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A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination

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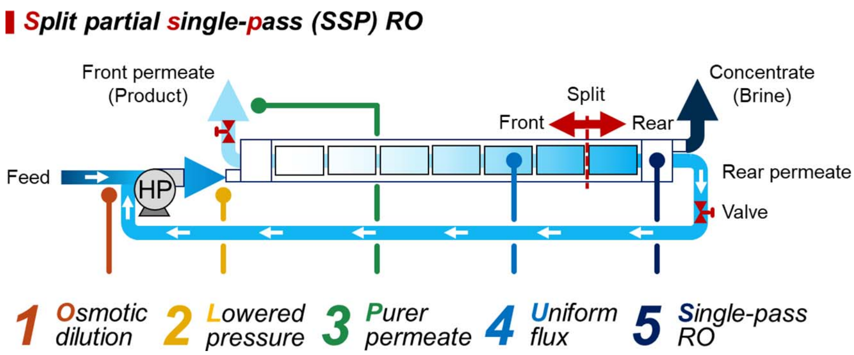
GRAPHICAL ABSTRACT



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ABSTRACT

Seawater reverse osmosis (SWRO) desalination is required to produce high-quality water to meet stricter water standards, which could be satisfied with single-pass RO through the advancement of reverse osmosis (RO) membranes. In this study, a novel single-pass RO configuration was proposed to further improve permeate quality. Split partial single-pass (SSP) RO is a design in which the permeate from the rear RO element(s) in a pressure vessel is blended with the RO feed. This blending resulted in the dilution of the feed, leading to the production of high-quality permeate with lower energy demand. Modeling of the RO process demonstrates that SSP RO had the highest energy efficiency when the permeate from the 7th element (i.e., the last one in the single pass RO configuration) was circulated back and mixed with the feed. For typical SWRO operating conditions, SSP RO was effectively able to improve permeate quality. In fact, SSP RO produced an approximately 15% purer permeate compared to conventional single-pass RO. SSP RO was also always more energy-efficient than the two-pass RO configurations. The economic feasibility of the design was assessed further and the possibility of its practical application explored.

Abbreviations: BP, boost pump; BWRO, brackish water reverse osmosis; CAPEX, capital expenditure; CC, capital cost; CCD, closed circuit desalination; DWEER, dual work exchanger energy recovery; ERD, energy recovery device; FF, flow factor; GSM, golden section method; HID, hybrid RO membrane inter-stage design; HP, high-pressure pump; ISD, internally staged design; OC, operation cost; OPEX, operating expenditure; PRO, pressure retarded osmosis; PV, pressure vessel; PX, pressure exchanger; RO, reverse osmosis; SEC, specific energy consumption; SPSP, split partial second pass; SSP, split partial single pass; SWIP, seawater intake and pretreatment; SWRO, seawater reverse osmosis; TDS, total dissolved solids; UPC, unit product cost; UPW, ultrapure water

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1. Introduction

To address the challenges of water scarcity arising from global climate change, seawater desalination is a promising method for producing freshwater from the ocean. This is primarily achieved through membrane-based or thermal-based desalination. Following the development of energy recovery devices (ERDs), reverse osmosis (RO)-based processes have become increasingly common worldwide in the pursuit of energy-efficient desalination. Most seawater reverse osmosis (SWRO) desalination plants employ single-pass (or single-stage) RO [1]. Single-pass RO is a compact configuration but the quality of the final product is inferior. To satisfy the growing demand for high-purity water, an additional step is required to treat the water produced by single-pass RO. Therefore, more recent SWRO desalination plants adopt a two-pass RO design.

Two-pass (or full two-pass) RO is a system in which the first-pass RO permeate is treated in its entirety at the second-pass RO. However, extra mineral recovery generally follows for water production. A common example of a two-pass RO configuration is partial two-pass (or partial second-pass) RO, in which a portion of the first-pass RO permeate bypasses the second pass and subsequently mixes with the permeate derived from this second pass. A more advanced partial pass design, split partial second-pass (SPSP) RO, has been applied in SWRO desalination plants. This design also adopts second-pass RO, but in this case, the first-pass RO permeate is collected at the front and rear of the pressure vessel (PV). The front permeate, which has lower total dissolved solids (TDS), bypasses second-pass RO, while the rear permeate is fed into the second-pass RO system, after which the two streams are blended. RO designs such as these that use second-pass RO improve permeate quality, but extra energy is required to run the additional RO step, which significantly increases the total energy consumption of SWRO plants.

The RO process accounts for most of the energy requirements for SWRO desalination plants. According to previous studies, RO systems with an ERD (excluding pretreatment and posttreatment) consume 2.4 to 3.8 kWh/m^3 depending on the SWRO plant in question (Table 1) [2–5]. The total specific energy consumption (SEC) of an SWRO plant varies depending on the operating conditions (e.g., feed and product salinity, water temperature), the type of ERD, and the RO configuration, and this has typically been found to range between 3.5 and 4.5 kWh/m^3 [6]. However, some SWRO plants have been reported to consume under 3.5 kWh/m^3 [7], which can be explained by the low salinity and high temperature of the feed, by the RO configuration, or by technological advances. Recent studies [8–10] have suggested that energy sources from outside an SWRO plant, such as renewable energy or energy harvested from pressure retarded osmosis (PRO), can reduce SEC. However, the total amount of energy required to operate an RO system remains unchanged. Thus, it is important to adopt a low-energy RO configuration in conjunction with the pursuit of supplemental energy sources.

Since a single-pass design is energy-efficient compared to two-pass designs, single-pass RO is preferred for application if the product quality satisfies the requirement. Single-pass RO also has more advantages over two-pass ROs such as reduced costs and low chemical usage. Recently, the advancement of RO membrane even allows single-pass RO to produce high-quality water. In particular, the high-selective membrane improves the product quality of first-pass RO and therefore additional RO step, such as brackish water reverse osmosis (BWRO), might not be required [11]. In spite of the development of high-performance membranes, a higher product quality is required for single-pass RO in some places where stringent water standards are applied for drinking water, industrial use, or agricultural irrigation (i.e., low boron and chloride concentration) [12]. Therefore, a new single-pass configuration is to be developed beyond conventional single-pass RO with the employment of advanced RO membranes.

To gain the benefits and correct the flaw of single-pass design, this study seeks to develop a new single-pass RO process with low energy requirements that produces permeate of high purity. As a result, split partial single-pass (SSP) RO is developed and proposed in this paper to produce higher-quality product with reduced energy consumption. Similar to SPSP, the first-pass permeate is collected from both sides of the PV in SSP but, rather than using the back permeate as the feed for second-pass RO, it is used to dilute the first-pass RO feed (i.e., the back permeate is fed back into the first-pass RO feed). With the adoption of this SSP RO design, high-purity permeate can be produced using single-pass RO and this also can reduce the SEC and operating costs of SWRO plants when compared to current RO systems that produce water of high purity.

In this paper, the SSP RO process is proposed and developed for the first time for SWRO desalination plants, and the performance and feasibility of the SSP RO design are examined using RO process modeling. The product quality, SEC, and economic benefits are also analyzed in comparison with other RO configurations under various operating conditions to determine the feasibility of SSP RO application.

Table 1
Comparison of the SEC for different SWRO desalination plants. Recent SWRO desalination plants have adopted two-pass RO systems to meet restrictive water standards.

Country	Location	TDS (mg/L)		Temperature (°C)	RO pass configuration	ERD type	SEC (kWh/m^3)		Reference
		Feed	Product				Total	RO system	
Australia	Perth	36,500	< 200[a]	20.2	Partial two pass	PX	3.6	2.4[d]	[2,13]
Israel	Soreq	40,800	< 300[a]	27.0	SPSP	DWEER	< 4.0	2.7[d]	[3,14]
	Hadera	40,700	< 270[a]	22.5	SPSP	PX	4.0	2.7[d]	[3,14,15]
	Ashkelon	40,700	< 80[b]	22.5	SPSP[c]	DWEER	3.9	3.0[d]	[3,16,17]
	Palmachim 1	42,000	< 300[a]	24.5	SPSP	Pelton turbine	3.5	2.9[d]	[3,18–20]
	Palmachim 2					PX		2.7[d]	
Saudi Arabia	Sadara	< 45,000	< 40[b]	26.5	Partial two pass	PX	4.4	3.1[e]	[4]
Singapore	Tuas (Singspring)	31,600	< 250[a]	30.6	Partial two pass	DWEER	4.1	3.1[d]	[3,21,22]
UAE	Fujairah	38,250	< 120[b]	29.0	Partial two pass	Pelton turbine	4.5	3.8[e]	[5]

TDS: total dissolved solids. SPSP: split partial second pass. ERD: energy recovery device. PX: pressure exchanger. DWEER: dual work exchanger energy recovery. SEC: specific energy consumption.
[a] After the remineralization process.
[b] Before the remineralization process.
[c] Additional BWRO passes are adopted to meet boron and chloride concentration standards.
[d] SEC of SWRO-ERD.
[e] SEC of SWRO-ERD and BWRO.