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Exergy Analysis of a 10,000 m^3/day Tajoura SWRO Desalination Plant

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Abstract

Exergy analysis is a valuable engineering tool for the design, optimization and performance evaluation. This paper conducts thermodynamic exergy analysis using actual plant operating data of seawater reverse osmosis (SWRO) plant at Tajoura Nuclear Research Center. Exergy flow rates are calculated all over the plant. The rates of exergy destruction and their percentages are determined so that the sites of highest exergy destruction can simply be recognized. The highest exergy destruction 48.32% happens in the 1st stage high pressure pump (HPP), where the second law efficiency of the plant was 25.65 % using the old style turbine and high energy consumption membranes. This shows that chances of development might be to reduce exergy destruction and make the plant operation more cost effective. The second law efficiency of Tajoura desalination plant was increased to 35.76% by using new membranes with high production rate and low energy consumption. Moreover, other things were taken into account for increasing the efficiency of the plant through the use of high efficiency energy recovery devices (ERD) such as pressure exchangers (PX).

Keywords: Exergy analysis; reverse osmosis; membranes; pressure exchanger.

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1. Introduction

The concept of exergy is based on both the first law of thermodynamic and the second law of thermodynamic. The analysis of operation data from several RO plants in the world revealed that the second law of efficiency of such plants is just 10-20%, which points out that there are tremendous opportunities in such plants for improvements. In contrast, the second law of efficiency of modern plants is over 50%. The efficiency of RO desalination plants can certainly be increased by using the second law analysis. It should be possible to at least double these values economically.

Doubling of the second law efficiencies will result in reducing the current energy usage for desalination by half. Raising the efficiencies to 20% to 40% is a very realistic goal since many engineering systems in operation have second law efficiencies well over 50% [1, 2].

Tajoura SWRO desalination plant uses reverse pump turbine as an energy recovery device (ERD), furthermore, the plant operated with an old design membrane, it seems that the thermodynamic analysis of Tajoura desalination plant is necessary to find out the highest exergy destruction and then the answer to decrease this waste of energy and save the energy consumption of the plant in order to decrease the unit product cost.

2. Process Description

The Tajoura SWRO desalination plant presented in Figure 2.1 with design parameters shown in Table 2.1, where the plant consists of two RO stages in two lines to produce10,000 m3/d of desalted water with a quality of 170 mg/L TDS.

Table 2.1: The major design parameters of Tajoura desalination plant

Item	First stage	Second stage
Number of RO racks	4	2
Pressure vessels configuration	1 stage	3 stages (24-12-6)
Number of pressure vessels	396	84
Number of membranes	2,376	504
Number of membranes per pressure vessel	6	6
Nominal diameter, inch	8	8
Membrane model	TFC 1501 PA	TFC 8600 PA
Design pressure, bar	69	41
Working pressure, bar	54	31
pH	5-6	5-6
Maximum temperature,oC	45	45
Feed flow, m^3/h	1,576	552
Permeate flow, m^3/h	552	426
Concentrate flow, m^3/h	1,024	84
Design salt rejection, %	98.6	98
Recovery, %	35	85
Permeate salinity, mg/L	1940	170
Feed salinity, mg/L	36,204	1,940

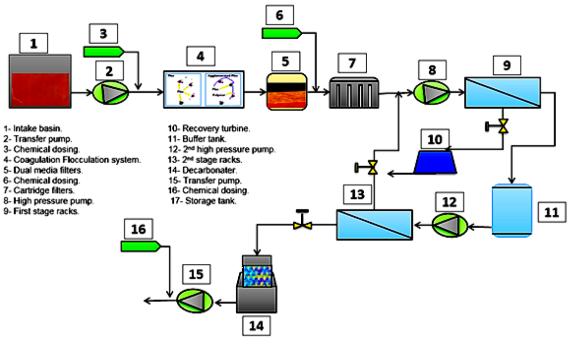

Figure 2.1: Schematic diagram of the SWRO desalination plant

The raw seawater goes from seawater intake head by gravity through two 760 mm diameter plastic pipes to its destination into 5,580 m^3 basin at the seashore. From the basin 750 m^3/hr (1,500 m3/hr for 100% operation) are pumped to the pretreatment section. The pretreatment consists of an online coagulation-flocculation, 8-media filters and 5 μm cartridge filters. Four chemicals are injected before the water enters the online coagulation. These are sulphuric acid for pH control, Copper sulphate for disinfection, sodium hydrogen sulphite for dechlorination and ferric chloride sulphate for flocculation. Sulphuric acid and anti-scalant are injected before 5 μm filters to prevent the scaling of the membranes by $CaCO_3$ and $CaSO_4$. From the pretreatment section, feed water is fed to the RO section by means of four high pressure pumps coupled to a recovery Turbine to recover about 30% of its energy requirement from the high pressure concentrate stream. The first stage consists of four racks each having a high pressure pump. Product of the first stage is collected in two inter-connected buffer tanks. The water from the buffer tank is fed to two racks of a second pass by mean of two high-pressure pumps. The concentrate from the second pass is recycled back and mixed with the feed to the first stage after cartridge filter.

The product water will go through a decarbonator to remove carbon dioxide, and before delivery to the storage tank water is treated for pH adjustment by sodium hydroxide and chlorination by calcium hypochlorite [3].

3. Exergy Analysis

The exergy analysis of the plant based on the listed below assumptions that has to simplify the

formulas without losing accuracy. The following assumptions are considered:

- All equipments of the plant operate at steady state conditions.
- Seawater salinity is assumed that is given only by NaCl.
- There is no concentration polarization at the membrane surface.
- Membranes are ideal, and therefore they do not cause any pressure drop as the product water crosses them.
- The environment temperature is taken as 25oC in all calculations.
- The salinity of the incoming raw water is constant.
- The kinetic and potential energies of streams are negligible.
- The seawater is an ideal solution.
- Salt, water, and saline water are incompressible substances.

The properties of the seawater depend on its pressure, temperature and salinity. The latter can be expressedin ppm (parts per million on a mass basis), as a percentage (sal), as a salt mass fraction (mf_s) or a salt mole fraction (x_s). mf_s and x_s are defined as [4, 5]:

$$\begin{aligned} mf_s &= m_s/M_m = N_sM_s)/N_mM_m \\ &= x_sM_s/M_m \\ &\mathit{and} \\ Mf_w &= M_w/M_m = x_w \end{aligned} \tag{3.1}$$

where m is mass, M is the molar mass, N is the number of moles, and x is the mole fraction. The subscripts s, w, and m stand for salt, water, and seawater, respectively.
The apparent molar mass of the seawater is

$$\begin{aligned} M_m &= m_m/N_m \\ &= (N_sM_s + N_wM_w)/N_m \\ &= x_sM_s + x_wM_w \end{aligned} \tag{3.2}$$

The molar masses of NaCl and water are 58.5 kg/kmol and 18.0 kg/kmol, respectively [6]. Mass fractions are used for salinity calculations, where mole fraction used for the minimum work calculations. Combining Equations 3.1 and 3.2 and noting that $x_s + x_w = 1$ gives the following relations:

$$\begin{aligned} x_s &= M_w/(M_s(1/mf_s - 1) + M_w) \\ &\mathit{and} \\ x_w &= M_s/(M_w(1/mf_w - 1) + M_s) \end{aligned} \tag{3.3}$$

Solutions that have a concentration less than 5 % are considered to be dilute solutions. Dilute solutions closely approximate the behavior of an ideal solution, and thus the effect of dissimilar molecules on each other is negligible. Seawaters and saline underground waters are all ideal solutions since they have about a 4% salinity [4, 5].
The enthalpy and entropy of a mixture are determined from

$$\begin{aligned} H &= \sum m_ih_i = m_sh_s + m_wh_w \\ &\mathit{and} \\ S &= \sum m_is_i = m_ss_s + m_ws_w \end{aligned} \tag{3.4}$$

Dividing by the total mass of the mixture gives the quantities per unit mass of mixture.

$$\begin{aligned} H &= \sum m_ih_i = m_sh_s + mf_wh_w \\ &\mathit{and} \\ S &= \sum mf_is_i = mf_ss_s + mf_ws_w \end{aligned} \tag{3.5}$$

The enthalpy of mixing of an ideal gas mixture is zero (no heat is released or absorbed during mixing), and thus the enthalpy of the mixture (and thus the enthalpies of its individual components) do not change during mixing. Therefore, the enthalpy of an ideal mixture at a specified temperature and pressure is the sum of the enthalpies of its individual components at the same temperature and pressure [7]. Then it follows that the enthalpy of a seawater which can be determined from the relation above by evaluating the enthalpies of individual components at the mixture temperature and pressure. The feed seawater to the desalination plant is at about 25°C, 1 atm, and a salinity of 36,204 ppm. These conditions can be taken as a conditions of the environment, then the properties at the dead state become $T_o = 298.15$ K, $P_o = 1$ atm $= 101.325$ kPa; salinity $= 36{,}204$ ppm $= 3.6204\%$.

4. Enthalpy and Entropy of Pure Water and Salt

Properties of pure water are obtainable in tabulated or computerized forms. Water properties estimated by the built-in functions of the Engineering Equation Solver (EES) software at combination temperature and pressure were used [6]. Furthermore, the equations 6 and 7 can be used for calculating enthalpy and entropy, respectively for pure water properties and provided very close values to that achieved by EES software.

$$\begin{aligned} h_w =& 141.355 + 4202.07 * t \\ & - 0.535 * t^2 + 0.004 * t^3 \end{aligned} \tag{4.1}$$

$$\begin{aligned} s_w =& 0.1543 + 15.383 * t - 2.996 * t^2 \\ & + 8.193 * t^3 - 1.370 * 10^{-7} * t^4 \end{aligned} \tag{4.2}$$

The state of salt at 0°C is taken as the reference state, then the enthalpy and entropy of salt at temperature T can be determined by following Equation

$$\begin{aligned} h_s =& h_{so} + C_{ps}(T - T_o) \\ & and \\ h_s =& h_{so} + C_{ps} ln(T/T_o) \end{aligned} \tag{4.3}$$

The specific heat of salt can be taken to be C_{ps} 0.8368 = kJ/kg.K. The enthalpy and entropy of salt at To = 25°C can be determined to be hso = 12.552 kJ/kg and s_{so}= 0.04473 kJ/kg.K, respectively(note that for incompressible substances and enthalpy and entropy are independent of pressure) [4]. The entropy of a component per unit mole in an ideal solution at a specified temperature T and pressure P is

$$\bar{S}_i = S_{i,pure}(T, \bar{P}) - R_u ln x_i \tag{4.4}$$

Then the entropy of a saline solution is the sum of the entropies of salt and water in the saline solutions.

$$\begin{aligned} \bar{S} =& x_s \bar{s}_s + x_w \bar{s_w} \\ =& x_s [\bar{S}_{s,pure}(T, P) - R_u ln x_s] \\ & + x_w [\bar{S}_{w,pure}(T, P) - R_u ln x_w] \\ =& x_x \bar{S}_{s,pure}(T, P) - R_u \left(x_s ln x_s + x_w ln x_w \right) \end{aligned} \tag{4.5}$$

The entropy of saline water per unit mass is determined by dividing the quantity above (which is per unit mole) by the molar mass of saline water. It gives:

$$\begin{aligned} S =& m f_s s_{s,pure}(T, P) + m f_w s_{w,pure}(T, P) \\ & - R_m (x_s ln x_s + x_w ln x_w) \\ & (kJ/(kg.K) \end{aligned} \tag{4.6}$$

The exergy of a flow stream is given as:

$$\Psi = h - h_o + T_o(S - S_o) \tag{4.7}$$

Then the rate of exergy flow associated with a fluid stream becomes:

$$\dot{X} = \dot{m}\Psi = \dot{m} \left[-h_o \left(s - s_o \right) \right] \tag{4.8}$$

Using the relations above, the specific exergy and exergy flow rates at various points indicated in Figure 4.1 are evaluated.

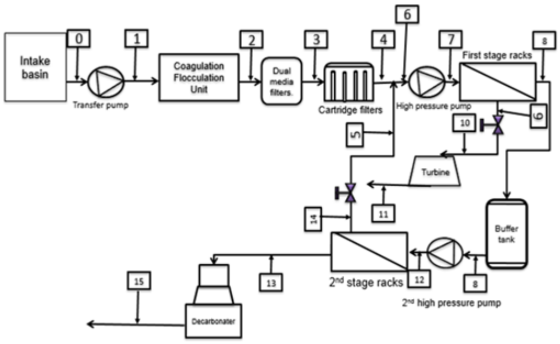

Figure 4.1: Schematic diagram of Tajoura reverse osmosis desalination plant

The exergy balance for any system undergoing any process is expressed as:

$$X_{in} = X_{out} - X_{destroyed} = \Delta X_{system} \tag{4.9}$$

For an adiabatic steady sate system which has no work interaction, the relation above simplifies to:

$$X_{destroyed} = X_{in} - X_{out} \tag{4.10}$$

The exergy efficiency of all components can be calculated as:

$$\eta_c = 1 - X_{destroyed}/X_{out} \tag{4.11}$$

Tajoura SWRO desalination plant was analyzed using the relations prescribed above. The exergy rate at all states and the rate of exergy change for

each component of the plant are calculated, and the results are tabulated in Table 2. The locations of the states are illustrated in the diagram of Tajoura plant shown in figure 2. The feed seawater enters the plant and the final permeate and concentrate leaving the plant are at the same dead state temperature and pressure, but at different salinities. Thus, the exergies of the concentrate line differ only due to the changed salinities and the old-style turbine installed in the brine stream for energy recovery. As it can be seen from table 2 the raw feed seawater at state 0 has zero exergy since it is at the dead state. The brine at state 11 leaves the system at a high salinity of 54,918.68 ppm and has a negative exergy rate of -211.6 kW. The plant contains three pumps. The total exergy rate of the various lines is the sum of the exergy changes across the pumps and is determined to be:

$$\begin{aligned} \Delta \dot{X}pumps = & \Delta \dot{X}_{seawaterpump} \\ & + \Delta \dot{X}_{1^{st}stagepump} \\ & + \Delta \dot{X}_{2^{nd}passpumps} \end{aligned} \tag{4.12}$$

$\Delta \dot{X}_{pumps} = 1,115.8kW$

Where the turbine was installed in the brine stream as energy recovery device, thus should be involved for calculating the overall exergy rate and is determined to be:

$\Delta \dot{X}_{turbines} = -318.68kW$

$\Delta \dot{X}_{pumps} + \Delta \dot{X}_{turbines} = 797.12kW$

For a combined pump motor efficiency of 76%, the exergy provided in the form of electricpower is:

$\dot{X}_{in,pumps} = \Delta \dot{X}_{pumps}/\eta_{pumpmotor} = 1,468.15kW$

$$\begin{aligned} \dot{X}_{destroyed,pumps} &= \dot{X}_{in,pumps} - \Delta \dot{X}_{pumps} \\ &= 352.36kW \end{aligned}$$

$$\begin{aligned} \dot{X}_{in,turbines} &= \Delta \dot{X}_{turbines} * \eta_{pumpmotor} \\ &= -248.57kW \end{aligned}$$

Then, the total exergy provided to this desalination plant becomes:

$\dot{X}_{in,total} = \dot{X}_{in,pumps} + \dot{X}_{in,trubine} = 1,219.59kW$

The minimum work input for a steadyflow adiabatic process is the work input required for a reversible adiabatic process, and is equal to the difference between the exergies of the leaving streams and the exergies of the entering streams, including the salinity exergy. Therefore, the minimum work input for the separation of 397.2 kg/sec seawater at 25°C, 1 atm, and a salinity of 36,204 ppm by the RO plant into 118.3 kg/sec fresh water with a salinity of 170 ppm and 21.11 kg/sec of brine disposal with a salinity of 54918.68 ppm at the same temperature and pressure is:

$$\begin{aligned} \dot{W}_{min} = & \dot{X}_{outgoingbrineandproductwater} \\ & - \dot{X}_{incomingseawater} \end{aligned}$$

$\dot{W}_{min} = 271.81kW$

It should be noted that the inlet and exit streams are at the same temperature and pressure, and thus, this work is entirely due to the composition difference. This desalination plant shows that, at identified rates might be accomplished using only 271.81 kW of exergy (or work input) instead of 1,219.59 kW. Then, the rate of wasted exergy throughout this process becomes:

$$\begin{aligned} \dot{X}_{destroyed,total} &= \dot{X}_{in,total} - \dot{X}_{in,min} \\ &= \dot{X}_{in,total} - \dot{W}_{min} = 947.78kW \end{aligned}$$

The Second Law efficiency of this RO plant is the ratio of the minimum exergy input required (which is equivalent to the minimum work of separation) to the total actual exergy input or, is determined by subtracting the ratio of the total exergy destruction to the total exergy input from one. It gives:

$$\begin{aligned} \eta_{II} &= (\dot{W}min)/(\dot{X}in, total) \\ &= (\dot{X}in, min)/(\dot{X}in, total) = 22.29 \end{aligned}$$

$\eta_{II} = 1 - (\dot{X}destroyed)/(\dot{X}in, total) = 22.29\%$

The calculations of the exergy destroyed in various components are shown in Table 4.1 and is shown in Figure 4.2. The width of the arrow is proportional to the exergy values. As seen from the Figure 4.2 the 1^{st} stage high pressure pump account for the largest exergy destruction (about 48.32 %) of total exergy input is destroyed where the most practical and useful technique to rise efficiency or decrease the power input of the plant meaningfully through replacing the old-style turbine with a modern pressure exchanger, followed by (15.46 %) due to mixing of the brine stream of the second stage to the suction of the first stage high pressure pump. It is not surprising since a mixing process has a potential to produce work when solutions of different concentrations are mixed reversibly. The next largest exergy destructions occur in the 1st and 2nd membranes modules which is (11.83 %) and (12.06%) respectively, of the total input exergy. However, before there was nothing can be done in order to eliminate or decrease this exergy destruction and recently several types of membranes are available with high rejection rate and low energy con-

Table 4.1: Rate of exergy change of major components

Component	Stream, No.	T, K	P, Kpa	Salinity, ppm	ψ (kJ/kg)	$\dot{m}$, kg/s	$\dot{X}$ (kW)	$\Delta\dot{X}$
Intake	0	298.2	101.325	36,204	0.0000	0.0	0.0	
Transfer pumps	1	298.2	480	36,204	0.4143	397.2	164.6	165
Flocculation	2	298.2	470	36,204	0.4143	397.2	164.6	0
Media filters	3	298.2	450	36,204	0.4143	397.2	164.6	0
Cartridge filters	4	298.2	400	36,204	0.3179	397.2	126.3	-38
Mixing (2nd Conc.)	5	298.2	400	230	8.4760	10.4	88.3	
After mixing	6	298.2	400	36,204	0.3179	99.4	31.6	-183
1st HPP	7	298.2	5400	36,204	5.1249	99.4	509.6	478
1st stage permeate	8	298.2	101.325	1,940	7.5633	34.7	262.6	-140
2ndThrottle Valve	9	298.2	5300	54918.68	1.6470	65.0	107.1	0
Before Turbine	10	298.2	5300	54918.68	1.6470	65.0	107.1	
After Turbine	11	298.2	101.325	54918.68	-3.2557	65.0	-211.6	-319
1st stage permeate	8	298.2	101.325	1940	7.5633	34.7	262.6	
2nd HPP	12	298.2	3100	1940	10.5959	69.4	735.8	473
2nd stage permeate	13	298.2	101.325	170	8.1707	59.2	483.4	
2nd stage conc.	14	298.2	2400	230	10.5246	10.4	109.6	-143
Throttling Valve	5	298.2	350	230	8.4462	10.4	88.0	-22
Before Decarbonater	13	298.2	101.325	170	8.1707	59.2	483.4	
After Decarbonater	15	298.2	101.325	170	8.1707	59.2	483.4	0

sumption. The remaining (12.33) % of exergy destruction is distributed among intake transfer pumps (2.996%), filtration unit (3.23%), Turbine (2.01%), 2nd HPP (2.26%) and 2nd stage throttling valve (concentrate) (1.83%).

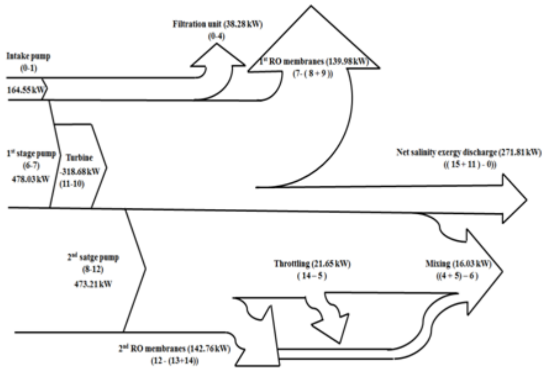

Figure 4.2: Exergy flow chart for the reverse osmosis desalination plant

5. A Proposed Alternative Design

The exergy analysis of SWRO Tajoura plant displays that the plant is working at a low efficiency compared to other well designed applications, an examination of the exergy loss throughout the plant states that the main exergy loss happens in the first high pressure pumps which account for (48.32 %) of total exergy input, where the most practical and useful technique to rise efficiency or decrease the power input of the plant meaningfully through replacing the old-style turbine with a modern pressure exchanger and advanced membranes. In the past there was nothing can be done to eliminate or decrease this loss of exergy economically as far as membrane manufacturer were worried about this problem a number of the membrane suppliers have been working actively on this development need. Systems are presently able to run at pressures up to 1200 psig (82.7 barg), which can rise the conversion of the plant to 50%. DOW Filmtec (SW30HRLE-440i) was selected for the next membrane replacement. As far as the pressure exchanger were selected as ERD for Tajoura SWRO plant, the pressure exchanger conversion efficiency of about 94%, and therefore the unit proposed to be installed in the desalination system saves 94% of the exergy destroyed due to the type of membranes used, brine throttling and the low efficiency turbine from state 9 to state 11. This corresponds to an amount of 299.56 kW. The decrease in the main pump power is 47.63 %, and

this raises the plant second law of efficiency from 25.65 % to 35.76%. This is a 28.27% pumping power reduction to the original power consumption. If the plant consumes electricity at 0.68 Libyan dinar (L.D)/kWh, the annual savings due to this 299.56 kWh electricity will be 1,784,388.73 L.D/yr. That is the pressure exchanger can save the plant about 1,784,388.73 L.D/yr just by taking benefit of the pressure that is currently being wasted by the membranes, throttling valves and low efficiency turbine which is the poorest in performance compared to the other ERDs.

6. Conclusions

The exergy analysis of Tajoura desalination plant shows a poorer value of a second law efficiency compared by the modern designed desalination plants due to utilizing low rejection and production membranes where high pressure is applied. furthermore, using an old design turbine which is the poorest in performance compared to the other ERDs. This study indicates that utilizing some new developed membranes by Dow Filmetic Company such as (SW30HRLE-440i) with high production and rejection rates along with low power consumption as well as using a modern ERD device such as PX can increase the second law efficiency to 35.76%, which will improve the economics of the desalination process due to important reduction in the energy consumption and feed pressure. Thus, an annual savings about 1,784,388.73 L.D/year can be achieved. It seems to be no doubt that the proposed alternatives will improve the performance of the plant.

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