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Renewable energy powered membrane technology: Safe operating window of a brackish water desalination system

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ABSTRACT

The safe operating window (SOW) of a renewable energy (RE) powered membrane filtration system for brackish water desalination is determined. The SOW is constrained by several factors: (i) operating limits of pump motor (pressure and flowrate), (ii) maximum recommended recovery, and (iii) the osmotic pressure of the feedwater. The membranes (and brackish feedwater salinities) used were BW30 (5500 and 10,000 mg/L), aged BW30 (5500 mg/L) and NF90 (5500 and 2750 mg/L). At lower salinities (2750–5500 mg/L) the main constraint was maximum recovery (30%), while at higher concentrations (10,000 mg/L) osmotic pressure played a more limiting role. The optimum operating strategy is ‘constant recovery’. This produces the highest flux at a given power consumption and thus the lowest specific energy consumption (SEC) while maintaining good retention. However, this operating strategy can be difficult to implement. Therefore, ‘constant set-point’ mode is recommended for this system in order to provide a robust and effective solution, despite a minor reduction in performance. This approach is attractive for being powered by a wind turbine or solar energy (photovoltaics) given the low SEC (~ 3 kWh/m^3) that enables operation over a very wide power range (70–280 W) in order to achieve the desired pressure range (5–11.5 bar). Overall, the SOW methodology can be used in the performance evaluation of a wide range of membrane filtration systems.

1. Introduction

The energy–water nexus experienced in remote areas means that the lack of safe drinking water is exacerbated by the scarcity of electricity that is required to power water purification systems [1]. The flow-on effect of energy shortages and the impact of climate change on water supply have major implications for rural poverty, as described by the United Nations Millennium Development Goals [2]. The development of low-pressure reverse osmosis (RO) and nanofiltration (NF) membranes [3] has triggered significant interest in applying membrane desalination as a cost-effective strategy for desalination of brackish groundwater. Thus, great potential exists for decentralised renewable energy powered membrane (RE-membrane) systems for overcoming the dearth of infrastructure and providing potable water in off-grid locations, from brackish groundwater sources in both developed and developing countries [4].

Integrated RE-membrane systems can avoid fossil fuel dependency and the subsequent greenhouse gas emissions, as well as ultimately lowering energy and water costs [5]. Such systems are also being considered for emergency water supply [6]. Although membrane filtration is sometimes regarded as being both a capital- and energy-intensive technology, the energy consumption is predicted to decrease significantly in the coming years due to advances in membrane technology [7]. Already, RE-membrane systems can be a cost-competitive clean water supply option for developing countries [8]. The potential for developing high permeability membranes for low recovery in brackish water desalination systems has been reported [9]. One of the key barriers to the widespread implementation of RE power systems is the lack of a cost-effective means of storing enough electricity to enable sufficient power to be provided to a load during cloudy or calm periods [10]. Traditionally, small wind and solar power systems have relied on using lead acid batteries for energy storage; however

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performance, maintenance and safety challenges of implementing this technology in remote locations remain [11]. However, via a paradigm shift, the realisation of directly connected RE-membrane systems that possess no energy storage components can allow the performance to vary with resource availability and actually realise *more robust* systems [12,13]. Nonetheless, the challenge of operating under fluctuating power conditions is not trivial. Indeed, in some ways, it goes against many of the 'design rules' used by RE and membrane filtration engineers alike: that a stable power source is required in order to achieve constant flow and pressure [14]. While it has been demonstrated that RE-membrane systems can function from a varying wind or solar resource, a significant lack of knowledge exists around what the actual constraints are in determining the performance of such systems and the best strategy for operation.

Therefore, the motivation for this research is to experimentally demonstrate, for the first time, a safe operating window (SOW) for a RE-powered reverse osmosis (RO) system and to determine the optimum operating strategy for variable power operation. Operating within the SOW is technically desirable as it will enable maximum potable water production at minimal cost, while reducing the risk of performance degradation caused by high recovery operation. The method developed can be applied to any other membrane system and demonstrates the possibility of operating without energy storage. The SOW concept was first proposed by Feron [14] for the transient operation of wind-powered seawater RO systems, observing that the operation is expected to encounter both intermittency (period of calm or darkness) as well as fluctuations in power according to the instantaneous wind speed or solar radiation. It was concluded that irregular operation would not cause any major problems as long as the cycling on/off of the plant was controlled such that the rate of pressure change and the frequency of cycling did not cause any damage to the membranes.

The SOW originally proposed by Feron was a curved-sided quadrilateral that is derived from the constraints from the membrane characteristics, which were defined as follows [14]:

i. maximum feedwater pressure: as determined by the mechanical strength of the materials used in the membrane;
ii. maximum concentrate flowrate (or crossflow velocity): limited by mechanical deterioration at high concentrate flowrates;
iii. minimum concentrate flowrate: risk of water quality and recovery-dependent scaling and fouling due to concentration polarisation; and
iv. maximum permeate concentration: defined by water quality guidelines. Feron [14] set this as 500 mg/L of total dissolved solids (TDS). The World Health Organisation (WHO) [15] notes that water with a TDS > 1000 mg/L is unpalatable. Therefore, a sodium chloride (NaCl) concentration of 1000 mg/L was used as the target value. Low pressure can cause the permeate to exceed the target value as the salt concentration in the permeate is inversely proportional to the difference between the applied pressure and the osmotic pressure gradient.

In essence, power fluctuations will affect pressure and feed flowrate – the combination of which will determine recovery and concentration polarisation, which in turn affects both fouling/scaling and permeate quality. Generally, when not only seawater is concerned, how a system responds to those parameters depends on the feedwater quality.

Feron [14] proposed two recommendations to allow wind-membrane seawater plants to deal with a variable wind resource: (i) vary the membrane area; or (ii) allow transient operation within the constraints of the SOW. The conclusion at that time was that neither option was economically beneficial as it involved either under-utilisation of expensive membrane area or a relatively minor increase in productivity for the increased complexity of the plant. While the work of Feron [14] has since been noted by several authors [16–19], as yet there has been no detailed experimental investigation or verification of an operating strategy for transient operation of wind-membrane plants within a SOW. Miranda and Infield [19] modelled a wind-membrane system for seawater desalination that included both a medium- and high-pressure displacement pump to allow independent control of the feed flowrate and pressure at any point within the SOW according to the available wind speed. However, further details on how this operating strategy could be applied were not provided, the testing was limited, and the requirement for having two pumps, motors and inverters would prove costly and reduce robustness. Moreno and Pinilla [17] used ROSA software [20] to determine the operating limits for a wind-powered seawater desalination plant. Minimum concentrate flowrate and the maximum feed flowrate were identified and the minimum operating pressure and feed flowrate required to produce adequate permeate quality determined. Experiments were aimed at verifying the ROSA analysis over a limited range and under steady-state conditions only.

Pohl et al. [16] used ROSA to investigate the use of four different operating strategies for transient operation of a RO system within a SOW. The simulations were performed using DOW SW30HR modules and 'standard' seawater [21] at 25 °C. The SOW was determined based on the manufacturer's data used as inputs to the constraints of Feron [14] above. Operating strategies investigated were [16]: (i) constant feed pressure, (ii) constant permeate recovery, (iii) constant feed flowrate, and (iv) constant concentrate flowrate. Constant recovery was found to be the optimum operating strategy based on the criteria of low specific energy consumption (SEC), production over a broad load range, good permeate quality, and low pressure variation. Operating the RO plant with constant feed pressure, as used in many conventional plants, resulted in low SEC but exhibited a narrow load range, which is unsuitable for transient operation. Hence, the wide load range necessary for transient operation could only be achieved by variation of feed pressure. However, at this point it should be noted that the impact of pressure variations on the performance and lifetime of the membrane module is largely unknown and requires further investigation [22]. The results of Pohl et al. [16] were not verified by practical experimentation and focussed purely on the membranes, while the performance curves for pumps and motors were not considered. Therefore, it is essential to determine an appropriate method of implementing chosen operating strategies and the mapping out the SOW.

Previous research by the authors resulted initially in the development of a photovoltaic-powered brackish water membrane desalination system [11,23], and subsequently extended to investigate the performance of such systems under both fluctuating [12] and intermittent [24] wind conditions. In addition, the potential of supercapacitor energy buffering was studied under controlled sinusoidal fluctuations of simulated wind speed [25]. This same system is used here to investigate best operating strategy and determine a SOW methodology, taking into account module choice and feed concentration.

2. Materials and methods

2.1. Wind-membrane system

The wind-powered brackish water nanofiltration (NF) or RO membrane system utilised here has been extensively described in a previous paper [12]. The key component of this system is a 300 W DC progressive cavity pump (Mono Sunsub SM022), which draws water through a polypropylene 1 μm microfilter (SupaGard, 1.2 L) with suction pressure of ~0.3 bar before pumping it through the