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Thermodynamic analysis of a stand-alone reverse osmosis desalination system powered by pressure retarded osmosis

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HIGHLIGHTS

- Diagrammatical analysis of the feasibility of stand-alone PRO driven RO
- Mathematical model with respect to FC number and ZB constraint is derived.
- Feasible operations of stand-alone PRO driven RO is analysed and optimized.
- Operations and performance of the PRO subsystem are analysed and optimized.

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ABSTRACT

In this study, a methodology is developed to assess the feasibility of a reverse osmosis (RO) desalination system powered by a stand-alone salinity driven pressure retarded osmosis (PRO) technology. First, the proposed hybrid RO–PRO system is analysed as a thermodynamic cycle and its feasibility is mathematically interpreted using a feasible condition (FC) number, several dimensionless operational variables and a number of constraints to represent the objective of zero brine discharge. Then, a study of the stand-alone feasibility of a hybrid seawater RO–PRO system is carried out. The results show that lower RO water recovery and higher dimensionless flow rate improve the stand-alone feasibility of the system. A subsystem, a look inside the PRO, is developed to study the applied pressure and the required membrane area to achieve the operations with optimum FC numbers. It is found that the optimum applied hydraulic pressure is inversely proportional to the dimensionless flow rate in the feasible range of stand-alone operations and more area of membrane is required by a larger FC number. Finally, a case study of a selected operation is presented based on its energy performance, and two influencing factors, the inefficiency of the components and the salinity concentration of the feed water.

1. Introduction

Water is one of the most abundant resources on earth. However, most of it, about 97%, is saline water in the oceans, and the remaining 3% is freshwater. Nowadays, the freshwater provision is becoming an increasingly important issue in various areas of the world [1]. Many of these places are either located in coastal regions with access to an abundance of seawater (SW) or near a volume of brackish ground water. Desalination has been demonstrated to be a promising and viable source of drinking water in those areas [2]. But an important factor impeding the wider use of desalination technologies to provide fresh water is the high economic cost involved, especially due to energy consumption [3]. Among the widely used technologies, reverse osmosis (RO) is considered to be the most efficient system to desalinate saline water with a substantially higher second law efficiency than other desalination processes [4]. However, the overall energy consumption is still enormous due to a huge number of RO plants in operation. According to the International Desalination Association, for 2011, reverse osmosis was used in 66% of installed desalination capacity (44.5 of 67.4 Mm^3/day), and in almost all new plants [5]. Many investigations have been carried out to reduce the energy cost of a RO process [6] including fabrication of high performance RO membrane with high water permeability and salt rejection [7], fabrication of efficient energy recovery devices [8], development of innovative systems [9] and integration with renewable energy sources (RESs) [10–14]. In addition, in the case of a RO system, another significant problem is the brine discharge. For inland desalination RO applications, the cost and technical feasibility of concentration disposal become the primary limitations [15]. The extensive development of RO desalination system in coastal areas using surface water discharge as concentrate disposal

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has the potential risk such as salinity variation [16] on the local receiving water and the larger surrounding sea.

Recently, salinity power harvesting from mixed streams with different concentrations has drawn significant attention [17–20]. In fact, power from natural salinity gradients has been identified as a candidate RES since the 1950s [21]. Salinity power harvesting possesses a great potential energy capacity, estimated to be 2 TW, which is about 13% of the current world energy consumption [22]. To this end, pressure retarded osmosis (PRO) is one of the most explored technologies [23]. PRO applies a hydraulic pressure on a draw stream to extract energy from a permeate stream which becomes pressurized as it enters the draw via a trans-membrane osmotic pressure difference, converting the chemical potential gradients into electricity by hydro-turbine [24]. After a rapid development in this field in the last decade, it has started to be utilized in reality [25]. In 2009, the world's first PRO plant was launched in Norway with a 4 kW capacity [26].

It is noted that the PRO process has been researched not only as an independent power plant [27,42], but also as pre- or post-treatment processes in the hybrid system integrated with RO plant for the purpose of reducing energy consumption and the discharge of high concentrated brine [28–30]. Compared with other current energy recovery devices (ERDs) for RO desalination plants (e.g. pressure exchangers and hydro-turbines), PRO is capable to significantly increase the second law efficiency of the process [31]. Feinberg et al. theoretically considered a hybrid RO desalination plant with two-stage PRO osmotic ERDs [32]. Sharqawy and Banchik derived systematic effectiveness-mass transfer unit (ε-MTU) modes of the membrane mass exchangers [33, 34], which effectively help in designing the RO, PRO and the hybrid membrane systems. Recently, a pilot system was designed and constructed to evaluate the RO energy reduction that can be achieved by a PRO process [35]. According to their experimental results, power densities for the RO–PRO system ranged from 1.1 to 2.3 W/m^2. Naturally a question arises. Can the energy consumption of a desalination plant be fully covered by salinity power? If possible, what operational conditions does the salinity power driven desalination plant require? Unfortunately, these answers cannot be directly found in the current literatures. Therefore, in this study, an investigation on the stand-alone feasibility of the hybrid system is carried out. Furthermore, in order to reduce the concerns on brine discharge, a zero brine discharge constraint is also considered. The targeted overcome of the hybrid system has zero liquid discharge, i.e. performing nearly 100% recovery on a brine stream and not requiring to dispose of any of the brine.

This research therefore aims to study the feasibility of a PRO-based stand-alone salinity power driven RO desalination plant with zero brine discharge. First, a hybrid system is proposed to be the basis for this investigation. Then, the operation of the hybrid system is studied based on the thermodynamic analysis in which key states of the saline streams are discussed. The stand-alone feasibility of the hybrid RO–PRO system, including the objectives of zero carbon emission and brine discharge, is mathematically interpreted. Furthermore, the required operations and the required membrane area of the PRO subsystem are studied. Finally, a case study on the feasible stand-alone operation is developed and the effects from the inefficiency of the pumps and energy recovery devices are also discussed.

2. Stand-alone salinity power driven reverse osmosis system by pressure retarded osmosis

A proposed stand-alone salinity power driven RO desalination system is illustrated in Fig. 1. The hybrid system consists of two sub-systems: desalination and power generation. In the first sub-system, seawater is desalinated using RO technology. The seawater is pressurized by the high-pressure pump (HP) and the energy recovery device (ERD) before it flows into the RO membrane module in order to maintain the reverse water permeation from the high concentration side to the low concentration side. Accordingly, two streams flow from the RO module: the permeated water (PW) and the concentrated brine water (CW). The CW is further used to pressurize the SW in the ERD before it flows into the PRO sub-system, and the PW is the product of the hybrid system. In another sub-system, the salinity power is generated by the PRO process with the pressurized brine water from the RO plant as the draw solution. Usually, low concentration impaired water bodies include sewage and waste water from household and industries, brackish water (BW), and other water with impurities [36]. These low concentration streams (secondary wastewaters and BW) or mixtures are the potential candidates for the feed solution for an osmotic membrane process [37]. The salt concentration of these water bodies, might not be more than that of the BW. In this study, the BW is selected as the feed solution for an early-stage investigation. The applied hydraulic pressure on the draw solution is controlled by adjusting the valve resistance on the draw solution flow channel. The feed solution flow rate is controlled by the boost pump (BP) and valves on the feed solution flow channel. Finally, the draw solution including the permeated water from the feed water is expanded in the hydro-turbine (HT) to generate electricity.

2.1. Thermodynamic analysis of the stand-alone hybrid RO–PRO system

Before further analysis of the hybrid system, some key states of the saline streams are presented in the pressure–flow rate (*P*–*Q*) diagram as illustrated in Fig. 2(a). At this stage, the pressure loss in the membrane and flow channels can be ignored and the efficiency of the pumps is assumed to be 100%. Also, the membrane is considered to be able to reject salt at a rate of 100% with no fouling effect. And due to the smaller amount of the energy consumed by the BP, in this study, the energy consumption is only considered as the work of the HP in the RO sub-system.

In Fig. 2(a), the energy consumed, recovered and generated can be represented by the area of the state diagram i.e., the energy

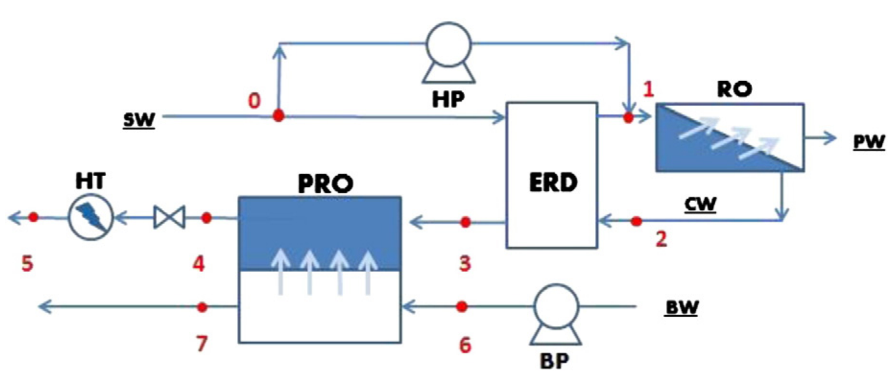

Fig. 1. Schematic diagram of the proposed stand-alone salinity power driven RO desalination system.