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Process intensification of seawater reverse osmosis through enhanced train capacity and module size – Simulation on Lanzarote IV SWRO plant

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HIGHLIGHTS

- Exergy and exergoeconomic analysis was performed to calculate specific energy consumption (SEC), effergy and water costs.
- The incorporation of all-16-inch modules on Lanzarote IV allowed more versatile train size design.
- The simultaneous increase in both train size and PV diameter provides technical, economical and plant footprint.

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ABSTRACT

Process intensification on seawater reverse osmosis (SWRO) plant can be realized through the increase of both train capacity and module size. The investigations were conducted based on a two-staged medium-sized (capacity of 25,000 m^3/day) SWRO plant, Lanzarote IV, Canary Island. Comparison between all-16-inch (first and second stages with GE Osmonics' AE-1600 and AG-1600, respectively) and mixed (only the first stage fitted with 16-inch) pressure vessels (PV) was also discussed herein. Exergy and exergoeconomic analysis was performed to calculate specific energy consumption (SEC), effergy and water costs. ROSA 9.1 (for 8-inch diameter modules) and Winflows 3.2 (for 16-inch diameter modules) were utilized to obtain energetic and technical data. The analysis revealed that the incorporation of all-16-inch modules on Lanzarote IV allowed more versatile train size design. The availability of the train was not the sole determining factor for the total cost of 16-inch PV-based configurations since the membrane capital cost only constitutes 2–3% of the total cost. In fact, the simultaneous increase in both train size and PV diameter can significantly offer operational advantages in term of technical, economical and plant footprint for a medium-size SWRO plant.

1. Background

While the stress on safe and clean water supplies continues to increase, many parts of the world are relying on seawater desalination to combat the water shortage scenario. However, large-scale desalination has long been associated with the sustainability issues due to its energy intensive process. To tackle this issue, there are continuous efforts in the desalination community to alleviate the specific energy consumption (SEC), water production cost and footprints of a desalination plants, particularly in the prevailing commercial seawater reverse osmosis (SWRO) plants. Despite the advancement made in membrane material development [1], attentions have also been placed on the process design of SWRO plants. In this context, the architecture of process design and choice of equipments such as membrane trains, pumps and energy recovery devices (ERD), just to name a few, can significantly affect the performance and energy cost of the SWRO plants.

Kim [2] addressed two possible ways in scaling up SWRO trains, namely train capacity and element size increase. Specifically, the enhancement in train capacity for SEC and water production cost reduction has been successfully implemented in plenty desalination plants across the globe [3–6]. In terms of the train architecture, the optimum train size can be vary for different SWRO plants, primarily depending on the number of pressure vessels (PV). Previous findings indicated that membrane train size, which typically consists of 8 × 40-inch membrane modules, influences the energy efficiency and overall availability of the plant where the arrangement of membrane PVs in oversized trains can be detrimental to the optimum working efficiency whereas overloaded modules and PV in the train is likely to fail during operation

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[7]. Since the size of train depends on the number of modules, it is necessary to minimize the module quantity while maintaining their high productivity and separation performances. Over the last decade, optimization based on module sizes has been a subject of interest to reduce the footprint SWRO spiral wound modules. The diameter and sometimes the length of the module are increased to render larger surface area which eventually lead to smaller floor space to achieve the same capacity as conventional smaller-diameter modules. Some manufacturers, e.g. Hydranautics, GE Osmonics, Toray and GrahamTek developed 16 × 40-inch modules as their standard large-diameter elements [8–9], while Koch opted the larger 18 × 61-in [10]. Typical 16 × 40-inch PV can produce 3–4 times as many permeate as the standard 8 × 40-inch PV, whilst Koch's 18 × 61-inch PV's capacity is enhanced by 5 folds.

Up to present, computational and experimental work on train and module size optimization have been scarcely reported. Yun [11] reported a largely economic report of one-staged, large-capacity brackish water RO (BWRO) plant that utilized 16 × 60-inch BWRO modules. The utilization of the modules has saved 12.4% of capital, operation, and maintenance costs owing to fewer modules and the ancillary units, such as train piping and interconnectors as well as membrane replacements, which were dictated by the number of modules in the plant. However, the system featured in the work was vastly different from that of used in SWRO plant in which this work was based on constant pump power, low pressure operation and TDS level that much lower that actual seawater. Thus, much smaller cost in power department, i.e. cost of power and capital cost of the pumps was required. Additionally, the effects of train size on the design and availability of equipments were also neglected in this work. Later, Ng [9] reported that average flux of the 16-inch PVs was found to be 2–2.6 times higher than that of standard 8-inch PVs and due to fewer amount of modules in the PVs (two and four in first and second stages, respectively), less applied pressure was needed, therefore the energy requirement was reduced about 12–16%. However, the analyses are merely technical and no estimation of capital cost and water cost were made. Moreover, exergy analysis which can determine the internal losses of work of the system hence the real technical efficiency has not been performed.

In order to fill the research gap, retrofitting simulation on Lanzarote IV SWRO plant was performed using 16 × 40-inch PV on the first high pressure stage and both stages. The effects of train sizes due to changing module number and pump efficiency due to given capacity were investigated and discussed. Exergy and thermoeconomic parametric analyses were applied to analyze the performance of each retrofitting.

2. Lanzarote IV SWRO plant

As in the years it came into service, Lanzarote IV SWRO plant was one of the most novel and innovatively designed desalination plants in Canary Islands, Spain [12]. Originally installed as 20,000 m^3/day, it has been upgraded to handle the capacity of 30,000 m^3/day. The operation of this plant is distributed into five almost identical membrane trains. As shown in Tables 1 and 2, the operation of train 1–4 involves 2 stages, namely high rejection and high flux stages, which is common and a necessity for SWRO plants processing high-salinity seawater [13]. The first stage is operated at high pressure whereas the second stage is operated at low pressure. Seawater specifications of the plant are shown in Table 3. As shown in Fig. 1, this configuration enables the SWRO section to distribute the workload of the system across the two stages, while complying the high permeate quality standard.

Table 1
The trains of Lanzarote IV SWRO plant characteristics [5].

Description per train	Train 1–4 (dual-stage)	Train 5 (one stage)
Seawater feed	580 m^3/h	595 m^3/h
1st pass permeate stream	262 m^3/h	250 m^3/h
2nd pass permeate stream	240 m^3/h	n/a
1st pass average recovery rate	42%	42%
2nd pass average recovery rate	90%	n/a
Brine water stream	345 m^3/h	345 m^3/h

n/a: not applicable.

Earlier, Penate and Garcia-Rodriguez [4,5] have addressed the process design issues of this plant and some recommendations have been made on the train size and ERD. The modifications on the train stage and arrangements of the streams as shown in Fig. 2 have been proven beneficial in which the SEC and water cost have been significantly reduced by around 25–30% and 20–30%, respectively. These studies have also further confirmed that optimum train size is desired for every SWRO plant to meet both economic and technical requirements.

3. Basic theories

3.1. Mass and energy balances

In order to depict the correlation of pump power, momentum, and recovery of the plant, the mass balance of the two-staged SWRO unit must be considered. The schematic flow chart is shown in Fig. 2. As quantity of low pressure brine is expected to be very low compared to that of feed stream (as reported by Penate and Garcia-Rodriguez [4]), the change of P_f is omitted.

The foremost important data is the recovery values of each stage, which usually presighted and used as fixed variables. Typically, the second stage has high recovery (70–90%, depending on the type of the module) and low pressure (10–15 bar), hence the brine on this stage is small in quantity, as well as momentum-wise. The momentum in second stage brine is so small such that it is negligible compared to that of the first stage. Thus, this particular stream could be recycled into the feed flow to slightly lessen the high salinity (which is common practice in arid, subtropic regions like Lanzarote) or stripped off its momentum using ERD. The recovery of first and second stages are shown in Eqs. (1) and (2), respectively. General mass and energy balance equations in this work is shown in Table 4. Pressure across the membrane barrier is calculated in accordance to its osmotic pressure (Eqs. (9)–(15)), which has to be overcome by the operating pressure [14]. This set of transmembrane pressure equations by Li [14] is general formulae that applies to any reverse osmosis case, hence it is applicable to both low and high pressure stages.

3.2. Exergy and exergoeconomic calculation

Exergy stream of salt water in ambient temperature and pressure state is defined as

$$\dot{E}_x = \dot{m}\left(-T_o\left(s_{gen} - s_{o,f} - R\left(\ln\frac{P}{P_O} + x_s \ln x_s + x_w \ln x_w\right)\right)\right) \tag{24}$$

where $\dot{E}_x$ is exergy stream, $\dot{m}$ is mass flow, s_{gen} is entropy generation, $s_{o,f}$ is initial entropy of the stream, x_s is salt mass fraction, x_w is water mass fraction, and T_o is ambient temperature. Note the absence of enthalpy difference, which is close to nil and omitted from the formula. The entropy of seawater had been reviewed by Sharqawy et al. [15]. Hence, the exergy value of streams is dictated by its momentum, which is distinguished by the pressure and (sea)water composition. Meanwhile, exergetic efficiency or effergy is defined as in Eq. (25).

$$\epsilon = \frac{\dot{E}_{x\ desired}}{\dot{E}_{x\ in} \times 100\%} \tag{25}$$

Exergoeconomic calculation with and without exergy destruction cost of typical SWRO plant is given in Eqs. (26) and (27), respectively.

$$\dot{E}_{xout} c_{i,out} = \dot{W}_{pump}\, c_{i,in} + \dot{E}_{xin} c_{i,in} + \dot{Z}^{om} + \dot{D} c_{i,in} \tag{26}$$