World Academy of Science, Engineering and Technology
International Journal of Chemical and Molecular Engineering
Vol:13, No:3, 2019

Exergy Analysis of Reverse Osmosis for Potable Water and Land Irrigation

M. Sarai Atab, A. Smallbone, A. P. Roskilly

Open Science Index, Chemical and Molecular Engineering Vol:13, No:3, 2019 publications.waset.org/10010103.pdf

Abstract**—**A thermodynamic study is performed on the Reverse Osmosis (RO) desalination process for brackish water. The detailed RO model of thermodynamics properties with and without an energy recovery device was built in Simulink/MATLAB and validated against reported measurement data. The efficiency of desalination plants can be estimated by both the first and second laws of thermodynamics. While the first law focuses on the quantity of energy, the second law analysis (i.e. exergy analysis) introduces quality. This paper used the Main Outfall Drain in Iraq as a case study to conduct energy and exergy analysis of RO process. The result shows that it is feasible to use energy recovery method for reverse osmosis with salinity less than 15000 ppm as the exergy efficiency increases twice. Moreover, this analysis shows that the highest exergy destruction occurs in the rejected water and lowest occurs in the permeate flow rate accounting 37% for 4.3% respectively.

Keywords**—**Brackish water, exergy, irrigation, reverse osmosis.

I. INTRODUCTION

THE tight bond between water and energy is impossible to break. Energy is necessary to treat water and water is required to access and convert primary energy [1]. In fact, this binding between water and energy is now receiving much attention, as pressure for both resources continue to mount. There is a variety of demands on the water supply, including: drinking water, industrial and irrigation, this will lead to more energy challenging.

There are several techniques to evaluate energy system performance. Exergy analysis considers energy in terms of both quantity (First Law of Thermodynamics) and quality (Second Law of Thermodynamics) [2]. Generally, in desalination analyses, the thermodynamic property exergy is broken down into physical and chemical exergy contributions. One key exception is the approach proposed by Cerci [3], where the physical exergy and chemical exergy are integrated, i.e. the chemical/concentration exergy is implicitly included in the entropy of mixing differences. The first law of thermodynamics is applied to each device of the proposed RO plant in a steady state condition. Integrating the study of the second law in the desalination process provides the chance to evaluate the potential to minimize the work input. Desalination is a pure separation process requiring work. Exergy analysis is an effective thermodynamic technique based on integrating the second law of thermodynamics with the mass and energy balance equations for a better understanding of the performance of the proposed system.

Exergy analysis of a two-pass RO unit with and without energy recovery turbine (ERT) and pressure exchanger (PX) has been conducted [4]. The results showed that the lowest energy consumption occurred when PX is utilized also it has a high exergy efficiency and highest minimum separation factor. The highest exergy destruction occurs at the membrane module followed by the high pressure pump, by utilizing ERT can be reduced approximately 35% [5].

In this paper, the exergy efficiency for the overall desalination system is defined as the ratio between the minimum work required for the separation process to the actual work supplied to the system. The viability of brackish water RO desalination plant with an energy recovery device has been studied. Brackish water plant producing 24000 m^3/day has been modelled and validated [6]. By using exergy as a guide for water drinking and irrigation, the model has been analyzed to match the Iraqi Main Outfall Drain (MOD) requirements.

II. RO PROCESS DESCRIPTION

MATLAB was used to design RO model, the schematic diagram of RO desalination unit is shown in Fig. 1, incorporated with a hydraulic turbine in Fig. 2, Table I shows the RO model equations. The main components of RO system are a pump unit that supplies high feed pressure (Pf) and flow rate (Qf) to a membrane, RO unit is a group of RO vessels, containing membrane modules, and energy recovery device such as hydraulic turbine that produces energy from rejected stream directly to a pump. The RO model was built and validated against previously reported measurement data [6], the difference between the RO model and reported measurement data was less than 4.6%. The stream numbers on the schematic diagram are indicators of the thermodynamic properties, as shown in Fig. 1 Stream no.1 represents the feed water which takes on the properties of brackish water for validation.

III. EXERGY ANALYSES

Exergy is the maximum obtainable useful work when a system is brought into equilibrium from its initial state to the ambient temperature (dead) state [7]. The system is considered to be at zero exergy upon reaching the environmental state,

M. Sarai Atab is with School of Mechanical and Systems Engineering, Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle Upon Tyne NE1 8ST, UK; and also with The University of Wasit, Wasit, Iraq.

A. Smallbone is with School of Mechanical and Systems Engineering, Sir Joseph Swan Centre for Energy Research, Newcastle University (corresponding author, phone: +4401912084954; e-mail: andrew.smallbone@newcastle.ac.uk)

A.P. Roskilly is with School of Mechanical and Systems Engineering, Sir Joseph Swan Centre for Energy Research

called the dead state. When temperature (T), pressure (p) and concentration (w) of the system reaches the environment state (T0, p0, w0), equilibriums of thermal, mechanical and chemical can be achieved.

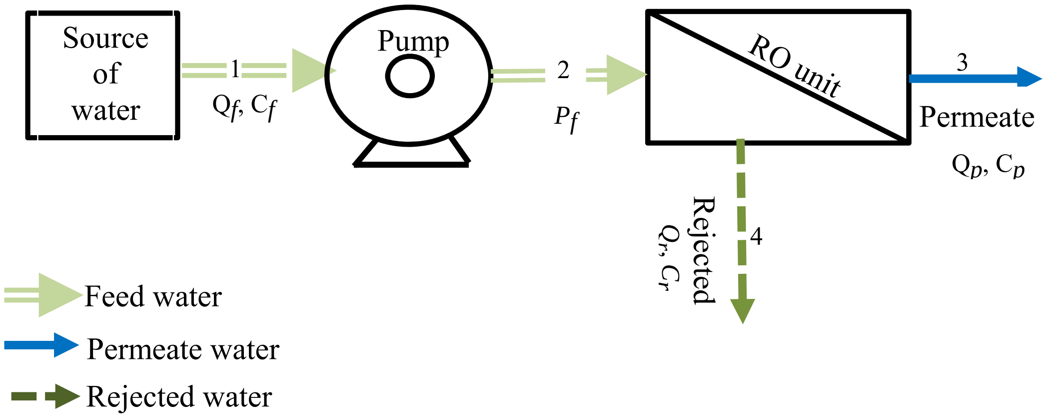

Fig. 1 Schematic representation of the RO desalination model without ERT

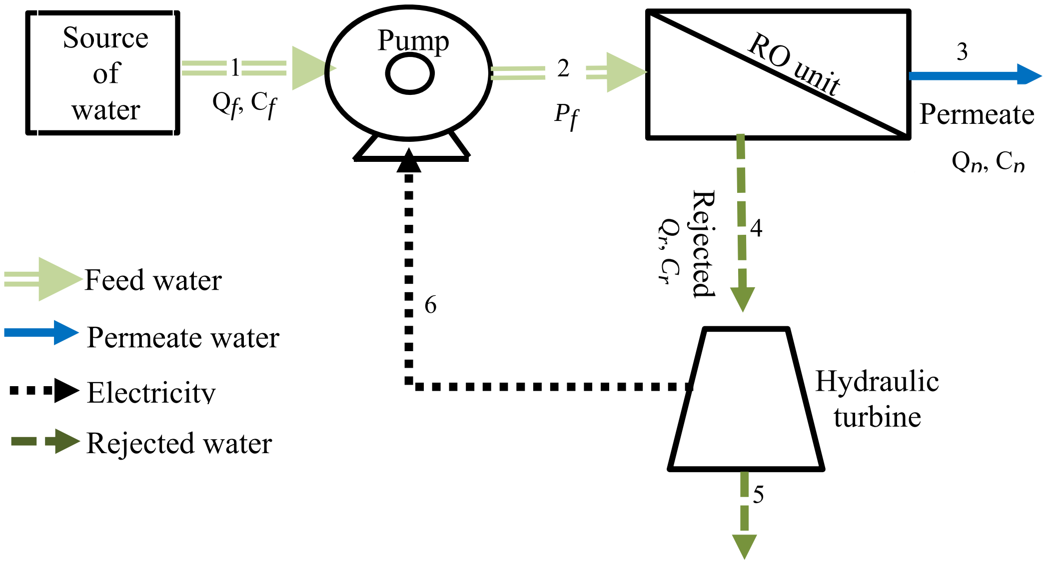

Fig. 2 Schematic representation of the RO desalination model with ERT

TABLE I
RO MODEL EQUATIONS

Meaning	Equation	Reference
Solvent transport	$J_W = A_w(\Delta P - \Delta\pi)$	[12]-[15]
Solvent Permeability	$A_W = \frac{D_w C_w V_w}{\delta_m \quad RT}$	[12], [15], [16]
Solute transport	$J_s = B_s(C_m - C_p)$	[13]-[15], [17]
Solute permeability	$B_s = \frac{D_s K_s}{\delta_m}$	[15], [16]
Salt rejection	$R = \left[1 + \frac{B}{A(\Delta\rho - \Delta\pi)}\right]^{-1}$	[15]
Osmotic Pressure	$\Delta\pi = RT \sum(n/v)$	[13], [16]
Temperature correction factor	$TCF = exp\left[\frac{E_m}{R}\left(\frac{1}{298} - \frac{1}{273+T}\right)\right]$	[18], [19]
Specific energy	$E = \frac{P_f Q_f (\varepsilon_{pump})^{-1} - P_r Q_r \varepsilon_{ERD}}{Q_p}$	-
Recovery ratio	$R = \frac{Q_p}{Q_f}$	-
Total mass balance	$Q_f C_f = Q_p C_p + Q_r C_r$	-
Delta pressure	$\Delta P = \frac{P_f + P_r}{2} - P_p$	-

In this way, exergy consists of a thermo-mechanical exergy and a chemical exergy. The thermo-mechanical exergy is the maximum work obtained when the temperature and pressure of the system changes to the temperature and pressure of the environment (T0, p0) without changing concentration [2], [8], [9].

It has been proved that the exergy model can have a substantial effect on the results and it is a powerful diagnostic tool in thermodynamics. Therefore, many researchers have performed exergy analyses of desalination plants and identified their destruction and efficiency [3], [9]-[11], and a number of exergetic analysis studies have been conducted to determine destruction exergy to improve the desalination plants [9], [10]. Tables I and II respectively show the equations and constants that have been used for the exergy calculations.

TABLE II
MODEL EQUATIONS FOR EXERGY CALCULATIONS [2], [8], [20]-[25]

Description	Equation
Total exergy of any stream	$E_T = E_{PH} + E_{CH} + E_{PO} + E_{KE}$
Specific exergy	$e_T = \frac{E_T}{\dot{m}}$
Specific exergy	$e_T = e_{PH} + e_{CH} + e_{PO} + e_{KE}$
Physical exergy	$e_{PH} = (h - h_0) - T_0(s - s_0)$
Enthalpy of seawater	$h_{sw=} h_w - w_s [b_1 + b_2 w_s + b_3 w_s^2 + b_4 w_s^3 + b_5 T + b_6 T^2 + b_7 T^3 + b_8 w_s T + b_9 w_s^2 T + b_{10} w_s T^2]$
Enthalpy of water	$h_w = 141.355 + 4202.070 \text{ x } T - 0.535 \text{ x } T^2 + 0.004 \text{ x } T^3$
Effect of the stream pressure on the enthalpy	$h_{sw}(T, p, w_s) = h_{sw}(T, p_0, w_s) + v(p - p_0)$
Entropy of seawater	$s_{sw=} s_w \; w_s [c_1 + c_2 w_s + c_3 w_s^2 + c_4 w_s^3 + c_5 T + c_6 T^2 + c_7 T^3 + c_8 w_s T + c_9 w_s^2 T + c_{10} w_s T^2]$
Entropy of water	$s_w = 0.1543 + 15.383 \text{ x } T - 2.996 \text{ x } 10^{-2} \text{ x } T^2 + 8.193 \text{ x } 10^{-5} \text{ x } T^3 - 1.370 \text{ x } 10^{-7} \text{ x } T^4$
Chemical exergy	$e_{CH} = \sum_{i=1}^{n} w_s (\mu_i^* - \mu_i^0)$
Chemical potential of water	$\mu_w = \frac{\partial G_{sw}}{\partial m_w} = g_{sw} - w_s \frac{\partial g_{sw}}{\partial w_s}$
Chemical potential of seawater	$\mu_s = \frac{\partial G_{sw}}{\partial m_s} = g_{sw} + (1 - w_s) \frac{\partial g_{sw}}{\partial w_s}$
Specific Gibbs function at T (°C)	$g_{sw} = h_{sw} - (T + 273.15) s_{sw}$
Differentiation of the Gibbs function	$\frac{\partial g_{sw}}{\partial w_s} = \frac{\partial h_{sw}}{\partial w_s} - (T + 273.15) \frac{\partial s_{sw}}{\partial w_s}$
Partial derivatives of enthalpy	$-\frac{\partial h_{sw}}{\partial w_s} = b_1 + 2b_2 w_s + 3b_3 w_s^2 + 4b_4 w_s^3 + b_5 T + b_6 T^2 + b_7 T^3 + 2b_8 w_s T + 3b_9 w_s^2 T + 2b_{10} w_s T^2$
Partial derivatives of entropy	$-\frac{\partial s_{sw}}{\partial w_s} = c_1 + 2c_2 w_s + 3c_3 w_s^2 + 4c_4 w_s^3 + c_5 T + c_6 T^2 + c_7 T^3 + 2c_8 w_s T + 3c_9 w_s^2 T + 2c_{10} w_s T^2$
Exergy efficiency	$\eta = \frac{W_{min}}{E_{input}}$
Exergy destruction	$\Psi_n = \frac{E_{d,n}}{E_{d,total}}$

IV. RESULTS AND DISCUSSION

Improving RO desalination for potable water and irrigation has been conducted through improving exergy efficiency. The detailed RO model of thermodynamics properties with and without energy recovery device was built in Simulink/ MATLAB and validated against actual data [6]. Simulation results of the thermodynamic properties of the indicated streams (Figs. 1 and 2) for RO desalination with and without ERT have been shown in Tables IV and VI [2]. This paper used the MOD in Iraq as a case study to conduct energy and exergy analysis of RO process.

Tables III and V demonstrate the exergy analysis results of RO desalination plant without and with ERT respectively. The result shows the importance of incorporating an energy recovery device in the hydraulic turbine, which through recovering the pressure from the rejected disposal water can improve its exergy efficiency from 16% to 32%, as shown in Figs. 3 and 4. Moreover, this analysis shows that the highest exergy destruction to produce drinking water and for irrigation occurs (without ERT) in the rejected water and lowest occurs in the permeate flow rate accounting 0.109 for 0.004 MW respectively. When ERT is utilized, the highest exergy destruction occurs in the pump which is approximately 0.08 MW and the lowest occurs in the same in the permeate flow rate, as shown in Figs. 5 and 6.

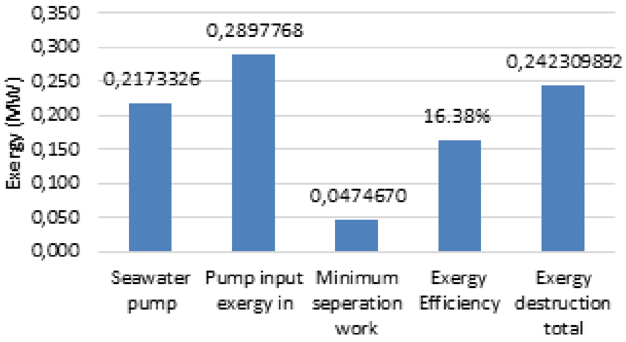

Fig. 3 Exergy of RO Brackish water plant without ERT

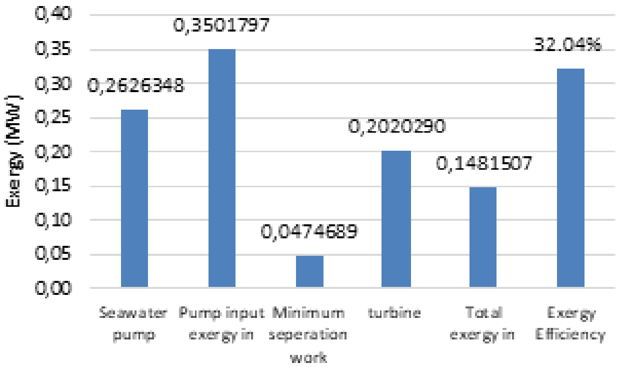

Fig. 4 Exergy of RO Brackish water plant with ERT

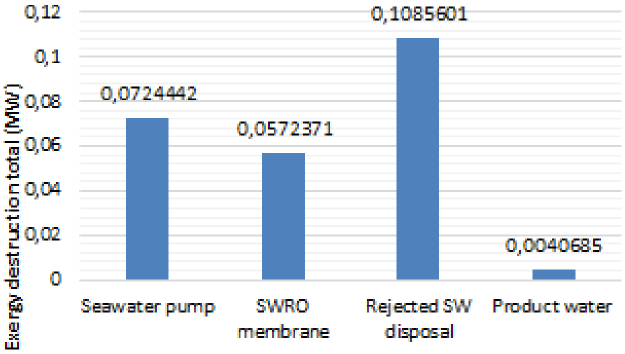

Fig. 5 Exergy destruction for each equipment for RO Brackish plant without ERT

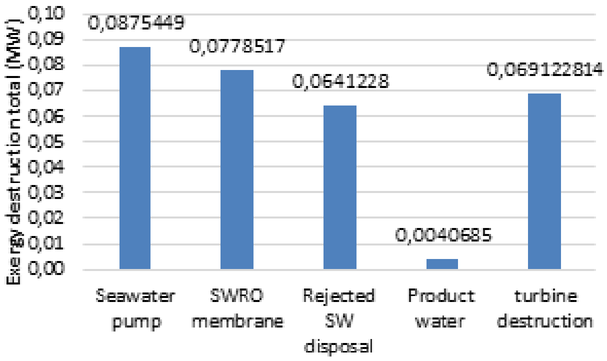

Fig. 6 Exergy destruction for each equipment for RO Brackish plant with ERT

It is clear from Figs. 7 and 8 that the recovery increases exergy efficiency gradually with a slight increase when ERT was used. The destruction of the model has been decreased by boosting the recovery from 30% to70%. Salinity also affected he exergy efficiency of the plant as shown in Fig. 9, however the destruction increases when the salinity increases.

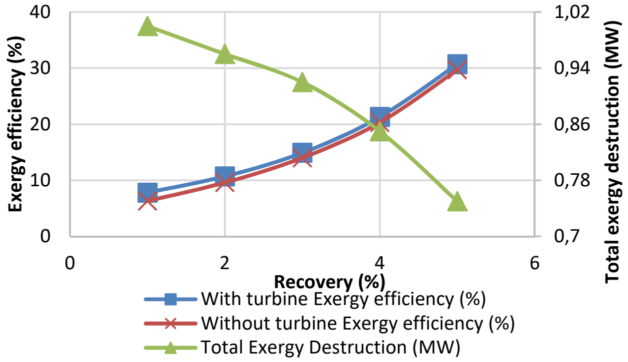

Fig. 7 Exergy destruction in each equipment

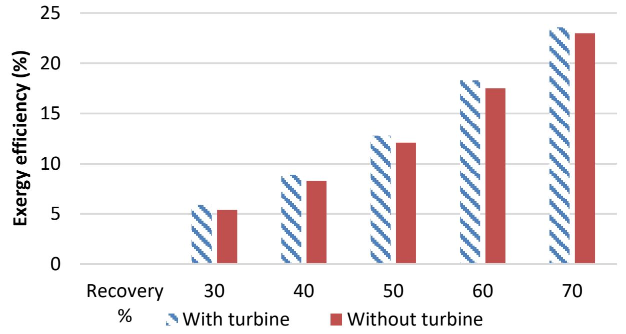

Fig. 1 Effect of recovery on exergy and destruction with and without ERT

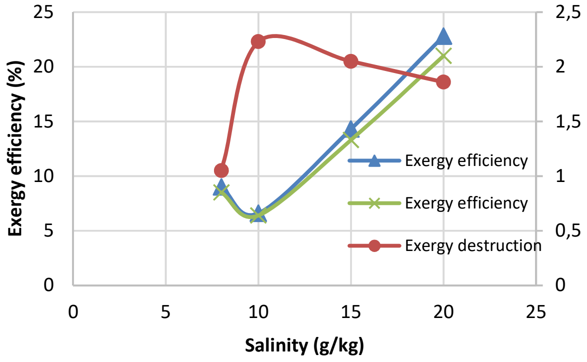

Fig. 9 Effect of salinity on exergy efficiency for drinking water with and without ERT

TABLE III
CONSTANTS USED TO CALCULATE THE ENTHALPY AND ENTROPY OF SEAWATER

$b_1 = -2.348 \times 10^4$	$b_6 = -4.417 \times 10^1$	$c_1 = -4.231 \times 10^2$	$c_6 = -1.443 \times 10^{-1}$
$b_2 = 3.152 \times 10^5$	$b_7 = 2.139 \times 10^{-1}$	$c_2 = 1.463 \times 10^4$	$c_7 = 5.879 \times 10^{-4}$
$b_3 = 2.803 \times 10^6$	$b_8 = -1.991 \times 10^4$	$c_3 = -9.880 \times 10^4$	$c_8 = -6.111 \times 10^1$
$b_4 = -1.446 \times 10^7$	$b_9 = 2.778 \times 10^4$	$c_4 = 3.095 \times 10^5$	$c_9 = 8.041 \times 10^1$
$b_5 = 7.826 \times 10^3$	$b_{10} = 9.728 \times 10^1$	$c_5 = 2.562 \times 10^1$	$c_{10} = 3.035 \times 10^{-1}$

TABLE IV
EXERGY ANALYSIS RESULTS FOR RO DESALINATION WITHOUT ERT

Equipment	Calculation method	Result	unit
Brackish water pump exergy in	E2 – E1	0.217	MW
Pumps input exergy in	Epp = (1/0.75) x ∑(E2 – E1)	0.289	MW
Minimum separation work	Wmin = E(3-A) + E(4-A)	0.047	MW
Exergy efficiency	Equation (17)	16.4	%
Total exergy destruction	Ed = Einput - Eoutput	0.242	MW
Exergy destroyed in pumps	Ed,pp = (1-0.75) x Epp	0.072	MW
Exergy destroyed in BWRO membrane	E d,BWRO = E3.E4-E5	0.057	MW
Rejected brackish water disposal	E d,RSWD =(E4-(E4-A))	0.109	MW
Product water disposal	E d,PWD = (E3- (E3 –A))	0.004	MW

TABLE V
EXERGY ANALYSIS RESULTS FOR RO DESALINATION WITH ERT

Equipment	Calculation method	Result	unit
Brackish pump exergy in	$E_2 - E_1$	0.350	MW
BWRO RO feed pump	$E_3 - E_2$	0.263	MW
Pump input exergy before ERT	$E_{PP} = \left(1/_{0.75}\right) X \sum(\mathrm{E2} - \mathrm{E1})$	0.467	MW
Exergy input from ERT	$E_{ERT} = W_{ERT}$	0.202	MW
Total exergy input	$E_{PP} - E_{ERT}$	0.265	MW
Minimum separation work	$W_{min} = E_{(3-A)} + E_{(5-A)}$	0.047	MW
Exergy efficiency	(17)	32.04	%
Total exergy destruction	$E_d = E_{input} - E_{output}$	0.303	MW
Exergy destroyed in ERT	$E_{d,ERT} = E_4 - E_5$	0.069	MW
Exergy destroyed in pumps	$E_{d,pp} = (1-0.75) \times E_{pp}$	0.623	MW
Exergy destroyed in BWRO membrane	$E_{d,BWRO} = E_2 - E_3 - E_4$	0.078	MW
Rejected brackish water disposal	$E_{d,RBWD} = (E_5 - (E_{5-A}))$	0. 064	MW
Product water disposal	$E_{d,PWD} = (E_3 - (E_{3-A}))$	0.004	MW

TABLE VI
SIMULATION RESULTS OF THERMODYNAMIC PROPERTIES OF THE INDICATED STREAMS (FIG.1) FOR RO DESALINATION WITHOUT ERT

Stream No.	Pressure (kPa)	Temperature (C)	Salinity (kg/kg)	Mass flow (t/h)	Specific exergy (kJ/kg)	Total exergy (MW)
1	101.3	25	0.015	91.36	0	0
2	2500	25	0.015	91.36	2.379	0.217
3	200	25	0.0002	41.1	0.796	0.033
4	2300	25	0.0273	50.25	2.535	0.127
3-A	101.3	25	0.0002	41.1	0.697	0.029
4-A	101.3	25	0.0273	50.25	0.375	0.019

TABLE VII
SIMULATION RESULTS OF THERMODYNAMIC PROPERTIES OF THE INDICATED STREAMS (FIG.2) FOR RO DESALINATION WITH ERT

Stream No.	Pressure (kPa)	Temperature (°C)	Salinity (kg/kg)	Mass flow (t/h)	Specific exergy (kJ/kg)	Total exergy (MW)
1	101.3	25	0.015	91.36	0	0
2	3000	25	0.015	91.36	2.875	0.263
3	200	25	0.0002	41.1	0.796	0.033
4	2800	25	0.0273	50.25	3.027	0.152
5	101.3	25	0.0273	50.25	1.651	0.083
3-A	101.3	25	0.0002	41.1	0.697	0.029
5-A	101.3	25	0.0273	50.25	0.375	0.019

REFERENCES

[1] Ranjan, K.R. and S.C. Kaushik, *Energy, exergy and thermo-economic analysis of solar distillation systems: A review.* Renewable and Sustainable Energy Reviews, 2013. 27: p. 709-723.

[2] Kotas, T.J., *The exergy method of thermal plant analysis.* London ao: Butterworths, 2012.

[3] Cerci, Y., *Exergy analysis of a reverse osmosis desalination plant in California.* Desalination, 2002. 142(3): p. 257-266.

[4] Eshoul, N.M., et al., *Exergy Analysis of a Two-Pass Reverse Osmosis (RO) Desalination Unit with and without an Energy Recovery Turbine (ERT) and Pressure Exchanger (PX).* Energies, 2015. 8(7): p. 6910-6925.

[5] El-Emam, R.S. and I. Dincer, *Thermodynamic and thermoeconomic analyses of seawater reverse osmosis desalination plant with energy recovery.* Energy, 2014. 64: p. 154-163.

[6] Sarai Atab, M., A.J. Smallbone, and A.P. Roskilly, *An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation.* Desalination, 2016. 397: p. 174-184.

[7] Tsatsaronis, G., *Definitions and nomenclature in exergy analysis and exergoeconomics.* Energy, 2007. 32(4): p. 249-253.

[8] Bejan, A. and M.J. Moran, *Thermal design and optimization*. 1996: John Wiley & Sons.

[9] Bejan, A., *Advanced engineering thermodynamics*. 2006, John Wiley & Sons, Hoboken, NJ

[10] Sharqawy, M.H., S.M. Zubair, and J.H. Lienhard, *Second law analysis of reverse osmosis desalination plants: An alternative design using pressure retarded osmosis.* Energy, 2011. 36(11): p. 6617-6626.

[11] Aljundi, I.H., *Second-law analysis of a reverse osmosis plant in Jordan.* Desalination, 2009. 239(1): p. 207-215.

[12] Wijmans, J.G. and R.W. Baker, *The solution-diffusion model: a review.* Journal of Membrane Science, 1995. 107(1–2): p. 1-21.

[13] Lee, S. and R.M. Lueptow, *Membrane rejection of nitrogen compounds.* 2001.

[14] Cheryan, M., *Ultrafiltration and microfiltration handbook.* 1998: CRC press.

[15] R.Rautenbach and R.Albrecht, *Membrane Processes*. 1981, West Germany: John Wiley and Sons Ltd.

[16] Avlonitis, S.A., M. Pappas, and K. Moutesidis, *A unified model for the detailed investigation of membrane modules and RO plants performance.* Desalination, 2007. 203(1–3): p. 218-228.

[17] Baker, R.W., *Membrane Technology and Applications*. 2004, John Wiley & Sons, Ltd., Chichester.

[18] Vince, F., et al., *Multi-objective optimization of RO desalination plants.* Desalination, 2008. 222(1–3): p. 96-118.

[19] DOW, *Design a Reverse Osmosis System: Design Equations and Parameters, Technical Manual* 2006.

[20] I. Dincer, M.A.R., Exergy, Energy, Environment and Simulation Development, *Exergy* Elsever, Oxford, 2007. firs ed.

[21] I. Dincer, M.A.R., Exergy, *Thermal Energy Storage Systems and Applications,* 2011. Second ed., John Wiley & sons, Oxford.

[22] Sharqawy, H.M., J.H. Lienhard V, and M.S. Zubair, *On exergy calculation of seawater with application in desalination systems* International Journal of Thermal Sciences, 2011. 50.

[23] Sharqawy, M.H., J.H. Lienhard, and S.M. Zubair, *Thermophysical properties of seawater: a review of existing correlations and data.* Desalination and Water Treatment, 2010. 16(1-3): p. 354-380.

[24] Vosough, A., et al., *Exergy concept and its characteristic.* International Journal of Multidisciplinary Sciences and Engineering, 2011. 2(4): p. 47-52.

[25] Al-Weshahi, M.A., A. Anderson, and G. Tian, *Exergy efficiency enhancement of MSF desalination by heat recovery from hot distillate water stages.* Applied Thermal Engineering, 2013. 53(2): p. 226-233.