Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 33 (2012) 404 – 414
Procedia Engineering
www.elsevier.com/locate/procedia

ISWEE'11

Thermodynamic Analysis of a Reverse Osmosis Desalination Unit with Energy Recovery System

A. Al-Zahrani, J. Orfi*, Z. Al-Suhaibani, B. Salim and H. Al-Ansary

Mechanical Engineering Department, College of Engineering, King Saud University, Riyadh, 11421, KSA

Abstract

A thermodynamic study is performed on a Reverse Osmosis (RO) desalination unit with and without energy recovery device. Such a study is based on the application of mass and energy balances on each subsystem as well as on the whole unit and using the properties of saltwater modelled as ideal solution. Three configurations of the desalination unit are considered. The first configuration includes a throttling valve in the rejection of concentrated brine side while the two others incorporate a hydraulic turbine and a pressure exchanger system (PES) respectively. The results show the variation of several performance indicators with several variables such as the feed salinity and temperature and the applied pressure. Examples of these indicators are the specific energy consumption (expressed in kWh/m3 of fresh water produced) and the recovery ratio. The results show the importance of incorporating an energy recovery device when the feed salinity is high. Besides, a theoretical minimum specific energy consumption was obtained and presented for the cases with and without pressure exchanger system.

Keywords: Desalination, Reverse Osmosis, Specific Energy consumption, Energy Recovery System.

---

* *Corresponding author.*
E-mail address: orfij@ksu.edu.sa

doi:10.1016/j.proeng.2012.01.1220

1. Introduction

A desalination process separates the feed saline water that can be brackish water or sea water into product water with low salinity and concentrated brine. Such a separation process requires an energy input that is function of several parameters such as the separation process itself, the salinity and the temperature of the incoming saline water. The minimization of this required energy is very important since it reduces the cost of producing the fresh water and decreases the generation of greenhouse gases and the disposal of various pollution products into sea or atmospheric air.

Current desalination processes require large amounts of energy in the form of electric energy to operate different types of pumps (high pressure pumps, pumps to transport liquid streams…) for Reverse Osmosis (RO) process or thermal energy to heat steam for the evaporation process in thermal desalination plants such as Multiple Effect Distillation (MED) and Multi Stage Flash (MSF). Therefore, the reduction of energy consumed to produce fresh water is one of the most active research areas in the desalination industry.

Reverse osmosis is a rather new technology with successful commercialization taking place in the 1970s. It is more energy efficient desalination method than the MSF method. However, the energy contained in the high pressure brine stream rejected to the atmosphere constitutes a wasted energy and should be recovered. The existing recovery systems are a hydraulic turbine and an advanced module using a pressure exchanger system (PES) between the discharged brine and the saline feed water.

Cerci et al. [1] developed a general relation for the minimum work input required for desalination processes using the second law of thermodynamics. This relation determines the minimum work input per unit mass of fresh water produced for various feed saline water and produced fresh water salinities. It is shown that the minimum energy consumption for the separation of a saline solution into pure water and concentrated brine is independent of the process and configuration of the desalination technology used for the separation. It is also found that the minimum energy required to separate saline water into fresh water and brine increases with the feed salinity for a fixed product quality and a recovery ratio. It also increases with the recovery ratio for fixed permeate and feed salinities [1].

The energy desalting consumption of a RO system was treated by several authors such as Agashichev and Lootah [2], Farooque et al. [3] and Sharif et al. [4]. A theoretical model allowing the analysis of the effect of feed proprieties (flow rate, concentration and temperature) on permeate recovery and energy consumption was developed by Agashichev and Lootah [2]. The results show in particular that higher feed temperature increases the permeate recovery and causes a drop of the net energy consumption. Farooque et al. [3] reported that the cost of energy consumed in Sea Water Reverse Osmosis (SWRO) process can reach 50 % of the total product cost of water and can be as much as 75% of the operating cost. They conducted an extensive analysis on energy consumption in Saudi SWRO plants based on real technical specifications and performance data of about one year. The investigation took into account the incorporation of various energy recovery devices which enabled saving reaching about 27% of total energy consumed by the high pressure pump. Recently, Sharif et al. [4] proposed a new approach to calculate the specific energy consumption (SEC) of Reverse Osmosis process. His approach enables to evaluate the minimum specific energy consumption which is independent of the membrane properties and defined as the minimum mechanical energy required to overcome the feed osmotic pressure. The variation of SEC with the recovery ratio, permeate flow rate, the membrane permeability is analyzed.

Abbas [5] and Al-Bastaki and Abbas [6] analyzed the performance of different configurations of industrial RO desalination plants using simplified modeling. The effect of the main operating variables such as the operating pressure and the feed low rate on the production rate is analysed.

The performance of this membrane process is very sensitive to different parameters such as the concentration and the temperature polarizations, the use of spacers in promoting mixing and the incorporation of energy recovery device. Sablani et al. [7] discussed the main reasons for flux decline and performance decrease of membrane separation processes. They presented a critical review of the theoretical studies and models on the concentration polarization in ultra-filtration and reverse osmosis.

Zhou et al. [8] investigated numerically the concentration polarization phenomenon in a spiral wound RO membrane channel with spacers. It was found in particular that the spacers help not only on promoting mixing but also have a depolarization effect.

Second law and exergy analyses were used to study the locations and amounts of losses in industrial RO plants. Cerci [9] considered a 7250 m^3 per day RO plant situated in California. He calculated the exergy destruction in the main components of the plant and showed that the largest exergy destruction occurred in the membrane modules reaching 74% of the total exergy input. The second law efficiency was found to be very low (around 4.3%). The author proposed alternative design to enhance such a performance.

The study of Aljundi [10] on an industrial RO plant in Jordan reveals that highest exergy destruction occurs within the throttling valves (around 57%) and in the two stages RO units (around 21%).

The present work aims to analyze systematically the performance of a basic Reverse Osmosis unit with and without energy recovery system using thermodynamic laws. Three systems are proposed and their performances are analyzed and compared. The first one, which is the basic one, is composed of a pump, a Reverse Osmosis module and a throttling valve. The second and the third ones use a recovery module namely a hydraulic turbine and a pressure exchanger system (PES), respectively.

1. Description and modeling of the systems

1.1. Systems description

The three configurations of a Reverse Osmosis desalination unit under consideration are illustrated in figures 1. The first configuration, Fig 1a, includes a throttling valve in the rejection of concentrated brine side while the two others incorporate a hydraulic turbine and a pressure exchanger system (PES) respectively, Fig 1b and Fig 1c.

1.2. Main assumptions

The following assumptions are considered in this study:

- Salt, water and saltwater are incompressible substances
- The kinetic and potential energy flows are negligible
- Saltwater is considered to be a dilute solution and is treated as an ideal solution
- The polarization effects are ignored
- The properties at the reference state are $T_0 = 298.15$ K, P_o= 1 atm, and $Sal_0 = 2450$ ppm.
- The RO module area is supposed equal to 37.16 m^2
- The state of the feed water at 8 is known.
- The permeate pressure at 9 as well as the pressure at point 11 for RO with PES are fixed at 101.325 kPa.
- The isentropic efficiencies of the turbine and the pumps are fixed at 85%
- The effectiveness of the PES is set to a constant value of 95%.

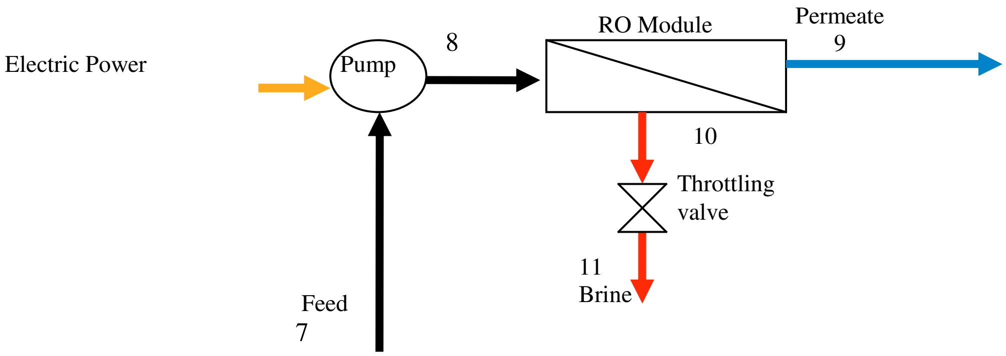

Fig.1a. RO unit using throttling valve

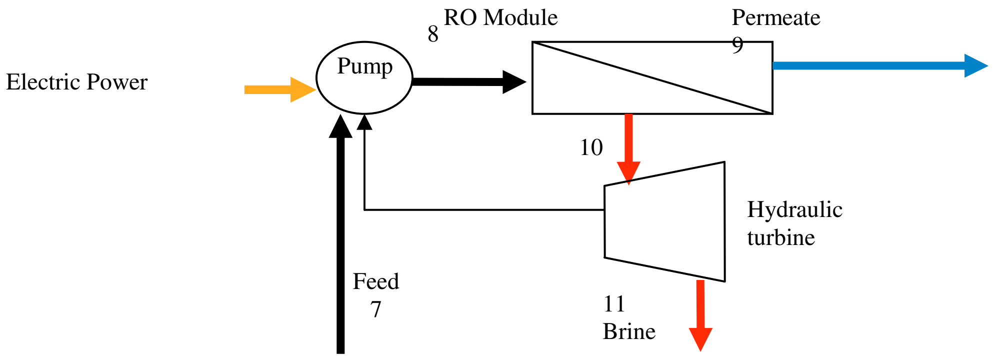

Fig. 1b. RO unit using a hydraulic turbine as a recovery device

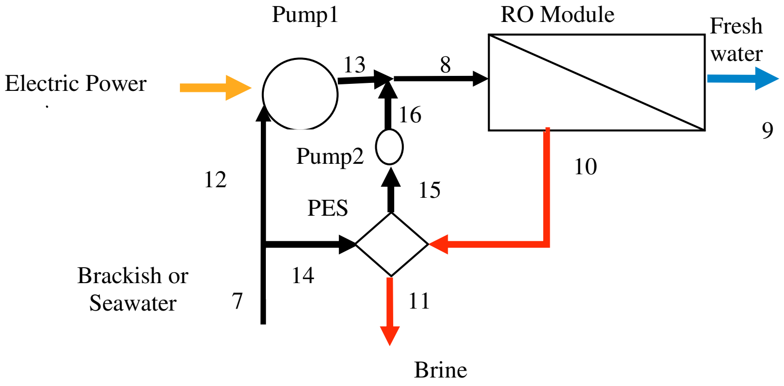

Fig. 1c. RO unit using a Pressure Exchanger System (PES).

1.3. Properties of salt and saltwater

The properties of the saltwater depend on its pressure, temperature and salinity. The latter can be expressed in 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 [1,11]:

$$mf_s = \frac{m_s}{M_m} = x_s \frac{M_s}{M_m} \quad \text{and} \quad mf_w = \frac{m_w}{M_m} = x_w \tag{1}$$

M_S and M_W are the molar mass of the salt and the pure water, respectively. Their values are 58.5 kg/kmol and 18.0 kg/kmol. M_m is the apparent molar mass of the saline water, given by:

$$M_m = \frac{m_m}{N_m} = \frac{N_s M_s + N_w M_w}{N_m} = x_s M_s + x_w M_w \tag{2}$$

Therefore, the relationship between salt mass fraction and salt mole fraction can be given as (Cerci [1]):

$$x_s = \frac{mf_s M_w}{M_s(1-mf_s) + mf_s M_w} \tag{3}$$

Where: $x_s + x_w = 1$ and $mf_s + mf_w = 1$

Saltwater of less than 5 % salinity is considered to be a dilute solution and can be treated as an ideal solution ([1],[11]). Such an ideal solution is a solution in which the effect of dissimilar molecules on each other is negligible. Extensive properties of a mixture are the sum of extensive properties of its individual components. Therefore, the specific heat and the enthalpy are determined using the following expressions ([1], [11]):

$$Cp_{sw} = mf_w Cp_w + mf_s Cp_s \tag{4a}$$

$$h_{sw} = mf_w h_w + mf_s h_s \tag{4b}$$

The specific heat and the enthalpy of pure water are calculated from standard relations [11]. Those for the salt are expressed as follows [12]:

$$Cp_s = 0{,}786 + 0{,}00279 \times (T - 273.15) \tag{5a}$$

$$h_s = h_{s0} + \int_{T0}^{T} Cp_s \, dT \tag{5b}$$

h_{s0} is the salt enthalpy at the reference temperature T_0 and pressure P_0. It is taken as h_{s0} = 21.0455 kJ/kg [10].

1.4. Modeling of the reverse Osmosis systems

Particular attention must be paid to the modeling of the pressure vessel of the RO module where the saline feed water (state 8) is separated in two streams (the drinkable permeate at 9 and the rejected brine at 10) by an appropriate membrane. The performance of an RO membrane depends on several operating parameters such as temperature, pressure and salinity of the feed water. Temperature affects the viscosity of the saline water. The membrane is considered as a porous environment. The specific flow rate of the solvent (water) through the membrane can be determined by following relation [12]:

$$J_w = \frac{D_w C_w V_w}{RTe} \times ((p_8 - p_9) - \Delta\pi) \tag{8}$$

where C_w (in kg/m) is the average concentration of water, V_w is the molar volume of H_2O (18 m^3/mol), T (in K) is the average temperature and e (2µm=$2x10^{-6}$m) is the membrane thickness. The coefficient of diffusion of the H_2O in the membrane is expressed according to the relation of Stock Einstein:

$$D_w = \frac{kT}{3\pi\mu(T,sal)d_s} \tag{9}$$

Where k is the constant of Boltzmann = 1.38 10^{-23} J/K, d_s is the diameter of Stokes = 0.076 $M_w^{0.4}$, M_w is the molar mass of water and µ is its dynamic viscosity.
$\Delta\pi$ is the osmotic pressure difference between the feed and permeate sides of the membrane: π_8-π_9. The variation of the osmotic pressure (kPa) with the salinity and the temperature is given by [13]:

$$\pi = \frac{(385sal(T+273.15)/(1000-10sal))}{0.14507} \tag{10}$$

On the other hand, the governing equations of the RO module are:

- Conservation of mass for the saline solution

$$r_1 \text{ (T, sal)} + r_2 \text{ (T, sal)} = 1 \tag{11}$$

- Conservation of mass for the salt

$$r_1 \, sal_9 + r_2 \, sal_{10} = sal_8 \tag{12}$$

- Conservation of energy

$$r_1 h_9 + r_2 h_{10} = h_8 \tag{13}$$

r_1 and r_2 are the recovery ratio and the brine rejection rate respectively, defined as:

$$r_1 = \dot{m}_9 / \dot{m}_8 \tag{14a}$$

$$r_2 = 1 - r_1 \tag{14b}$$

The recovery ratio is determined by the relationship given by Agashichev and Lootah [2]:

$$r_1(T, sal) = \frac{J_w(T, sal) A_{mem}}{\dot{m}_8} \tag{15a}$$

Where A_{mem} (m^2) is the area of the membrane.

Zhou et al. [8] gave, for a particular membrane operating at approximately 25°C, the following expression:

$$r_1(T_0 = 25°C, sal) = 1 - (\pi_8 - \pi_9)/(P_8 - P_9) \tag{15b}$$

Therefore, the recovery ratio variation can be given by:

$$r_1(T,sal) = r_1(T = 25°C, sal) \times \frac{J_w(T,sal)}{J_w(T = 25°C, sal)} \tag{15c}$$

On another hand and for the basic configuration shown in Fig 1a, the energy consumed (kW) in the RO process is by the high pressure pump:

$$E_{basic} = \frac{\dot{m}_8(P_8 - P_7)}{\rho_7 \eta_p} \tag{16a}$$

The minimum value of this quantity corresponds to the energy required to overcome the feed osmotic pressure:

$$E_{basic-min} = \frac{\dot{m}_8(\pi_8 - \pi_9)}{\rho_7} \tag{16b}$$

Where π_8 and π_9 are the osmotic pressures of the feed and the permeate respectively.

Therefore, the theoretical specific minimum energy (in kWh/m^3) can be expressed as:

$$e_{basic-min} = \frac{E_{basic-min}}{\dot{m}_9} = \frac{\pi_8 - \pi_9}{\rho_7 r_1} \tag{16c}$$

This equation corresponding to the theoretical minimum work per unit product of the reverse osmosis process was also found by Sharif et al. [4] and is consistent with the analysis of Spiegler and El Sayed (see [4]). Sharif et al. [4] obtained this expression from a general equation giving the specific energy consumption of the reverse osmosis process and taking into account several effects including those of the membrane reflection coefficient, the concentration polarization and the pressure losses along the membrane element. Equation (16c) corresponds to the ideal state in which the membrane reflection coefficient, the concentration polarization factor and the hydraulic pressure losses factor are equal to one.

When introducing a pressure exchanger system, the energy is consumed mainly by the two pumps, see Fig 1c.

$$E_{PES} = \frac{\dot{m}_{12}(P_{13} - P_{12})}{\rho_{12}\eta_{p1}} + \frac{\dot{m}_{15}(P_{16} - P_{15})}{\rho_{15}\eta_{p2}} \tag{17a}$$

The minimum value of this energy is:

$$E_{PES-min} = \frac{\dot{m}_8(\pi_8 - \pi_9)}{\rho_7} - \frac{\dot{m}_{10}(\pi_{10} - P_{11})}{\rho_{10}} \tag{17b}$$

3. Results and Discussion

The above system of equations had been solved using the EES software. The Engineering Equation Solver package (EES) [16] is known to be appropriate and widely used for these types of thermodynamic studies.

The RO module resistance to the permeate flow, R_m (Pa.s.m^{-1}) can be written as:

$$R_m = \frac{\rho_9 \times (\Delta P - \Delta\pi)}{J_w} \tag{18}$$

The values of this resistance depend on the membrane characteristics. Table 1 gives an idea on the range of variation of R_m considered in different previous studies.

Table 1 : R_m values from some previous works

Reference	[5]	[6]	[16]	[17]	[18]	[2] (T=25°C)
R_m (Pa.s.m^{-1})	1.0710^{11}	8.4110^{10}	1.2710^{11}	2.4310^{11}-7.2910^{11}	3.3310^{11}	2.4910^{11}

Fig 2 shows the influence of the temperature on the values of the membrane resistance as calculated by the developed model in this work. These values are within the range of values presented in table 1. The figure indicates that R_m increases with lowering the feed temperature. This can be understood when we consider that at higher temperature, the sea water viscosity decreases offering a lower resistance to the permeate flux. On another hand, it is shown that an increase in the feed salinity induces a slight increase in the value of R_m.

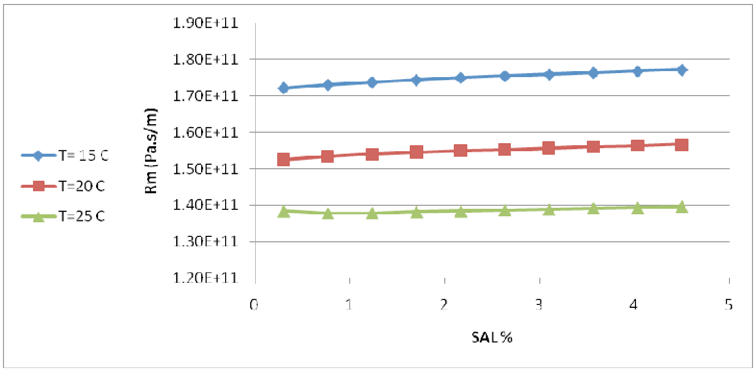

Fig. 2. : R_m at different salinities and temperatures.

Table 2: Comparison between computed recovery ratio and results of Zhou et al. [8] for different salinities at feed pressure of 5 MPa

Salinity %	0.1	0.5	1	2	3
Zhou et al.[8]	0.983	0.915	0.830	0.657	0.481
This work	0.991	0.927	0.846	0.680	0.510

Table 2 compares the computed recovery ratio with the results found in [8]. One can see that the differences are very small.

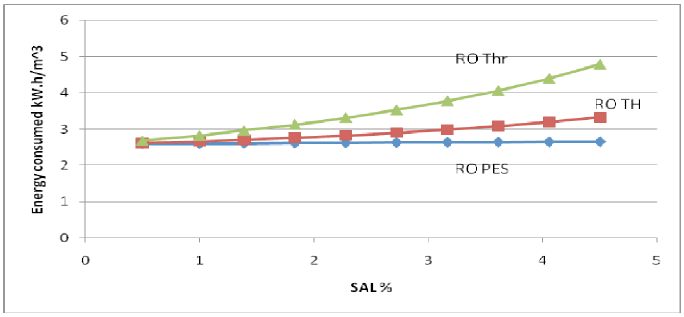

Fig.3: Effect of feed salinity on the specific energy consumption (kWh/m^3) for the three RO systems (pressure P_8= 8000 kPa) (Thr , TH and PES refer to Throttling valve, Hydraulic turbine and Pressure Exchanger respectively).

Figure 3 compares the specific energy consumption (kWh/m^3) for the three systems described in figures 1. It shows that using an energy recovery device reduces the consumed energy in particular at higher feed salinities. When using a PES, this reduction can be around 50 % when the applied pressure and the feed salinity are high. It is of interest to mention that these values of energy consumption are slightly lower than what is reported in some previous works (Farooque et al. [3], Sharif et al.[4]) since some practical effects such as those of the concentration polarization and pressure losses are not considered here.

Figure 4 shows the variation with the applied pressure of the feed mass flow rate $\dot{m}_8$, the permeate mass flow rate $\dot{m}_9$ and the recovery ratio r1. Increasing P8 results in an increase of $\dot{m}_8$ and $\dot{m}_9$ while the recovery ratio approaches an asymptotic value for higher P8. This asymptotic value depends on the feed salinity and temperature.

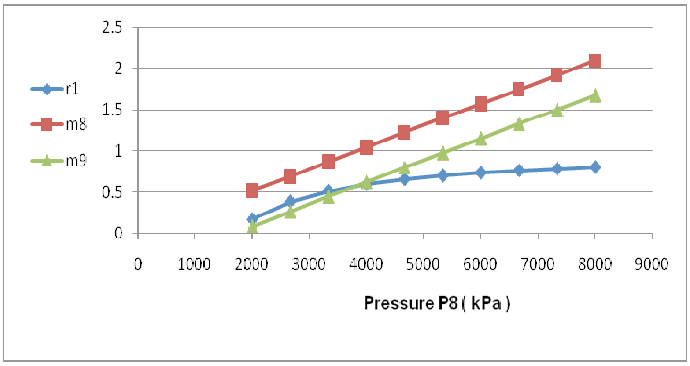

Fig.4: Variation of $\dot{m}_8$ and $\dot{m}_9$ and r1 with the feed pressure ((feed Salinity =2%)

Figure 5 gives the variation of the applied pressure P8 on the specific energy consumption for the RO unit with and without the pressure exchanger system. The RO-Basic Min curve refers to the ideal case given by the equation (16c). Sharif et al. [4] predicted higher values (around 2 kWh/m^3) since they included the effects of concentration polarization, membrane reflection and pressure losses.

Besides, the specific energy consumption is not constant; it increases with the applied pressure P8 as can be understood from equation (16a). The situation is different when the feed salinity is increased to 2 % (20 000 ppm) as shown in Fig 6.

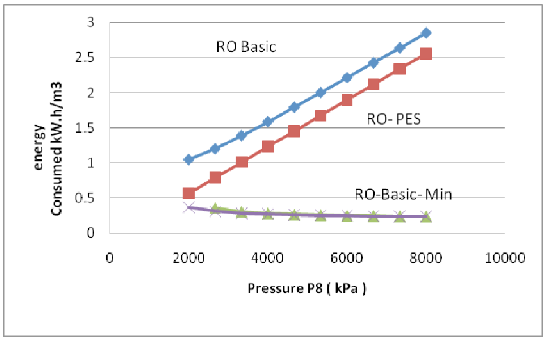

Fig.5. Specific energy consumption (kWh/m^3) variation with P8 for RO system with and without PES (feed Salinity =1%)

The ideal specific energy consumption is higher than 0.5 kW/m^3 and depends on the applied pressure. Its behaviour is closely related to the variation of the recovery ratio as indicated in the equation (16c). When incorporating a recovery device, the effect of P8 on the specific energy consumption is the same as in the previous case with lower feed salinity (1%). However, without PES, the specific energy consumption decreases when the applied pressure is low and then increases linearly when P8 is higher than a particular value of around 3.5 MPa.

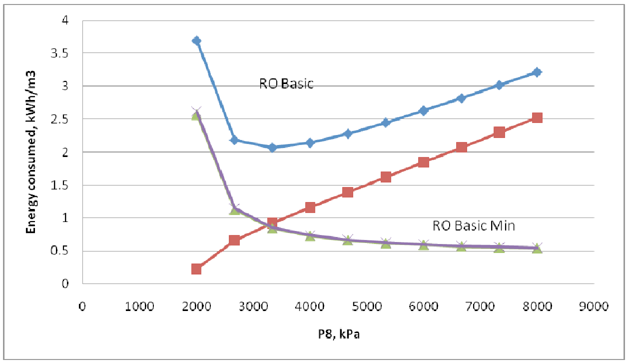

Fig.6 Specific energy consumption (kWh/m^3) variation with P8 for RO system with and without PES (feed salinity =2%).

4. Conclusion

This work concerns a thermodynamic analysis for the estimation of the energy consumption of a basic reverse osmosis process with and without energy recovery device. Three configurations of the desalination unit are considered and modeled. The first configuration includes a throttling valve in the rejection of concentrated brine side while the two others incorporate a hydraulic turbine and a pressure exchanger system (PES) respectively. The analysis is based on the mass and energy balances for the salt using the properties of saltwater considered as ideal mixture.

The results compare the specific energy consumption for the three systems for a wide range of the applied pressure and feed salinity. They show the importance of incorporating an energy recovery device when the feed salinity is high. Besides, a theoretical minimum specific energy consumption was obtained for the cases with and without pressure exchanger system. It was also shown that the specific energy consumption behavior depends on the feed salinity. It increases with the applied pressure almost linearly when the feed salinity is low.

Acknowledgements

The authors would like to thank the NPST (National Plan for Science & Technology) program and King Saud University for funding the research reported in this paper through the project number (08-ENE340-2).

References

[1] Cerci Y, Cengel Y, Wood B, Kahraman N and Karakas, ES. Improving the thermodynamics and economic of desalination plants: Minimum work required for desalination and case studies of four working plants. *Technical report,* University of Nevada; 2003.
[2] Agashichev S and Lootah K. Influence of temperature and permeate recovery on energy consumption of a reverse osmosis system. *Desalination* 2003; 154: 253-266.
[3] Farooque AM, Jamaluddin ATM, Reweli AR, Jalaluddin PAM, Al Marwani SM, Al Mobayed AA and Qasim AH. Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices. *Desalination* 2008; 219: 137-159.
[4] Sharif AO, Merdaw AA, Al Bahadili H, Al Taee A, Al Aibi A, Rahal Z and Derwish GAW. A new theoretical approach to estimate the specific energy consumption of reverse osmosis and other pressure driven liquid phase membrane processes. *Desalination and Water Treatment* 2009; 3: 111-119.
[5] Abbas A. Simulation and analysis of an industrial water desalination plant. *Chemical Engineering and Processing* 2005; 44: 999-1004.
[6] Al-Bastaki NM and Abbas A., Modeling an industrial reverse osmosis unit. *Desalination* 1999; 126:33-39.

[7] Sablani SS, Goosen MFA, Al Belushi R and Wilf M. Concentration polarization in ultrafiltration and reverse osmosis: a critical review. *Desalination* 2001;141: 269-289.

[8] Zhou W, Song L and Guan TK. A numerical study on concentration polarization and system performance of spiral wound RO membrane modules. *J. Membrane Science* 2006; 271:38-46.

[9] Cerci Y. Exergy analysis of a reverse osmosis desalination plant in California. *Desalination* 2002;142:257-266.

[10] Al Jundi I. Second Law analysis of a reverse osmosis plant in Jordan. *Desalination* 2009;239:207-215.

[11] Cengel YA and Boles MA. *Thermodynamics, an Engineering approach*, Sixth edition, Mc Graw Hill; 2007.

[12] Bouzayani N, Galanis N and Orfi J. Comparative study of power and water cogeneration systems. *Desalination* 2007;205: 243-253.

[13] Shamseen AM. Simulation study of reverse osmosis desalination system powered by combined solar and wind power plants. *PhD thesis*, University of Athens, 1993.

[14] Bouzayani N, Galanis N and Orfi J. Thermodynamic Analysis of Combined Electric Power Generation and Water Desalination plants. *Applied Thermal Engineering* 2009;4:624-633.

[15] Klein SA Engineering Equation Solver, www.fchart.com/ees/

[16] Abbas A. On the performance limitation of reverse osmosis water desalination systems. *International Journal of Nuclear Desalination* 2007;3:205-218.

[17] Maurel A. Techniques séparatives à membranes – considérations théoriques. In: *Techniques de l'Ingénieur*, Paris, 2003, J2790.

[18] Kaghazchi T, Mehri M, Takht-Ravanchi M and Kargani A. A mathematical modeling of two industrial seawater desalination plants in the Persian Gulf region. *Desalination* 2010; 252:135-142.