there was a larger degree of wind fluctuation. With the minimum wind speed dropping to below 2 m/s around noon. Under these adverse conditions, the system operated with only a very short period of interruption (Fig. 5c). The interruption of feed water flow occurred when the pressure in the stabilizer fell below 517 kPa.
Fig. 6. Product water flow rate for experiment conducted on July 7, 1999.

The rate of freshwater production in the July 7 experiment is shown in Fig. 6. At an average ambient wind speed of 5 m/s, a freshwater flow of 2.7 l/min (or about 4000 l/d) can be produced; this volume is sufficient to meet the freshwater demand of a typical remote community [12]. It is possible to increase the freshwater production by using several RO units in series.

Performance of the RO process is usually evaluated by two parameters: 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 the permeate concentration and $C_f$ is the feed water concentration. The recovery rate indicates the permeate discharge produced from a given feedwater discharge, or $Y = (Q_p/Q_f) \times 100\%$, where $Q_p$ is the permeate discharge and $Q_f$ is the feed water discharge. For both experiments, the TDS concentration of permeates ($C_p$) was below 100 mg/l. In the July 7 experiment, the average rejection rate was 96.8% and the recovery ratio was 19.3%. In the July 13 experiment, the rejection rate was 97.8% and the recovery ratio was 23.0%.

4.2. Efficiency of wind energy conversion

The energy input of the prototype system is the wind power absorbed by the windmill. This energy can be calculated by

$$P_{\text{wind}} = \frac{1}{2} \rho A C_p V^3$$

where $P_{\text{wind}}$ = power generated by the windmill (W), $\rho$ = air density (kg/m$^3$), $V$ = wind speed (m/s), $A$ = rotor swept area (m$^2$) and $C_p$ = power coefficient.

From Betz’s Law, the maximum value of $C_p$ is about 59%. In practice, the value can vary between 15% and 45% or more for different kinds of windmills and for different sites.

Fig. 7 shows the available wind power calculated by Eq. (3) where $\rho$ equals 1.20 kg/m$^3$ and $C_p$ equals 0.3. The data for average wind speed per minute recorded by an anemometer were used in the calculation. Fig. 7 also shows the pressure energy of the water delivered by the wind pump, which is the water flow pressure energy into the stabilizer, as calculated by
Fig. 7. Average wind power and water power generated by the windmill in the July 7, 1999, experiment.

\[ P_{\text{water}} = 0.24 \, Q \, P \]  \hspace{1cm} (4)

where \( P_{\text{water}} \) = the energy of the water delivered by the wind pump (W), \( Q \) = water flow rate (l/min) and \( P \) = pressure head of pumped water (kPa).

The energy efficiency of the prototype system can be calculated by \( P_{\text{water}} / P_{\text{wind}} \). Fig. 8 shows energy efficiency as a function of ambient wind speed. It indicates that the energy delivered by the wind pump to the feedwater is much smaller than the energy provided by ambient wind. The

Fig. 8. Energy efficiency of desalination system under varying wind speeds in the July 7, 1999, experiment.
average energy efficiency was 35%, and it decreases as the speed of ambient wind increases.

5. Conclusions

Most past studies of wind-powered desalination used the wind power indirectly — that is, it was used to generate electricity and then the electricity was used for desalination by thermal or membrane processes [17]. In the prototype system developed by this study, wind energy was used directly to raise the feedwater pressure for RO desalination. It involves less energy conversion and thus higher efficiency and system simplicity.

Brackish water desalination by RO requires much lower feedwater pressure than seawater desalination. This lower pressure can be generated and delivered by moderate wind speed ranging from 4.5 to 9.0 m/s. Brackish groundwater is available in many remote Pacific islands, which are also subject to constant trade winds at 5 m/s or higher. Therefore, wind-powered RO brackish water desalination is an attractive water supply alternative for remote Pacific islands.

The prototype wind-powered RO desalination system constructed on Coconut Island in Hawaii consists of a multi-vaned wind pump, a flow/pressure stabilizer, an RO unit, and a data acquisition and control mechanism. It was tested in two field experiments conducted on July 7 and 13, 1999. With the control subsystem developed by this study, the system was operational even when the ambient wind was highly variable.

Field data indicated that a feedwater flow of about 13 l/min could be maintained by this system at an average wind speed of 5 m/s. The average recovery ratio, which is the ratio of permeate flow to feedwater flow, was about 20%. The average rejection rate, which indicates salt removal, was about 97%.

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. The use of a modern thin-blade wind turbine for wind-powered RO desalination system should be investigated by first solving the start-up problem.

A major problem in the RO process is fouling, which is the scaling or plugging of membrane surfaces over time by organic and inorganic substances present in the feedwater. Fouling prevention requires the pretreatment of feedwater or the addition of antiscalants. The brackish feedwater used in the prototype experiments, which was prepared by mixing tap water with pure sodium chlorides, required only a simple microfilter for pretreatment. The fouling problem and pretreatment requirement will be investigated in future studies.

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References


