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A CASE STUDY OF DECENTRALIZED OFF-GRID WATER TREATMENT USING REVERSE OSMOSIS

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ABSTRACT

Decentralized water treatment consists of a variety of water treatment techniques for dwellings, industrial facilities, homes, and businesses independent of the power grid. According to the United States Geological Survey, brackish groundwater is abundant in the southwestern states including California; hence it can potentially be considered a new source for California's water portfolio. Most of membrane-based desalination technologies (e.g. reverse osmosis) have high energy demand and cost. Using renewable energy (mostly solar photovoltaics) in concert with membrane-based water desalination can be utilized to develop decentralized and off-grid brackish water desalination systems especially for remote and rural regions. In this paper, the results of a case study on decentralized off-grid brackish water system have been presented and discussed. The system utilizes a high pressure pump that can provide a feed flow rate of 2.2 gpm of at 140 psi. The system is run by solar photovoltaic panels through a battery bank. The results of the study show that the system is capable of treating brackish water at a salt rejection rate of more than 97.5% and a recovery rate up to 80%.

INTRODUCTION

Water crisis is going to be the greatest challenge that human race has been exposed to in the recorded history soon. World Economic Forum identified the water crisis as the first and third global risk based on impact to society in 2015 and 2016, respectively [1]. Statistics show that 1 in 10 people worldwide and 8 of 10 people who live in rural areas do not have access to safe drinking water [2]. Data show that the number of people worldwide who have a cellular phone is more than the ones who have access to sanitary toilet [3]. Although the number of people who live in remote rural areas of the world has a decreasing trend, the number of people who live in those areas is more than 46% of world's population [4].

Decentralized water treatment systems can potentially provide the people who live in remote areas with a reliable source for drinking water. The design requirements of decentralized water treatment systems have parallels with centralized systems; however, there are important considerations that should be noted. In general, decentralized water treatment systems are expected to be robust, affordable in terms of capital cost, low-maintenance, and energy-efficient. Access to the power grid is usually limited in rural areas and operation of decentralized water treatment systems should ideally be grid-independent. The residents of remote communities often rely on brackish groundwater, rainwater from cisterns, or water found in open ponds, streams or rivers.

Water reuse is an appealing option to increase water availability for remote rural areas. Water reuse is a fairly new trend, as new water treatment technologies have been developed over the years. It should be noted that water reuse applications require different water quality specifications and thus demand different treatments varying from simple processes to more advanced ones.

Membrane technologies provide a cost-effective solution for water and wastewater treatment and desalination. These technologies appear to be a reliable alternative for conventional water treatment methods. The membrane

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technologies can be classified into two main categories: pressure driven membranes such as reverse osmosis and electrical driven membranes such as electro dialysis. Pressure driven membranes are in four different types based on the membrane pore sizes: Microfiltration (MF, screens particles from 0.1 to 0.5 microns), Ultrafiltration (UF, screens particles from 0.005 to 0.05 microns), Nanofiltration (NF, screens particles from 0.0005 to 0.001 microns), and Reverse Osmosis (RO, ranging molecular size down to 10 MWCO) [5].

Literature on decentralized RO-based water treatment is limited. Many of the decentralized membrane water treatment systems that currently exist are larger scale and a majority of the systems treat brackish water and seawater. The systems are most commonly used in small communities of several households and villages, but not to the extent that it is considered a plant. Elsaad et al. [6] from MIT developed a decentralized RO-based water treatment system to produce potable water for a village in Yucatan Peninsula of Mexico. Their system was able to treat groundwater as well as rainwater collected in cisterns at a feed flow rate of 1.9 gpm. The high pressure pumps of the system was powered by two 400W solar PV panels. In a similar approach, Qiblawey et al. [7] developed a photovoltaic-driven Reverse Osmosis (PV-RO) system in Jordan that is capable of producing 132 gallons of permeate daily with a feed water flow rate of 0.67 gpm. In their technology a softener unit is considered before the RO system as a pre-treatment step to eliminate mineral ions that cause scale problems. In addition to the softener, a train of 5-micron sediment filter, a granular activated carbon filter, and a 1-micron sidemen filter was used.

In a different and more recent effort, Gökçeks [8] developed a wind-driven RO system for remote locations in Turkey to desalinate seawater. They tested the RO system in conjunction with a variety of wind turbines, ranging from 6 to 30 kW. The excess power generated by wind turbines were exported to the local power grid. They demonstrated that their wind-driven system produces water at a rate of 4.4 gpm and at a slightly higher cost compared to a grid-tied desalination unit.

In the current study, the preliminary results of Decentralized Renewable Off-grid Water Treatment (DROWT) project are presented. The developed technology incorporates a solar driven RO filtration system that is designed to operate independent of the power grid. Although the ultimate goal of the project is developing a water reuse technology for dwellings in remote areas, the system is also applicable for brackish water desalination.

REVERSE OSMOSIS THEORY

RO is a membrane-based technology that is widely used for water treatment. In this method, raw water that includes particles and contaminants, is pushed through a semi-permeable membrane. The membrane is only permeable to water due to its small molecular size and impermeable to dissolved and suspended particles. The flowrate of the RO process product (permeate) is found by Eq. (1)

$$Q_w = \left(\Delta P_{Hyd} - \Delta P_{Osm}\right) \times K_w \times S \qquad (1)$$

where Q_w is the permeate flow rate, ΔP_{Hyd} is the hydrostatic pressure across the membrane, ΔP_{Osm} is the osmotic pressure of the feed water, K_w is the water permeability coefficient, and S is the wetted surface area of the membrane [9] . In order for RO process to generate product flow, the hydrostatic pressure across the membrane must overcome the osmotic pressure of the feed water. The osmotic pressure of the feed water is found by Eq. (2)

$$\Delta P_{Osm} \approx RT\left(C_{feed} - C_{per}\right) \qquad (2)$$

where R is the ideal gas constant (8.3144598 kg m^2 s^{-2} K^{-1} mol^{-1}), T is the temperature of feed water (K), and C_{feed}, C_{per} are molar concentration of dissolved species (mol m^{-3}) in feed and permeate flows, respectively. Since the concentration of the dissolved solids in the permeate flow is smaller than that of feed water (i.e., $C_{feed} \gg C_{per}$), the osmotic pressure of the feed water is almost linearly related to the concentration of dissolved solids in the feed water. The molar concentration of dissolved solids is commonly represented by Total Dissolved Solids (TDS) and the electrical conductivity of the feed water.

CONFIGURATION OF THE SYSTEM

In this effort, a solar-driven and off-grid water treatment system is fabricated, and tested. Figure 1 illustrates the configuration of the test setup. The hydraulic circuit of the system include the following components. A low pressure 12V DC pump (Seaflow 12V, 4.5 GPM Model No. SFDP1-045-040-41) is used to receive the raw water from the feed tank and pressurize it to about 75 psi, and send the water to an array of two micro-filtration(MF) units (Polystyrene Plastic, 4gpm, 5 microns), a ½ inch spring check valve is installed downstream of the low-pressure pump to prevent backflow. Pressure gauges are installed upstream and downstream of the MF configuration. A secondary high-pressure pump (PumpTec Model No. 350U) is installed downstream of the micro filters to increase the pressure beyond the osmotic pressure of the feed (maximum of 150 psi). Similarly, a check valve is installed downstream of the secondary pump to prevent backflow and damp potential vibration of the flow. An analog pressure gauge and a digital pressure transducer are installed downstream of the high pressure pump.

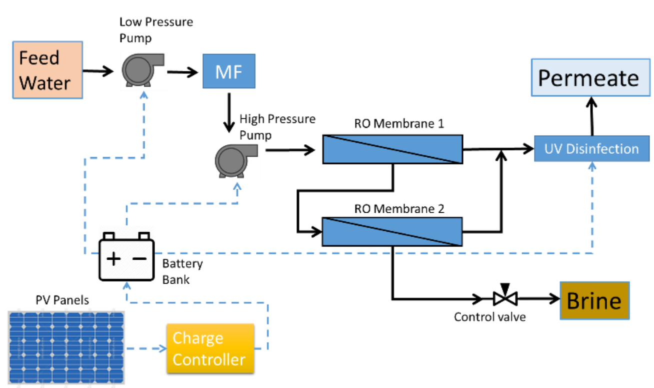

Figure 1 – Hydraulic and Electrical Circuits

The high pressure water is sent to a train of two Toray 4” RO membranes (Model No. SU-710L) that are installed in 2 stages with 1x1 configuration. The reject of the first membrane is fed to the second membrane for increasing the recovery rate. The brine of the second membrane passes through a digital, Arduino-compatible flowmeter before being collected in the disposal tank.

The permeate flows from both membranes are combined and diverted through an Ultra Violet (UV) disinfection unit. The UV disinfection unit (Viqua Model No. S2Q-P/12VDC) ensures that the micro-organisms that may have escaped through the RO process are deactivated by the UV light. The treated water was then sent through a digital flow meter and sent to permeate storage tank as seen on Figure 1. The recovery rate and feed pressure of the system is manually regulated by an accurate needle-valve that is installed on the reject line of the second stage.

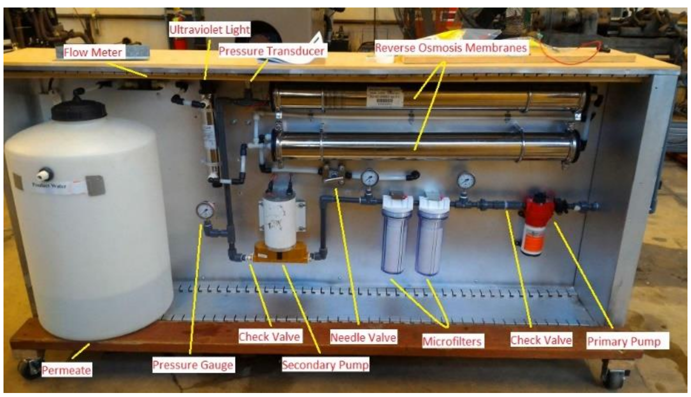

Figure 2 – Configuration of the system

The low- and high-pressure pumps as well as the UV disinfection unit are powered by a two wet-cell lead acid batteries that operate at 12V and are rated at 115 amp-hrs. The batteries are charged by two 115 Whr NewPowa solar panels through a charge controller (Sun YOBA Solar Charge Controller Solar Controller 80A 12V 24V Solar80). The pressure transducers and flow meters are connected to an Arduino MEGA 2560 for data acquisition. The energy consumption of the system is evaluated by measuring the amount of DC current that is withdrawn from the battery bank during the tests.

EXPERIMENTAL PROCEDURE

The feed water was prepared by solving lab grade sodium chloride (NaCl, 99% purity) in deionized water. The salt was added to the deionized water until the solution reaches a conductivity of 2000 µS/cm which is within the range of brackish groundwater. Per the quality assurance protocol, the experiment was performed after calibration of flow mater sensors, pressure transducers, electrical conductivity sensors, and current sensors. At first, the needle valve (control valve) was remained fully open and the low-pressure pump was turned on to receive the feed water from the tank and push the water through MF units. Once the flow is stabilized, the high-pressure pump was turned on and the system ran for a twelve minutes before data acquisition starts. The data acquisition system read and recorded the values of all sensors with a resolution of 5-second. The data was stored on a SD memory card.

The recovery rate and feed pressure are controlled by the needle valve, installed on the concentrate line. Recovery rate is defined as the ratio of permeate flow to the feed flow rate. Closing the needle valve on the concentrate line, increases the hydraulic resistance imposed on the concentrate line and the total resistance of the hydraulic circuit. As a result, the feed pressure and the recovery rate increase, leading to generation of more product. The needle valve was adjusted to reach higher feed pressures and a new set of data was recorded every $\Delta P_{feed} = 20$ psi. The test was carried out until a maximum feed pressure of 140 psi was achieved. Increasing the feed pressure beyond 140 psi leads to extremely high recovery rates and was avoided to prevent damaging the RO membranes due to fouling.

RESULTS AND DISCUSSION

Figure 3 illustrates the change in feed and permeate flow rates and recovery rate as a function of feed water pressure. The permeate flow rate and the recovery rate show an increasing trend with the feed water pressure. The linear change in permeate flow rate and recovery rate are in agreement with the theoretical predictions of Eq. (1). Since the osmotic pressure across the membrane (ΔP_{Osm}) does not significantly change by increasing the hydraulic pressure, it is expected that the permeate flow increases almost linearly with feed water pressure. The feed flow rate does not significantly change during the test; however a minor reduction is observed due to increased hydraulic resistance in concentrate line.

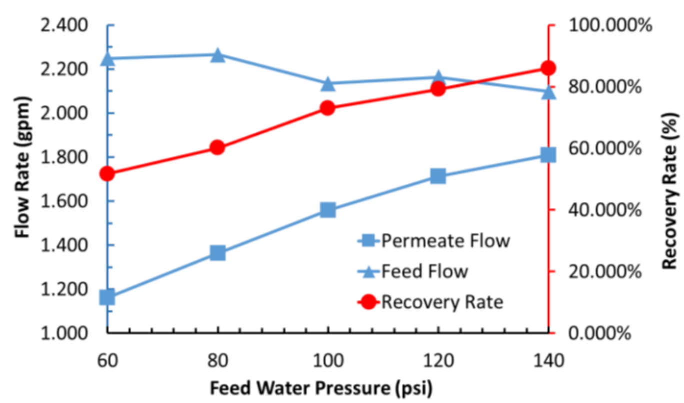

Figure 3 – Feed and permeate flow rates and recovery rate as a function of feed water pressure

The effectiveness of RO process in desalinating the feed water is shown in Figure 4. The conductivity of the permeate flow is plotted as a function of feed water pressure. The results show that the conductivity of the permeate flow (20~50 µS/cm) is significantly reduced in comparison to the feed water (2000 µS/cm), leading to a salt rejection rate of more than 97.5%. Increasing the pressure of the feed flow leads to higher conductivity of permeate flow due to the fact that more salt molecules will penetrate through the membrane and show up in the permeate at higher feed pressures.

Energy consumption per unit volume of the permeate flow (aka Specific Energy Consumption or SEC) as a function of feed water pressure is plotted in Figure 4. The variations of SEC during the test exhibits an interesting trend. Higher feed water pressure leads to generation of more permeate water volume and increased consumption of energy concurrently; however, the effect of permeate volume on the SEC appears to be more dominant in smaller recovery rates (or feed water pressures). The results show that the effect of energy consumption will be more significant in the higher recovery rates. As a result, the values of SEC start to increase at higher feed water pressures, leading to appearance of a minima. This phenomenon has been previously reported by Li [10] in an effort to optimize the operation of brackish water RO desalination plants. The optimal operation point of the current system appears to be at about 120 psi of feed water pressure. The existence of an optimal point for specific energy consumption is an important consideration when designing an off-grid system that relies on solar energy.

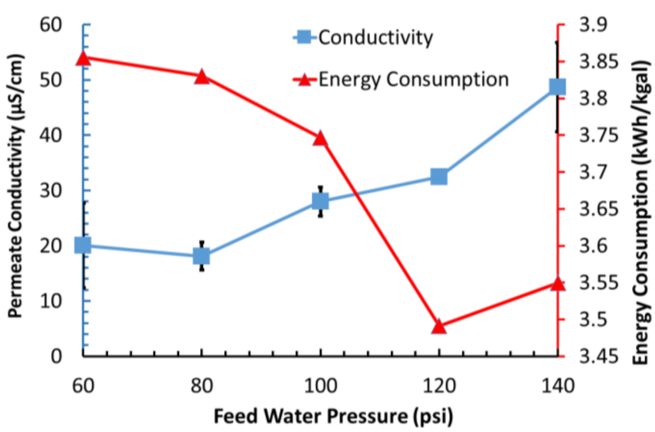

Figure 4- Energy consumption per unit volume of product and conductivity of permeate flow as a function of feed water pressure. The conductivity of the feed is ~2000 µS/cm

CONCLUDING REMARKS

In this effort, a decentralized grid-independent, zero carbon-footprint water treatment system is developed. The system utilizes a micro-filtration pretreatment, a two-stage reverse osmosis, and an ultra violet disinfection posttreatment. The system is solely powered by solar-photovoltaic panels through a battery bank.

The developed system is capable of desalinating and disinfecting a permeate flow rate of 1.2-1.8 gpm with a recovery rate of 60-80%. A minimum salt rejection rate of 97.5% is achieved at 140 psi of feed water pressure.

A preliminary energy consumption analysis show that the specific energy consumption of the system varies between 3.5-3.85 kWh/kgal. The results of this study show that the specific energy consultation of the system reaches a minima at intermediate recovery rates.

FUTURE WORK

The ultimate goal of the Decentralized Renewable Off-grid Water Treatment (DROWT) project is developing a commercially available, standalone, portable, and grid-independent water treatment for graywater reuse and ground water desalination. In the next steps, the team will work on reducing the footprint of the system and increasing the robustness and reliability of the system along with a more rigorous data analysis. In addition, contaminants of emerging concerns (CECs) [11] will be studied in graywater treatment using this process.

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