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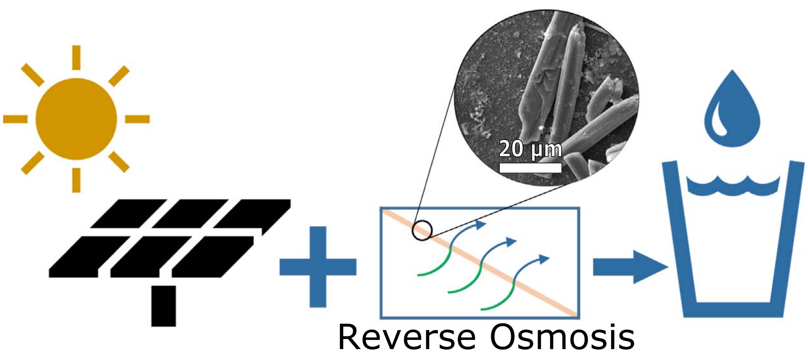
Experimental quantification of the effect of intermittent operation on membrane performance of solar powered reverse osmosis desalination systems

M. Freire-Gormaly*, A.M. Bilton

Water and Energy Research Lab, Department of Mechanical and Industrial Engineering, University of Toronto, 5 Kings College Rd., Toronto, ON M5S 3G7, Canada

GRAPHICAL ABSTRACT



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ABSTRACT

Many remote communities lack access to reliable clean water and electricity, leading to the development of renewable powered desalination systems. To reduce costs of energy storage, many of these systems operate intermittently. However, the impact of intermittent operation on membrane fouling is still not well understood. This article presents an experimental investigation of the effect intermittent operation characteristic of renewable powered desalination systems has on membrane performance. Three operating conditions were investigated: use of anti-scalant or no anti-scalant; intermittent or continuous operation; and rinsing with 8 L of lab-grade clean water prior to shut-down or no rinsing. The results show intermittent operation increases the rate of membrane scaling. However, maintenance with rinsing prior to shut-down maintains higher membrane permeability than without rinsing. Membrane autopsy using scanning electron microscopy showed the fewest scale deposits for intermittent operation with anti-scalant and rinsing. On the sixth day of operation, the average normalized permeability declined to 87 ± 9% for intermittent operation with anti-scalant and with rinse. All other operating conditions declined to nearly zero with the exception of continuous operation with anti-scalant, which declined to 30 ± 4%. These experimental results will be used in future work to develop robust design algorithms for renewable powered desalination systems.

* Corresponding author.
E-mail address: m.freire.gormaly@utoronto.ca (M. Freire-Gormaly).

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1. Introduction

1.1. Motivation

According to the World Health Organization, 663 million people lack access to clean drinking water [1], and this is expected to increase as half of the world's population will be living in water-stressed regions by 2025 [2]. Solar power is well-suited as a power source for desalination technologies due to the high correlation between water stressed regions and areas of high solar resource [1]. Similarly, for regions with good wind resource (typically islands) wind turbines have been coupled with desalination technologies [3].

Solar and wind power are intermittent and require expensive energy storage to maintain a consistent power supply. Solar power is intermittent on two main time-scales, first on a daily time-scale due to the solar insolation at a particular location follows a bell shape from zero before sunrise rising to a peak at midday and decreasing to zero at sunset, second on a shorter time-scale due to cloud cover which induces power production fluctuations. To make renewable powered desalination systems cost-effective, several researchers have removed the majority of the energy storage [4–8]. This led to the need to operate the desalination systems with variable operating conditions and intermittently with long shut-down periods overnight. This variable and intermittent operation is well accepted in the literature [6,9–11] to be linked to premature fouling of the reverse osmosis membranes. The effects of variable operating conditions on shorter time-scales caused by the inherent variability of the sun have been studied [12–14] and it was shown that solar powered reverse osmosis systems without batteries were able to produce high quality permeate water while tolerating fluctuations in solar irradiance. However, to date, there has not been an experimental study explicitly evaluating the impact of intermittent operation (from long shut-down periods overnight) on membrane fouling.

In this paper, the effect of intermittent operation on membrane fouling was investigated. The effect of typical operating conditions, such as the addition of anti-scalant and membrane rinsing, were also evaluated. These results will be used in future work to influence the operational design of improved solar desalination systems which take into consideration the membrane fouling caused by intermittent operation.

1.2. Background and literature review

Several existing renewable powered reverse osmosis systems have been installed and studied previously [4,5,15–17]. Studies on existing renewable powered reverse osmosis systems tend to focus on either the pilot-scale implementation [9,11,18,19] or the design and cost optimization [3,20–22]. All renewable powered desalination systems have inherent intermittent operation due to the intermittent nature of the power source. For example, wind power is only available during wind gusts. As well, solar power is only available during daylight hours and varies with cloud cover. Many researchers claim intermittent operation leads to increased membrane fouling rates [6,9–11] and high fouling rates have been observed in operating plants with several years of data [23]. However, to our knowledge these claims have not been thoroughly experimentally verified nor has the effectiveness of remedial actions, such as permeate rinsing, been studied.

Experimental studies are needed to show the effect of intermittent operation on membrane fouling, as membrane replacement can be a challenge for remote areas and is a major operating cost for these small scale systems. Also, the effect of simple interventions that can be undertaken for these small-scale solar powered systems, such as anti-scalant addition and rinsing of the membranes prior to shut-down, require investigation. Use of anti-scalants for prevention of mineral scaling is well established as one of three main strategies to control scale formation [24]. Other strategies, such as changing the feed water characteristics through complex pre-treatment, and optimization of the system operating conditions are challenging to implement for small-scale reverse osmosis systems. For these systems, small brine volumes are desired for minimal environmental impact and design simplicity (minimal pre-treatment and minimal chemical addition) is preferred for ease of use in remote communities.

Previous studies on anti-scalant efficacy have focused on the ability of anti-scalants to delay the onset of specific mineral scales [25–27], on the mechanisms of scale formation [10,24,28–30] and on the effect of pH on scale formation [31]. The anti-scalants available on the market fall in three main categories: phosphonates, phosphates, and polycarboxylates. Of these three categories, only polycarboxylates are environmentally benign [24,32], making them appropriate for implementation in renewable powered reverse osmosis systems, which have minimal brine post-treatment [6]. The commercial polycarboxylate anti-scalants delay mineral scales by threshold inhibition, crystal modification resulting in a crystal that is unable to adhere to the membrane surface, and by delaying the clustering of scale nuclei and charged ions to prevent scale crystal formation. To date, studies investigating the effect of prolonged anti-scalant contact with the membrane during extended shut-down periods, typical of renewable powered desalination systems, have not been conducted.

1.3. Approach

In this paper, the membrane fouling caused by intermittent operation is experimentally examined. The operating conditions are chosen to be representative of a small-scale solar powered reverse osmosis system located in La Mancalona, Mexico [6]. This system uses a set of solar panels, one lead-acid battery (12 VDC) and an off-the-shelf charge controller. The reverse osmosis system is operated during daylight hours, at a constant pressure and feed flow-rate with anti-scalant for between 4 and 8 h per day (dependant on the community's water consumption) to refill a large permeate water storage tank. Prior to shut-down, the system is rinsed with permeate water and is off for the remainder of the day until the next day.

The operating conditions investigated in the experimental system were the use of an anti-scalant, the use of clean water for rinsing the membranes prior to extended shut-down and the role of intermittent operation vs. continuous operation. The trade-off between anti-scalant usage, permeate water rinsing and membrane fouling was investigated. Surrogate water was tested because shipping the required water volumes from the remote target community in La Mancalona, Mexico was unfeasible.

The system located in La Mancalona, Mexico [6] was designed with minimal battery storage. Although many solar powered reverse osmosis systems operate in a load-following manner, the La Mancalona, Mexico plant operates continuously at a constant flow rate and pressure. Solar powered reverse osmosis systems that operate at a constant flow rate and pressure with extended shut-down periods have been installed in Morocco under the ADIRA project [33].

The effect of intermittent operation and the operating conditions was evaluated using a custom designed experimental system. The experimental system allows for testing different operating conditions (e.g. anti-scalant, intermittent operation, continuous operation, rinsing before shut-down) and online continuous monitoring of the system parameters (e.g. pressure, conductivity, permeate flow rates). The experimental system also has autonomous controls to maintain a consistent recovery ratio using an automated needle valve and consistent feed water concentrations through monitoring of the equalization tank.

This paper presents the lab-scale experiments to quantify the membrane permeability decline due to intermittent operation typical of renewable energy powered reverse osmosis systems. In addition, permeability changes and salt rejection changes due to operating conditions were experimentally evaluated. After experiments were completed, a membrane autopsy was conducted to determine the