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Exergy analysis of a seawater reverse osmosis plant in Jeddah, Saudi Arabia

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ABSTRACT

In this work the performance of a seawater reverse osmosis plant, located in Jeddah, Saudi Arabia, is analyzed by using the exergy analysis. Recently developed seawater property correlations at high pressures have been used. To get the most accurate results, seawater has been modeled as a non-ideal solution. In addition to physical exergy, chemical and mixing exergies have also been taken into account. The activity coefficients have been modeled as salinity dependent. Exergy flowrates of streams for major process equipment are calculated and exergy destruction around each of the equipment is estimated. MS Excel spreadsheet is used to calculate mass, energy, and exergy balances at a heavy load of distillate production (~1,200 kg/s) at 35°C in the summer. It is found that the maximum exergy destruction occurs at the pumps (~51%) and reverse osmosis modules (~21%) followed by the dual media filters (~13%) and the mixers (~12%). The SEC is calculated to be 4.88 kW/m^3. The results have been compared with the previous studies. The second-law efficiency of the plant is determined to be 29.4%. This efficiency is low and several measures can be done to improve it by decreasing inlet exergy to the plant and controlling exergy losses during process operation.

Keywords: Reverse osmosis; Desalination; Exergy analysis; Seawater; Process design

1. Introduction

The National Development Plans for the Kingdom of Saudi Arabia indicate that in view of rapidly growing population of the city of Jeddah an adequate supply of water meeting public health standard is essential. Unfortunately, the city of Jeddah is situated in the most water deficit location of the Kingdom. The desalinated water from Red Sea is the only potable water source. The population of Jeddah has increased from 0.9 million in 1980 to 4.9 million in 2020, that is almost 450% increase in a span of 40 y. In the same period the production of desalinated water has increased from 56.7 to 791 million m^3/y [1]. Despite the significant increase in desalination capacity the demand and supply gap is getting wider. The government under vision 2030 is putting utmost importance to deal with the water shortage problem of Jeddah by heavily investing in seawater desalination plants.

Generally speaking, seawater desalination plants are categorized either as thermal (MSF, MED, MVC) or reverse osmosis membranes (RO). Being highly energy intensive thermal methods are preferred when co-generation of electricity greatly reduces the overall cost of the process. In the absence of co-generation RO is a preferred choice. RO is comparatively cost effective, environment friendly, easier operation and maintenance, high purity, excellent for purifying brackish water and can be used for waste water treatment. Because of all these reasons 80% of worldwide desalination capacity is based on RO [2]. Moreover, the state owned SWCC (Saline Water Conversion Corporation)

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has been gradually replacing MSF plants in Jeddah with state-of-the-art RO plants [3].

A state-of-the-art RO plant, that produces 450,000 tons of potable water daily, roughly costs around $700 million (for instance Yanbu Phase 4 Plant, Saudi Arabia). Obviously with such a huge investment comes the need to run the plant smoothly and efficiently by putting in place best optimization procedures such as the exergy analysis.

Exergy analysis is a method that can be used effectively to isolate and improve process plant equipment and parameters that contribute to lower plant efficiency. This energy optimization procedure has tremendously decrease energy consumption in industrial plants. For the past few years the energy intake in a normal RO plant has been reduced from 20 kWh/m^3 to less than 2 kWh/m^3 [4]. In this method coupled with energy and mass balances the exergy destruction or the loss of work potential is ascertained across a unit or system. The higher the exergy destruction the lower is the thermodynamic efficiency of the system. Thus units giving higher exergy destructions are indicated and ways are adopted to decrease high exergy losses. For example, if the actual exergy decrease is much higher than the thermodynamic exergy decrease then there is always a chance to improve the thermodynamic efficiency [5].

Several researchers have carried out exergy analysis of seawater reverse osmosis (SWRO) plants. For example, exergy analysis of a single-stage reverse osmosis with turbine as ERD was performed by Romero-Ternero et al. [6]. The plant efficiency was calculated to be around 48.5%. The equipment that caused most exergy loss were identified as RO modules (35%) and turbine (24%). Blanco-Marigorta et al. [7] carried out exergy analysis of two stage RO plant with three different types of ERDs. The thermodynamic efficiencies were calculated as 26.8% for the pressure exchanger, 28.4% for the turbine and 32.8% for the Dual Work Energy Recovery. Again the highest exergy destruction took place around the RO modules as well as the high pressure pump. The other most cited exergy investigations for several types of RO plants have been reported by Cerci [8], Aljundi [9], Gasmi et al. [10], Sharqawy et al. [11], Knutson [12], Sharqawy et al. [13], Al-Zahrani et al. [14], Kahraman et al. [15], Peñate and García-Rodríguez [16], Qureshi and Zubair [17,18], Soin et al. [19], Eshoul et al. [20] and Mistry et al. [21]. Almost all findings indicated the most exergy destruction to occur in RO modules and high pressure pumps. The authors suggested to prefer ERD such as Pelton turbines, pressure exchangers and variable frequency drives and efficiency pumps to improve plant efficiency A comparison between different research work on case studies has been summarized in Table 1. In conclusion, only few researchers have used real plant data to actually determine the extent of exergy destruction and the component causing it. Even in those studies, some considered seawater/brackish water as an ideal solution, some chose to model only physical exergy, and most evaluated seawater properties at atmospheric pressure. These assumptions might have affected their calculations.

The objective of this study is to analyze the exergy destruction and second-law efficiency of a SWRO III distillation plant located in Jeddah at seawater temperatures of 35°C in the summer. Algebraic mass, energy and exergy balance equations are developed around each equipment and solved by using real plant data. The seawater is considered as a non-ideal solution and the contribution to exergy by chemical and mixing effects have been considered. Moreover, recently developed seawater property correlations [22] at high RO pressures have been utilized. MS Excel spreadsheet is used for computations. In addition, the

Table 1
Summary of recent exergy analysis research

Investigator	RO plant type	Plant capacity (m^3/d)	Plant exergetic efficiency	Energy recovery device	Major exergy destruction	Suggested remedies
Cerci [8]	One-stage RO, brackish water	7,250	4.3%	None	RO module	PX installation increased efficiency from 4.3% to 4.9%
Kahraman et al. [15]	RO, NF, and EDR brackish water	2,594	8.0%	None	RO modules and high pressure pumps (39.7%)	Variable frequency drives and efficiency pumps
Aljundi [9]	Two-stage RO, brackish water	552.7	4.1%	None	Throttling valve (56.8%), RO units (21%)	Variable frequency drives and efficiency pumps, replacement of throttling valve by ERD like PX
Gasmi et al. [10]	4-Double stage RO lines	30,000	NA	None	HPP (44% of total exergy loss)	Booster interstage pumps, Pelton turbine
Sharqawy et al. [11]	One stage RO, brackish water	7,250	<2%	None	RO module	Pressure-Retarded Osmosis Method
Al-Zahrani et al. [14]	NA	NA	NA	NA	NA	NA
Eshoul et al. [20]	Two pass RO seawater	3,048	27.3%	NA	HPP and RO modules	Pressure exchangers and turbines

activity coefficients of water and sodium chloride in seawater have been considered as a function of seawater salinity.

2. SWRO plant description

The plant under study is located in the proximity of Red Sea Port City of Jeddah, Saudi Arabia and designated as Jeddah SWRO-III. The plant is one of 32 plants administered by the Saline Water Conversion Corporation (SWCC) of the country. A schematic of the plant is shown in Fig. 1.

The seawater is first pretreated to remove particulates, debris, micro-organisms, suspended solids and silt by using chemical dosing systems like sulfuric acid (for pH control), ferric chloride (for minimizing the turbidity) and polymer (for coagulation). The chemical injection takes place in static mixers. The chemically treated water is then passed through dual media filters (DMF). The filtered water is then pumped to electro-chlorination plant, and three filtered water pumps which feed filtered water to the 1st pass RO units (1–8) through cartridge filters.

Pretreated seawater is supplied to the suction of the 1st pass high pressure pump. The pump provides the high-pressure feed water stream to the turbo charger (ERD, or energy recovery device) which further boosts the pressure then to the RO unit membranes. The turbo charger is a hydraulic device designed to transfer pressure energy from the RO concentrate stream to the RO feed water stream within an RO. The permeate produced goes to a common pipe where the pressure and free chlorine are measured before going to feed the train A 2nd pass RO units. This 2nd pass feed water has SBS (sodium bisulfate) injection point. The SBS dosing is provided for neutralization of any free chlorine that might be present in the feed water.

The 1st pass RO units permeate pipe is also connected to the permeate tank to allow for any imbalance between the train 1st pass RO permeate production and the train 2nd pass RO feed flows. The portion of 1st pass permeate which will be further treated by the 2nd pass units will be adjusted by the operators to compensate for any variations in feed water temperature and salinity as well as any variations in operations which may affect the RO permeate quality such as membrane cleaning.

Each train A and B have four 2nd pass RO units to process the permeate water from the eight 1st pass RO units of each train. The 2nd pass RO concentrate leaving the 2nd pass RO unit is recycled back to the 1st pass RO feed water header to be used as feed to the 1st pass RO units. The 2nd pass high pressure pump provides the pressurized 1st pass RO permeate water to the 2nd pass RO unit membranes. The permeate from the 2nd pass RO is sent to the permeate storage tank. The plant design data is given in Table 2 whereas operational data is given in Table 3. It should be

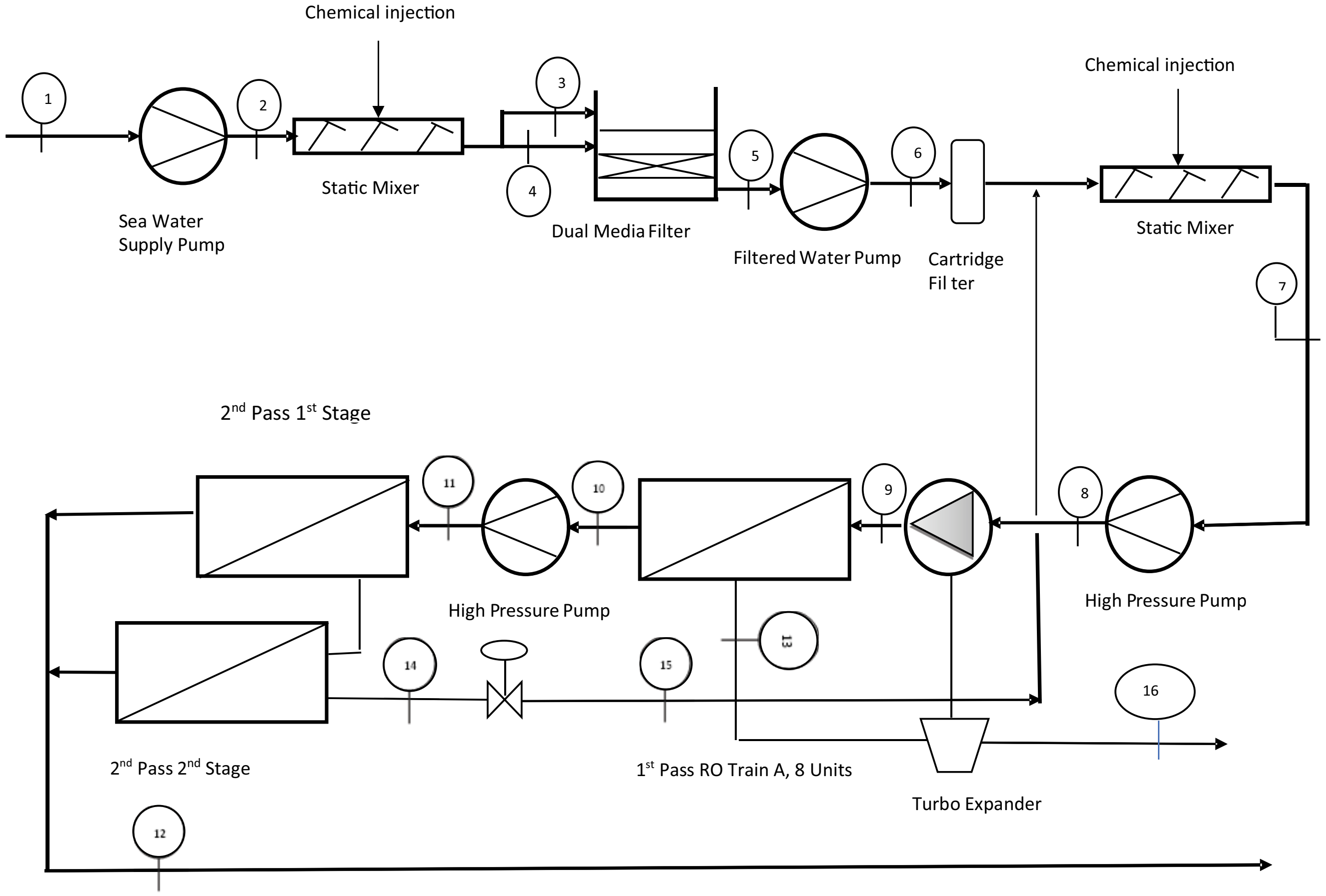

Fig. 1. Schematic of SWRO plant, Jeddah.

noted that the plant has two identical trains viz. train A and train B. Here we only make exergy analysis of train A. Therefore, the total production of the plant is considered half of the design production.

3. Model formulation

To carry out exergy analysis for the purpose of evaluating plant efficiency a mathematical model was developed. The details of the models are as follows:

3.1. Model assumptions

Following assumptions were made to simplify the model:

- The restricted dead state temperature is 25°C and the pressure is 0.101 MPa.
- The global dead state temperature is 25°C, the pressure is 0.101 MPa and the salinity is 40,000 ppm.
- NaCl is the only electrolyte present in the seawater.
- All pumps' efficiencies are taken as 86%.

Table 2
Plant design data

Seawater temperature (°C)	35
Seawater salinity (ppm)	40,000
Feed seawater (m^3/d)	604,300
Permeate flow (m^3/d)	240,000
Product TDS	<200
Pretreatment	Coagulant + DMF
Number of trains	Two trains – 1st pass 16/2nd pass 8
Conversion rate	1st pass 42%/2nd pass 92%

3.2. Governing equations

For a given system under consideration one can generally write mass, energy, and exergy balances for a steady state process as follows [5]:

3.2.1. Mass balance

$$\text{Overall: } \sum m_i = \sum m_o \tag{1}$$

$$\text{Salt balance: } \sum m_i x_i^s = \sum m_o x_o^s \tag{2}$$

where m is the mass and x^s is the mass fraction of the salt.

3.2.2. Energy balance

$$\text{Overall: } \sum m_i \hat{h}_i = \sum m_o \hat{h}_o \tag{3}$$

where $\hat{h}$ is the specific enthalpy.

3.2.3. Exergy balance

Exergy is defined as the availability of useful energy or maximum work potential of a system at a given state in a specified environment. Therefore, the difference between actual work potential and the exergy indicates the room for improvement in system's design and/or its operation. Being closed to entropy in nature it is also not a conserved property (no generation of entropy means no destruction of exergy for a reversible process) and depends on both the state of the system and the surroundings [5].

Therefore, under steady state conditions, an exergy (ξ) balance on an open system control volume yields an extra

Table 3
Plant operational data (Temp. ~35°C)

No.	Description	Pressure (MPa)	Flow (tons/h)	Chloride (mg/L)	TDS (mg/L)	NaCl (mg/L)
Stream 1	Seawater inlet	0.101	12,900	22,051	40,000	36,352
Stream 2	Seawater to plant	0.202	12,900	22,051	40,000	36,352
Stream 3	Feed to DMF	0.150	12,900	22,051	40,016	36,352
Stream 4	Rinsing water[a]	0.150	1,146	22,051	40,016	36,352
Stream 5	From DMF	0.101	12,900	22,051	40,016	36,352
Stream 6	To static mixer	0.550	12,800	22,051	40,016	36,352
Stream 7	From static mixer	0.250	13,200	21,461	40,016	36,352
Stream 8	To turboexpander	3.61	13,200	21,461	40,016	36,352
Stream 9	From turboexpander	6.86	13,200	22,051	40,016	36,352
Stream 10	From 1st pass (permeate)	0.101	5,400	243	420	400
Stream 11	To 2nd pass module	1.22	4,740	243	420	400
Stream 12	To storage	0.101	4,350	4	7	6.6
Stream 13	To turboexpander	6.29	7,810	37,477	66,830	61,782
Stream 14	To throttle valve	0.970	394	3,843	6,641	6,335
Stream 15	To recirculation	0.550	394	3,843	6,641	6,335
Stream 16	To backwash tank	0.180	781	37,477	66,830	61,782

[a] Rinsing water flow is done intermittently.

destruction term (conversely to generation term in case of entropy) 'ξ_d' as follows:

$$\xi_{\text{heat\_transfer}} - \xi_{\text{work}} - \xi_{\text{in}} - \xi_{\text{out}} = \xi_{\text{destruction}} \tag{4}$$

Which upon substitution of definitions become:

$$\sum\left(1-\frac{T_d}{T_i}\right)\dot{Q}_l - \dot{W} + \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{\text{dstr}} \tag{5}$$

The first term on the left-hand side represents exergy transfer rate due to heat, the second-term represents exergy transfer rate due to work, the third and fourth terms represent exergy transfer in and out of the system respectively whereas the term on the right-hand side represent rate of exergy destruction during the process. It should be noted that in developing the above equations the heat transfer to a system and the work done by the system has been taken as positive quantities.

The exergy analysis of SWRO Jeddah plant consists of exergy balances for pumps, static mixers, dual media filters, turbo charger and RO modules. Simplifying Eq. (4) for these equipment gives the following equations:

$$\text{SWRO modules: } \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{d\_\text{SWRO}} \tag{6}$$

$$\text{Static mixers: } \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{d\_\text{SM}} \tag{7}$$

$$\text{Dual media filter: } \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{d\_\text{DMF}} \tag{8}$$

$$\text{Turbocharger: } \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{d\_\text{TC}} \tag{9}$$

$$\text{Pumps: } -\dot{W} + \sum_{\text{in}}\dot{m}\xi - \sum_{\text{out}}\dot{m}\xi = \dot{\xi}_{d\_P} \tag{10}$$

In RO plants where nuclear, magnetic and surface tension effects are not present the exergy associated with mass, that is, 'ξ' is usually taken as the sum of kinetic, potential, physical, mixing and chemical exergies:

$$\xi = \xi^{\text{ke}} + \xi^{\text{pe}} + \xi^{\text{ph}} + \xi^{\text{ch}} + \xi^{M} \tag{11}$$

The changes in kinetic and potential exergies can also be ignored due to the fact that changes in these exergies across a control volume are insignificant. Thus,

$$\xi = \xi^{\text{ph}} + \xi^{\text{ch}} + \xi^{M} \tag{12}$$

The above forms of exergy merit further discussions as follows.

3.2.3.1. Physical exergy (ξ^{ph})

The physical exergy is written as the exergy due to temperature and pressure effects and determined as follows:

$$\xi^{\text{ph}}_{T,P} = \left(h-h_d\right) - \left(s-s_d\right)T_d \tag{13}$$

Because of significant pressure differences across SWRO plant, the physical exergy has been taken into consideration.

3.2.3.2. Exergy of mixing (ξ^{M})

At the environment temperature and pressure (T_d, P_d) the exergy due to mixing of substances is given by:

$$\xi^{M} = h^{M} - T_d s^{M} \tag{14}$$

For a perfect mixture (or ideal solution) h^M is considered zero whereas s^M is given as:

$$s^{M} = -\sum_i x_i R \ln\left(x_i\right) \tag{15}$$

Therefore, the exergy due to mixing for an ideal solution is given by:

$$\xi^{M} = \sum_i x_i R T_d \ln\left(x_i\right) \tag{16}$$

For a non-ideal mixture, h^M is not zero so the exergy due to mixing is given as:

$$h^{M} = h_{\text{mix}} - \sum_i x_i h_i \tag{17}$$

$$s^{M} = s_{\text{mix}} - \sum_i x_i s_i \tag{18}$$

$$\xi^{M} = h_{\text{mix}} - \sum_i x_i h_i - T_d\left(s_{\text{mix}} - \sum_i x_i s_i\right) \tag{19}$$

The above exergy calculation is based on the fact that both the mixture and the components are at the same temperature T_d. If the temperature is different from the reference temperature T_d then the exergy due to mixing is given by the following equation

$$\xi^{M} = h_{\text{mix}} - \sum_i x_i h_i - T_d\left(s_{\text{mix}} - \sum_i x_i s_i\right) - \sum RT\left(T-T_d\right)x_i\left(\frac{\partial \ln a_i}{\partial T}\right)_{p,\text{xi}} \tag{20}$$

where a_i is the defined as the ionic/atomic activity.

Almost all previous exergy studies have modeled seawater as an ideal solution due to low salt concentration and total dissolved solids (TDS) (4%–6%). Strictly speaking, seawater is not an ideal solution due to the presence of electrolytes such as Na^{+1}, Cl^{-1}, Mg^{+2}, Ca^{+2}, K^{+1} etc. (Table 4 shows major composition of seawater in different locations of the world). Even though in very low amounts their strong presence can be felt just by drinking and swimming. A comparison of fresh water and sweater properties (Table 5) shows a noticeable difference [23]. In this study, therefore, we have considered seawater as a non-ideal solution. Additionally, Ulfsbo et al. [24] conducted temperature dependency analysis of activity coefficients of ions in seawater. Their work suggested that ionic activity is independent of temperature within the range of SWRO process. Hence the second-term on the RHS of Eq. (18) can be ignored. Thus,

$$\xi^{M} = h_{\text{mix}} - \sum_i x_i h_i - T_d\left(s_{\text{mix}} - \sum_i x_i s_i\right) \tag{21}$$

In the above equation enthalpy and entropy of the mixture can be obtained from the seawater property relations developed by Nayyer et al. [22]. The enthalpy and entropy of pure water can be obtained from steam tables or from correlations. The data obtained from Jeddah plant reported TDS and salinity separately. The salinity is reported as chlorides. Moreover, in the literature NaCl has been reported as about 86% of all electrolytes present in seawater. In our study, therefore, we have included NaCl as the only electrolyte present in the seawater.

The standard molar entropy of solid phase NaCl has been reported to be 72.1 J/mol K (25°C, 1 atm). As an approximation we ignore the effects of temperature and pressure on the entropy of pure NaCl. The enthalpy of pure NaCl is given as 0.18 kJ/kg [25].

3.2.3.3. Chemical exergy (ξ^{ch})

The chemical exergy is defined as the exergy of chemical substances with reference to their standard states or most stable states in the environment. The environment is usually taken as species in air, seawater or lithospheric solids at normal temperature and pressure [26]. The chemical exergy for any species is calculated under standard conditions if affinity of the reaction and exergy of reactant and products are known. Once chemical exergy of a species is estimated at standard conditions of T_d and P_d then chemical exergy at other temperatures and pressure can be determined [26]. The molar chemical exergy of the non-ideal liquid mixture is calculated by following formula [27]:

$$\xi^{\text{ch}} = \sum x_i \xi_i^{o,\text{ch}} + \sum_i x_i R T_d \ln\left(\gamma_i x_i\right) \tag{22}$$

The standard molar chemical exergy of NaCl is 14.2 kJ/mol whereas that of water is 0.9 kJ/mol [28]. For the determination of activity coefficient of water in a non-ideal electrolytic solution we used the correlation by Miyawaki et al. [29] given as:

Table 5
Comparison of seawater and fresh water properties

Property	Seawater	Fresh water
Density, g/cm³, 25°C	1.02412	1.0029
Specific conductivity, ohm/cm, 25°C	0.0532	–
Viscosity, millipoise, 25°C	9.02	8.9
Vapor pressure, mm/Hg, 20°C	17.4	17.34
Isothermal compressibility, vol/atm, 0°C	46.4×10^{-6}	50.3×10^{-6}
Temperature of maximum density, °C	–3.25	3.98
Freezing point, °C	–1.91	0.00
Surface tension, dyne/cm, 25°C	72.74	71.97
Velocity of sound, m/s, 0°C	1,450	1,407
Specific heat, J/g °C, 17.5°C	3.898	4.182

Table 4
Major composition of seawater in different seas

Ion	Typical seawater	Mediterranean	Arabian Gulf	Red Sea
Chloride (Cl^-)	18.98	21.20	23.00	22.219
Sodium (Na^+)	10.556	11.8	15.85	14.255
Sulfate (SO_4^{2-})	2.649	2.95	3.2	3.078
Magnesium (Mg^{2+})	1.262	1.40	1.76	742
Calcium (Ca^{2+})	400	423	500	225
Potassium (K^+)	380	463	460	210
Bicarbonate (HCO_3^-)	140	–	142	146
Strontium (Sr^{2+})	13	–	–	–
Bromide (Br^-)	65	155	80	72
Borate (BO_3^{3-})	26	72	–	–
Fluoride (F^-)	1	–	–	–
Silicate (SiO_3^{2-})	1	–	1.5	–
Iodide (I^-)	Less than 1	2	–	–
Others				
TDS	34,483	38,600	45,000	41,000

$$\gamma_w = \left(1 - x_s\right)\exp\left(\alpha x_s^2 + \beta x_s^3\right) \tag{23}$$

where for NaCl (aq.), we have $\alpha = 1.825$, and $\beta = -20.78$.

The activity coefficient for NaCl as function of salinity is obtained by regressing the data presented in [24]. The following equation was obtained with $R^2 = 0.98$.

$$\ln\left(\gamma_{\text{NaCl}}\right) = -0.076\ln\left(S\right) - 0.144 \tag{24}$$

where S is the salinity in g/kg.

3.2.4. Plant exergetic/thermodynamic efficiency

Although several definitions exist regarding exergetic efficiency, in this work we have expressed exergetic efficiency as a dependent on raw materials, fuel and product exergies [30]. The fuel exergy is the exergy required to produce product exergy. The fuel exergy comprises all the inlet exergies such as pump work, incoming seawater exergy or any heat transfer to increase the temperature of the system. On the other hand, product exergy comprises exergies associated with all the streams leaving the plant such as permeate and concentrated brine. Thus, for Jeddah plant we define exergetic efficiencies as follows:

3.2.4.1. Equipment exergetic efficiencies

(i) Pump

$$\eta_{\text{pump}} = \frac{\dot{\xi}_{\text{out}} - \dot{\xi}_{\text{in}}}{\dot{W}} \tag{25}$$

(ii) Pressure exchanger

$$\eta_{\text{pressure\_exch}} = \frac{\dot{\xi}_{\text{seawater\_out}} - \dot{\xi}_{\text{seawater\_in}}}{\dot{\xi}_{\text{brine\_in}} - \dot{\xi}_{\text{brine\_out}}} \tag{26}$$

(iii) RO modules

$$\eta_{\text{RO\_module}} = \frac{\dot{\xi}_{\text{permeate}} \mp \dot{\xi}_{\text{brine}}}{\dot{\xi}_{\text{seawater\_in}}} \tag{27}$$

(iv) Mixer

$$\eta_{\text{mixer}} = \frac{\dot{\xi}_{\text{out}}}{\dot{\xi}_{\text{in}}} \tag{28}$$

(v) Dual media filter

$$\eta_{\text{DMF}} = \frac{\dot{\xi}_{\text{out}}}{\dot{\xi}_{\text{in}}} \tag{29}$$

3.2.4.2. Overall process exergetic efficiency

In this work we consider concentrated brine leaving the plant as a product, hence,

$$\eta_{\text{plant}} = \frac{\sum \dot{\xi}_{\text{products}}}{\sum \dot{\xi}_{\text{fuel}} + \sum \dot{\xi}_{\text{raw\_material}}} = \frac{\dot{\xi}_{\text{permeate}} + \dot{\xi}_{\text{brine}}}{W_{\text{pumps}} + \dot{\xi}_{\text{seawater}}} \tag{30}$$

3.3. Properties estimation

To estimate exergy of flow streams, accurate values of several seawater properties are needed. A number of correlations have been developed to estimate thermodynamic properties of seawater such as enthalpy, entropy, heat capacity, thermal conductivity, density, viscosity, surface tension etc. In this work recently developed correlations for SWRO at high pressure conditions, developed by Nayyer et al. [22], are used.

4. Results and discussions

MS Excel is used to perform the calculations. The choice of Excel spreadsheet was made due to its availability, simplicity, and almost no cost compared to other software such as MATLAB, EES, Polymath etc. Additionally, the SWRO is an isothermal process due to which the thermal properties become constant and the mathematics involved become simple.

The operational/design data obtained from the Jeddah plant is given in Table 3. The salinity has been reported in terms of chlorides. With 1:1 ratio of Na:Cl the weight of the NaCl is calculated and tabulated in the same table. The weight of NaCl is less than TDS because TDS involve other dissolved solids as well. Moreover, the units of salinity are reported in mg/L whereas in seawater correlations units of salinity used are g/kg or kg/kg. [26]. For dilute solutions mg/L can be approximated as 1 ppm, and therefore we have taken 1 g/kg = 1,000 mg/L.

4.1. Plant current exergy status

With SWRO plant data available total exergy of each streams (Fig. 1) was calculated. This is reported in Table 6.

As mentioned above, to calculate the specific enthalpy and specific entropy the correlations developed by Nayyer et al. [22] are used. To check the accuracy of the calculations the values obtained from the correlations were compared with those published in [31] and the results matched exactly (Figs. 2 and 3). The decrease in entropy with the increase in salt concentration is due to the fact that entropy of sodium is much lower than that of water at standard conditions which compensates for the increase in entropy due to mixing. The enthalpy also decreases with the salinity. This is because when the NaCl dissolves in water the enthalpy of water is consumed to break the NaCl bond. Therefore, higher the salinity the lower is the enthalpy of seawater at a given temperature.

The physical exergy values were estimated with reference to the restricted dead state. That is, in determining the physical exergy the salinity was kept constant at 40 g/kg which gave the exergy change only due to thermomechanical effect. The chemical exergy values were estimated with reference to the global dead state. That is, in evaluating the chemical exergy the temperature and pressure were kept constant and only variation in the salinity were taken

Table 6
Streamwise total flow exergy

No.	Description	ξ^{ph}[a]	ξ^{ch}	ξ^{M}	ξ^{Total}
Stream 1	Seawater inlet	0.10	0.00	0.00	0.10
Stream 2	Seawater to plant	0.19	0.00	0.00	0.19
Stream 3	Feed to DMF	0.14	0.00	0.00	0.14
Stream 4	Rinsing water	0.14	0.00	0.00	0.14
Stream 5	From DMF	0.10	0.00	0.00	0.10
Stream 6	To static mixer	0.49	0.00	0.00	0.49
Stream 7	From static mixer	0.23	0.0065	0.00	0.24
Stream 8	To turboexpander	2.73	0.0065	0.00	2.74
Stream 9	From turboexpander	5.30	0.006	0.00	5.30
Stream 10	From 1st pass module	0.10	1.87	–0.06	1.91
Stream 11	To 2nd pass module	1.07	1.87	–0.06	2.88
Stream 12	To storage	0.10	1.97	0.00	2.07
Stream 13	To turboexpander	5.46	0.19	1.84	7.50
Stream 14	To throttle valve	0.85	1.13	–0.73	1.25
Stream 15	To recirculation	0.49	1.13	–0.73	0.89
Stream 16	To backwash tank	0.17	0.19	1.84	2.20

[a] Exergy units are in kJ/kg.

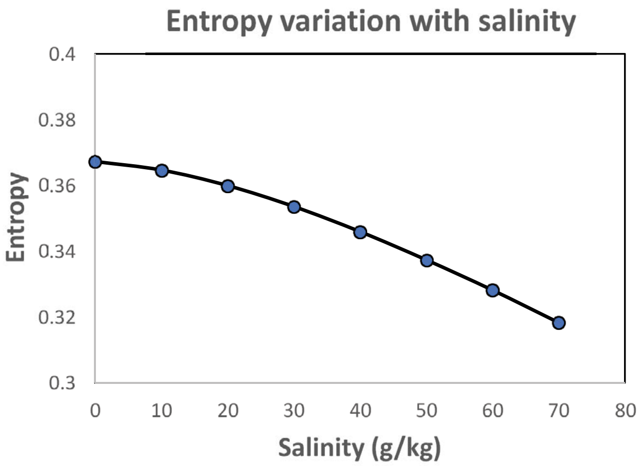

Fig. 2. Calculations of specific entropy (kJ/kg K) $T = 25°C$, $P = 0.101$ MPa.

into consideration [31]. Likewise mixing exergy values were calculated with reference to the global dead state.

The values of physical, chemical and mixing exergies are given in the Table 6. The physical exergy values are all above zero because either temperature or pressure or both are above the global dead state. The value of chemical exergies with reference to the dead state first decrease until the dead state is reached and then increase as shown in Fig. 4. Thus chemical exergy is positive on either side of the global dead state because the concentration different causes chemical potential difference which makes the chemical exergy positive [31]. The variation of mixing exergy with salinity is plotted in Fig. 5. As the salinity starts to increase the mixing energy decreases and then begins to increase. This can be understood by considering

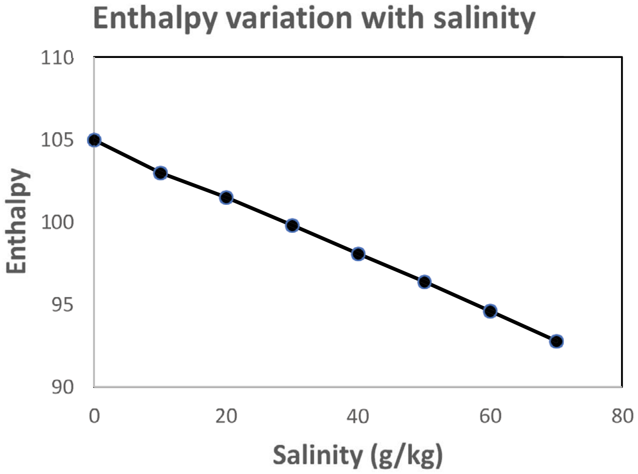

Fig. 3. Calculations of specific enthalpy (kJ/kg) $T = 25°C$, $P = 0.101$ MPa.

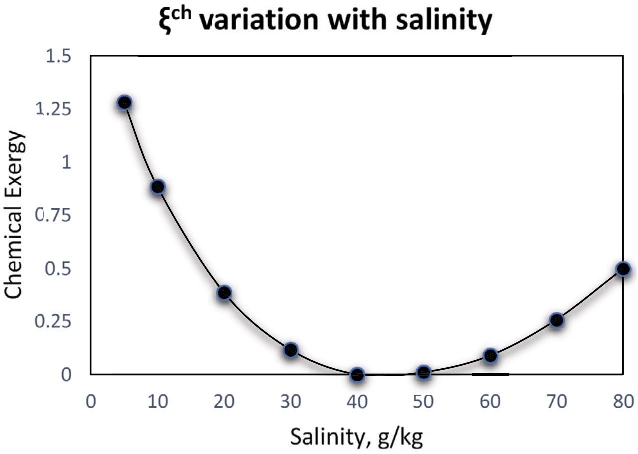

Fig. 4. Chemical exergy variation with salinity $T = 25°C$, $P = 0.101$ MPa.

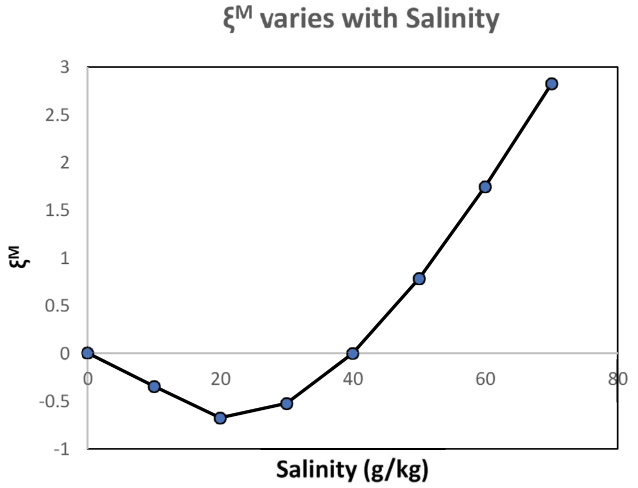

Fig. 5. Mixing exergy variation with salinity $T = 25°C$, $P = 0.101$ MPa.

two factors, that is, entropy increase due to mixing and entropy decrease due to the addition of solid NaCl(Cr) which has very low entropy compared to H_2O(l). At low salinities the mixing entropy dominates and the exergy calculations becomes negative. As the salinity is gradually increased the entropy increase due to mixing is offset by the low entropy of NaCl and thus exergy calculations become positive. Because positive exergy is the useful work done by the system when it is above the dead state then negative exergy could be defined as the work done on the system when it is below the dead state. Thus negative exergy values are realistic and should be considered to improve exergy calculations.

4.1.1. Estimation of equipment and plant exergetic efficiency

In Table 7, the equipment wise exergetic efficiencies, exergy destructions and exergy destruction ratio are listed. The major exergy destruction is caused by pumps (~51%), followed by RO modules (~21%) and about 28% by mixer, DMF and turboexpander combined together. Moreover, we compared our work to the work of Eshoul et al. [20] which also performed exergy analysis of 2-Pass SWRO. The comparisons of design data and the exergy data are given in Tables 8 and 9 respectively. They predict lower pumps' and higher RO module exergy destruction compared to us. We have included mixing exergy, temperature dependency of activity coefficients and high pressure seawater thermodynamics properties which do not seem to be included by Eshoul et al. [20]. Their calculations should therefore be updated.

Table 7
Equipment and plant exergetic efficiencies

Equipment	η	ξ_d	ξ^d_{ratio} (%)
Pump (seawater intake)	38.75	61.25	12.08
Pump (filtered water)	67.38	32.62	06.43
Pump (high pressure 1)	22.94	77.06	15.19
Pump (high pressure 2)	13.24	86.76	17.11
Turboexpander	92	8	1.58
RO module1	49.22	50.78	10.01
RO module2	39.71	60.29	11.89
Mixer	32.73	67.27	13.26
Dual media filter	36.84	63.16	12.45
Overall plant	29.40	70.60	–

Table 8
Comparison of this work and Eshoul et al. [20] – process

Process conditions	Eshoul et al. [20]	This work
Type of SWRO system	Two pass	Two pass
Seawater temperature (°C)	25.0	35.0
Seawater flow to the plant (tons/h)	327	12,900
Seawater salinity (g/kg)	36	40
SWRO feed pump pressure (barg)	65.0	67.80
Permeate flow	147.4	5,090
Recovery ratio (%) – 1st pass	45.00	42.00
Brine rejected (tons/h)	180	7,810
Dual media filter	71.48	28.52

4.1.2. Minimization of exergy destruction

Most of the previous research was conducted on the exergy analysis without energy recovery devices such as Pelton turbine, pressure exchangers and turboexpanders. Then the ERDs were recommended. In our case we already have a turboexpander as an ERD which has exergy destruction ratio of about 1.5%. In this work, therefore, we have focused on how to modify the process to minimize the exergy destruction and to reduce the SEC by recommending some modifications, wherever possible, in the current process as follows:

Mixer accounts for almost 10% of exergy destruction. One mixer before 1st pass RO HP pump can be eliminated by injecting sodium bisulfate directly before the pump suction.

Pumps contribute to almost 51% of the total exergy destruction. The HPP2 has the highest exergy destruction. We, therefore, recommend an ERD to be installed to drive the pump as is the case with the HPP1. This could result in the significant drop in the pump power [8]. The seawater

Table 9
Comparison of this work and Eshoul et al. [20] – equipment

Process conditions	Eshoul et al. [20]	This work
Overall plant efficiency	27.3	29.4
Pumps exergy destruction ratio	0.37	0.52
RO modules exergy destruction ratio	0.36	0.26
SEC (kW/m^3)	7.2	4.88

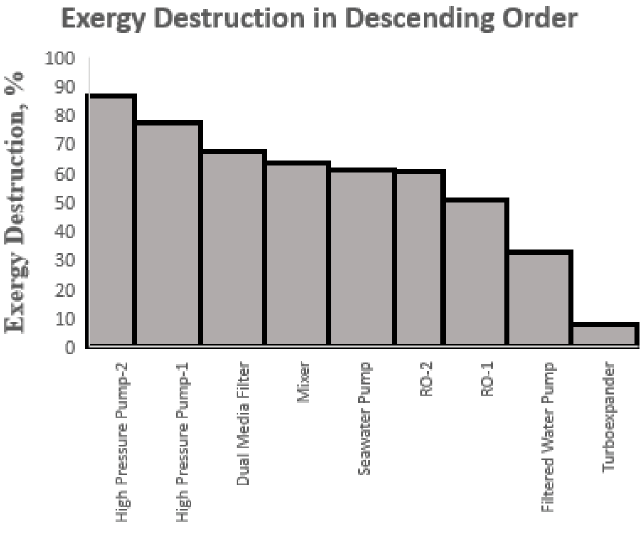

Fig. 6. Equipment wise exergy destruction.

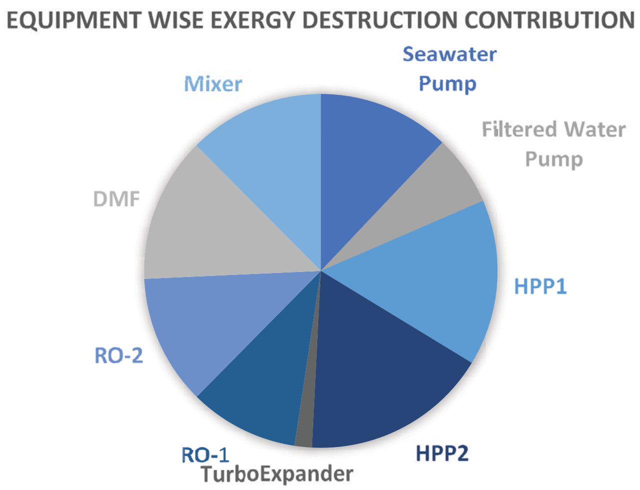

Fig. 7. Equipment wise exergy destruction ratio.

pump and the filter water pumps could be run on the hybrid mode. That is, both could be made to run on electrical and solar power. With plenty of hot sun shine available in Jeddah all the year this could be best the option. However, a detailed economic study is needed to check the feasibility of this option.

We also suggest consideration of the option of recently developed hybrid desalination technology [32,33]. It is reported that with this technology the brine exiting the SWRO can be further treated by multi evaporation and in an adsorption/desorption cycle and thereby reduce the SEC to about 1.7 kW/m^3.

Nothing can be done to decrease exergy destruction across existing RO modules. The only option would be to replace them with state-of-the-art RO modules that require lesser pressure. However, this option is not being considered.

5. Conclusions

In this work a comprehensive analysis of the exergetic performance of a SWRO plant located in Jeddah, Saudi Arabia has been made. The plant is using a turbo expander as an ERD with SEC of the plant being 4.88 kW/m^3. Moreover, the overall exegetic efficiency of the plant is 29.4 which is quite low. It is determined that high pressure pumps cause almost half of the total exergy destruction followed by other equipment. Some modifications in the process design have been presented such as elimination of a mixer and the inclusion of an ERD device for the 2nd high pressure pump. The possible use of solar power to drive seawater and filter water pumps is recommended. Additionally, the use of hybrid desalination technology which is said to improve SEC to about 1.7 kW/m^3 should be considered.

Symbols

$\hat{h}$	—	Specific enthalpy, kJ/kg
m	—	Mass flowrate, kg/s
Q	—	Rate of heat transfer, kW
R	—	Ideal gas constant, kJ/kg K
T_d	—	Temperature at the dead state, K
W	—	Rate of shaft work, kW

Greek

η	—	Efficiency
ξ	—	Exergy associated with mass flow, kJ

Subscripts

o	—	Out
i	—	In
d	—	Dead state

Superscripts

s	—	Salt

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