

A conceptual membrane arrangement design in the high pressure vessel for seawater desalination

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Abstract

The wide applications of Reverse Osmosis (RO) membranes in seawater desalination and various industrial processes have encouraged researchers and scientists to investigate the phenomena of water and salt diffusion through the membrane. Typically, the high pressure RO membrane vessel is loaded with membrane elements having the same flux and salt rejection rate. It has been conceived that when different types of RO elements are loaded into the pressure vessel in a special arrangement according to their permeability and salt rejection rate, this arrangement has the potential for reducing the energy consumption of the RO plant. A conceptual design is introduced here to describe this new idea. The effects of feed salinity and temperature were investigated in this paper using the ROSA Filmtec membrane design software. A two pass membrane treatment process was designed for desalting seawater at different salinities varied from 35000 ppm to 43000 ppm. The results showed a net energy saving from 2.5% to 3% (depending on the feed salinity) could be achieved. The effect of the feed temperature was also investigated and the new design was found to be more energy efficient.

Keywords: water and salt permeability, RO, pressure vessel, energy consumption.

1 Introduction

Reverse Osmosis (RO) seawater desalination is becoming a common trend for fresh water supply in large and small cities. As water scarcity problems intensify every day due to population growth and the degradation of freshwater quality, SWRO plants were built around the world to provide potable water from



seawater. The application of RO membranes were extended beyond seawater desalination to provide high quality water to various pharmaceutical and food industries [1, 2]. RO has an advantage over thermal desalination because of its lower energy requirements [1, 3–5]. There are great many examples of successful RO plants for seawater desalination operating without major disruptions [4, 6–8]. The RO membranes, however, require an intensive pretreatment compared to the thermal technologies [9, 10]. Furthermore, RO technology suffers from several drawbacks including scaling and biofouling. Anti-scalants and various chemical compounds were used for fouling control in the RO system [4, 6]. Typically, a predetermined dose of anti-scalants are added to the feed stream to prevent the precipitation of scale elements in the RO membrane. In the current paper a theoretical study was introduced to describe the effects of using RO elements of different permeabilities in the pressure vessel on the power consumption and the membrane performance. The Reverse Osmosis System Analysis (ROSA) software was used throughout this study to simulate the RO membrane performance under different environment conditions. Filmtec Brackish Water RO (BWRO) and Seawater RO (SWRO) membranes of different permeabilities were investigated in this study. The effects of seawater TDS, temperature were studied.

2 Theory

SWRO and BWRO membranes have different water and salt permeabilities depending on the membrane applications. Typically, BWRO membranes are more permeable than SWRO membranes but they have a lower salt rejection rate. In this study different SWRO and BWRO membranes were investigated in an attempt to optimize the design of element arrangements into the high pressure vessel in a two pass RO desalination plant. The water and salt permeabilities of different types of RO membranes are listed in Table 1.

In two pass membrane desalination, SWRO membranes are used in pass 1 followed by low pressure BWRO membranes in pass 2. A schematic diagram of

Table 1: Characteristics of filmtec membranes.

Filmtec membrane	Area (m2)	%Re	Aw (L/m ² h bar)	B (m/d)	Testing condition
SW30HRL E-400i	37	0.9975	1.056	0.00189	32000 ppm NaCl, 5 ppm boron, 55 bar, pH 8, 25 C and 8% recovery
SW30XLE -400i	37	0.997	1.28	0.00276	32000 ppm NaCl, 5 ppm boron, 55 bar, pH 8, 25 C and 8% recovery
BW30-400	37	0.995	3.14	0.00543	2000 ppm NaCl, 15.5 bar, pH 8, 25 C and 15% recovery
BW30LE-440	41	0.99	5.32	0.0108	2000 ppm NaCl, 10 bar, pH 8, 25 C and 15% recovery



a SWRO-BWRO process is described in fig. 1. A portion of pass1 permeate is usually blended with a pass 2 permeate as required. Whilst pass 2 concentrate is recycled back and mixed up with the pass 1 feed. Two different cases were investigated in this paper, in case one the same SWRO/BWRO membranes were loaded into the RO/BW pressure vessel as described in fig. 2A. In the second case, two different types of SWRO membranes were loaded into the pressure vessel with SWRO elements of higher permeability at the end (fig. 2A). As shown in fig. 1, three pressure vessels of 7 elements each were used in pass one

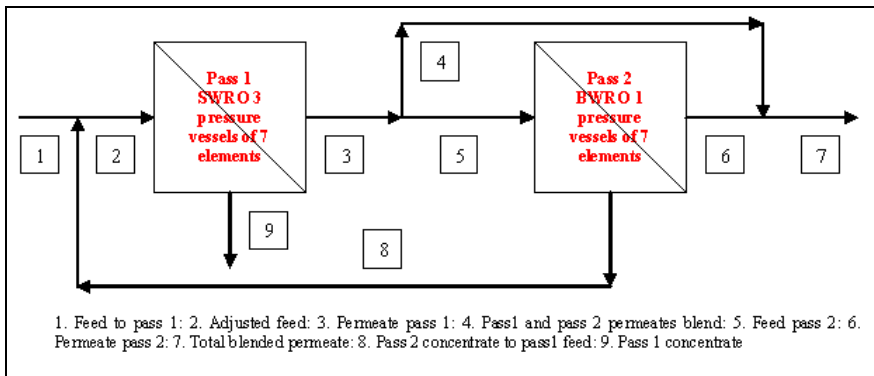


Figure 1: Two passes SWRO and BWRO desalination process.

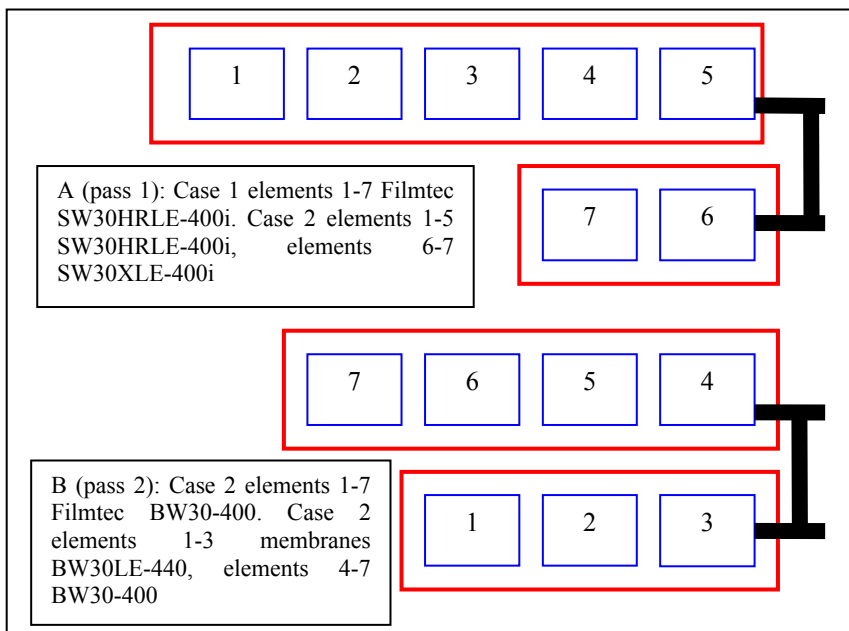


Figure 2: SWRO and BWRO membrane arrangement in the pressure vessel.

to produce enough permeate feed to pass 2 in which one pressure vessel of 7 elements was used. Both salinity and temperature of seawater were investigated in this study. Different seawater temperatures ranged from 15°C to 35°C were investigated then seawater temperature fixed at 25°C and different salinities from 35000 ppm to 43000 ppm were investigated (table 2). The TDS of permeate from case 1 and 2 should be identical or at least very close. The testing procedure of case 1 and 2 is described in table 2.

Table 2: Testing condition for cases 1 and 2.

Design	Salinity (ppm)	Pf 1 st pass (bar)	Pf 2 nd pass (bar)	Temp. °C	SWRO membranes	BWRO membranes
Case 1	41000	70.77	18.22	15	7 elements SW30HRLE-400i	7 elements BW30-400
	41000	68.99	14.66	20		
	41000	67.86	12.06	25		
	41000	66.92	10.14	30		
	41000	66.36	8.8	35		
	35000	58.02	11.97	25	7 elements SW30HRLE-400i	7 elements BW30-400
	37000	61.2	12	25		
	39000	64.2	12.03	25		
	41000	67.84	12.06	25		
	43000	71.34	12.09	25		
Case 2	41000	69.66	12.1	15	5 elements SW30HRLE-400i & 2 elements SW30XLE-400i	3 elements BW30LE-440 & 4 elements BW30-400
	41000	68.05	9.96	20		
	41000	67.07	8.4	25		
	41000	66.05	7.28	30		
	41000	65.18	6.52	35		
	35000	57.07	8.3	25	5 elements SW30HRLE-400i & 2 elements SW30XLE-400i	3 elements BW30LE-440 & 4 elements BW30-400
	37000	60.18	8.33	25		
	39000	63.37	8.37	25		
	41000	66.66	8.4	25		
	43000	70.07	8.34	25		

*Recovery rate in 1st pass is 50% and 2nd pass is 75%.

The performance of SWRO and BWRO membranes were predicted by ROSA 6.1 software. Case 1 represents the conventional design in which a similar type of membrane element was used in the pressure vessel while in Case 2 two different types of membrane elements were used in the pressure vessel. In Case 2, five elements SW30HRLE-400i were placed in the lead position followed by 2 elements SW30XLE-400i which had higher permeability and slightly lower salt rejection rate than SW30HRLE-400i.

3 Optimization number of RO elements in the pressure vessel

It is very important to optimize the number of each type of RO and BW elements in the pass 1 and 2 pressure vessels. The approach used here was as following:

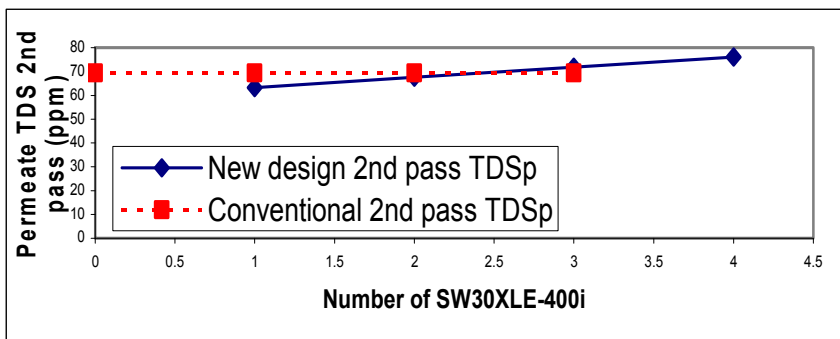
1. Design two passes conventional SWRO-BWRO system in which the same membrane elements were used in each pressure vessel.
2. Design two passes SWRO-BWRO system in which 2 types of SWRO were used in pass 1 while the same BWRO membranes were used in

pass 2. The specific power consumption (E_s) and permeate TDS of each case was recorded and compared with the conventional design. In this step the number of each type of RO membranes will be optimized and determined.

3. Design 2 pass SWRO-BWRO system in which the type and number of SWRO membranes were fixed from step 2 but two different types of BWRO membranes were used in pass 2.

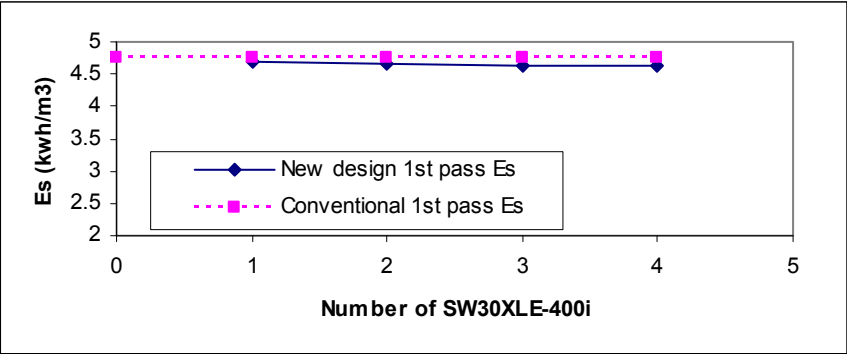
Results from ROSA showed an increase in the permeate TDS with increasing the number of SW30XLE-400i elements in the pressure vessel. When 2 SW30XLE-400i elements were placed into the tail position of the pressure vessel the permeate TDS was slightly lower than in the conventional SWRO (fig. 3). If the number of SW30XLE-400i increased to 3 elements the permeate TDS increased higher than in the conventional system. Therefore 2 SW30XLE-400i elements were used in pass 1. The specific power consumption decreased linearly with increasing the number of SW30XLE-400i elements but that was at the cost of permeates TDS (fig. 4). Based on these results, 2 elements SW30XLE-400i and 5 elements SW30HRLE-400i were used in the pass 1 SWRO pressure vessel. Step 3 was followed to optimise the number of BWRO in pass 2. As shown in fig. 6, the permeate TDS increased with increasing the number of BW30LE-440 in the pressure vessel.

For instance, when the number of BW30LE-440 elements increased to 5 the permeate TDS was 69.43 ppm; this was slightly higher than the permeate TDS in the conventional design system. On the other hand, results showed a continuous drop in the specific power consumption with increasing the number of BW30LE-440 in the pressure vessel. In general, the permeate TDS tended to increase when the number of BW30LE-440 increased. From figs 6 and 7, and to be on the safe side, three BW30LE-440 and four BW30-400 elements were used in the pass 2 pressure vessel.



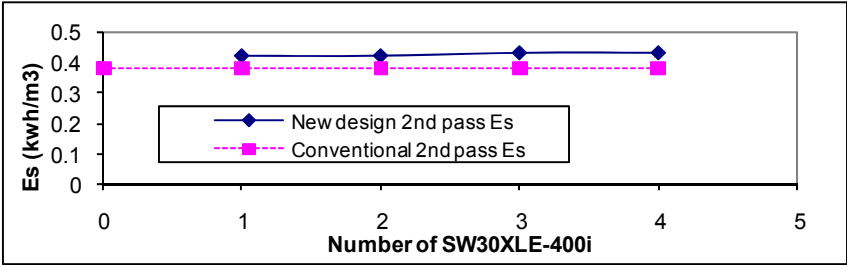
Testing condition: feed flow 24.3 m³/h, feed TDS 41000 ppm, %R 1st pass 50%, %R 2nd pass 73.3%, temp 25°C.

Figure 3: Effect SWRO elements number on the permeate TDS.



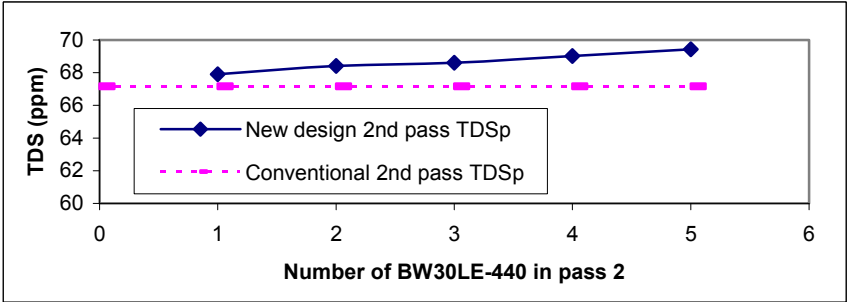
Testing condition: feed flow 24.3 m³/h, feed TDS 41000 ppm, %R 1st pass 50%, %R 2nd pass 73.3%, temp 25 °C.

Figure 4: Effect of SWRO elements number on the Es.



Testing condition: feed flow 24.3 m³/h, feed TDS 41000 ppm, %R 1st pass 50%, %R 2nd pass 73.3%, temp 25 °C.

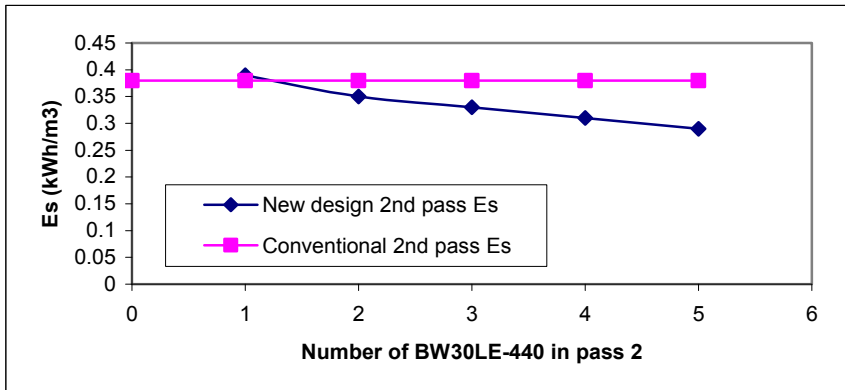
Figure 5: Effects of SWRO element number on the Es of 2nd BWRO membranes.



Testing condition: feed flow 24.3 m³/h, feed TDS 41000 ppm, %R 1st pass 50%, %R 2nd pass 73.3%, temp 25 °C.

Figure 6: Effect of BW30LE-400 elements number on the permeate TDS.





Testing condition: feed flow 24.3 m³/h, feed TDS 41000 ppm, %R 1st pass 50%, %R 2nd pass 73.3%, temp 25 °C.

Figure 7: Effect of BW30LE-400 elements number on the permeate TDS.

4 Results and discussion

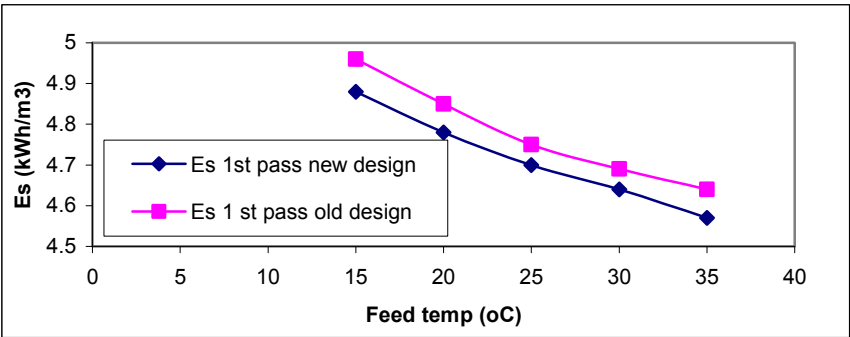
Each case 1 and 2 has 10 experiments (table 2); experiments 1.1 to 1.5 investigated the variation of feed temperature and experiments 1.6 to 1.10 the effect of feed salinity on the RO performance (table 3). The effects of feed water salinity and temperature on the membrane performance were investigated to compare the differences between the old conventional and new design in terms of permeate quality and energy requirements. As shown in table 1, different feed water temperatures were investigated to cover the climatic change in feed temperature throughout the year. The effect of feed temperature increase on the pass 1 SWRO performance is shown in fig. 8. The energy consumption in the conventional design was slightly higher than in the new design; this was because of the tighter structure of the SWRO membranes used in the conventional design and the higher feed pressure required in the conventional design (fig. 9). A similar observation was noticed in the pass 2 BWRO membrane in which the energy consumption of the conventional design was higher than in the new design (fig. 10). In the latter design a loose structure membrane, BW30LE-440, was used. The overall power consumption in the conventional and new designs showed that the new design was slightly more energy efficient than the old design (fig 11). The permeate TDS from the conventional and new design were almost the same which means there was no compromise in the permeate quality (fig. 12).

A range of salinities from 35000 ppm to 43000 ppm was investigated in this study. It was found that the energy requirements in pass1 were lower in the new design. This trend was recorded for all feed salinities tested in this study (fig. 13). This observation was also noticed in pass 2 BWRO membrane (fig. 14). As a result the total energy requirements for seawater desalination were higher in the old design compared to the new design (fig. 15).

Table 3: Operating condition for simulation tests.

Test No	Feed Temp. °C	Feed Salinity mg/l	Pass 1			Pass 2		
			Pf (bar)	Feed [] (bar)	Es (kWm3/h)	Pf (bar)	Feed [] (bar)	Es (kWm3/h)
1.1	15	41000	69.66	28.34	4.89	12.1	0.13	0.45
1.2	20	41000	68.05	28.97	4.8	9.96	0.19	0.37
1.3	25	41000	67.07	29.24	4.7	8.4	0.26	0.32
1.4	30	41000	66.03	29.84	4.64	7.28	0.37	0.28
1.5	35	41000	65.18	30.11	4.56	6.52	0.51	0.26
1.6	25	35000	57.07	24.55	3.99	8.3	0.22	0.32
1.7	25	37000	60.18	25.97	4.21	8.33	0.23	0.32
1.8	25	39000	63.37	27.41	4.43	8.37	0.24	0.33
1.9	25	41000	66.66	28.86	4.66	8.4	0.25	0.33
1.10	25	43000	70.07	30.32	4.9	8.43	0.27	0.33
2.1	15	41000	70.77	28.01	4.96	18.22	0.11	0.55
2.2	20	41000	68.99	28.61	4.85	14.66	0.16	0.45
2.3	25	41000	67.86	29.16	4.75	12.06	0.23	0.38
2.4	30	41000	66.92	29.76	4.69	10.14	0.32	0.32
2.5	35	41000	66.36	30.35	4.64	8.8	0.46	0.29
2.6	25	35000	58.02	24.76	4.04	11.97	0.19	0.39
2.7	25	37000	61.2	26.21	4.26	12	0.21	0.39
2.8	25	39000	64.45	27.67	4.49	12.03	0.22	0.39
2.9	25	41000	67.84	29.13	4.72	12.06	0.23	0.4
2.10	25	43000	71.34	30.60	4.96	12.09	0.24	0.4

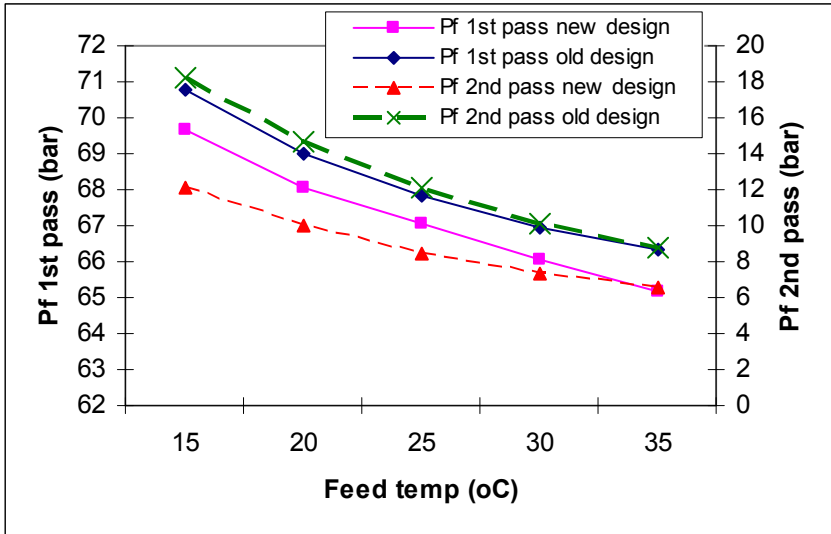
* Recovery rate in 1st pass is 50% and 2nd pass is 75%, Feed flow rate is 24.3 m³/h (± 0.2). Type and arrangement of SWRO and BWRO membrane elements.



Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, feed TDS 41000 ppm.

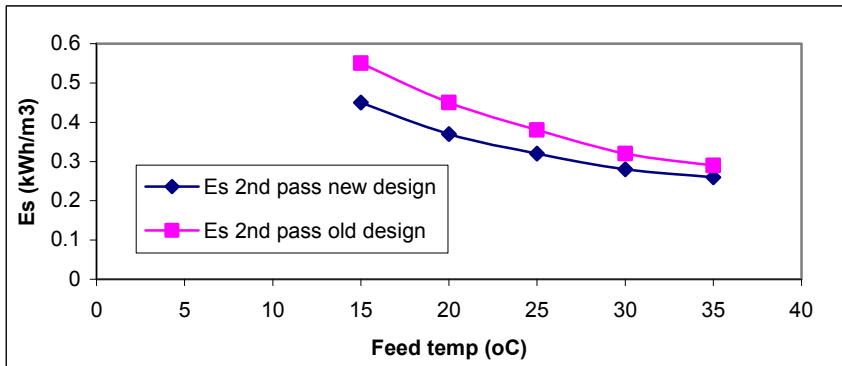
Figure 8: Effect of feed temperature on 1st pass SWRO energy consumption.





Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, feed TDS 41000 ppm.

Figure 9: Feed pressure variations with feed temperature.



Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, feed TDS 41000 ppm.

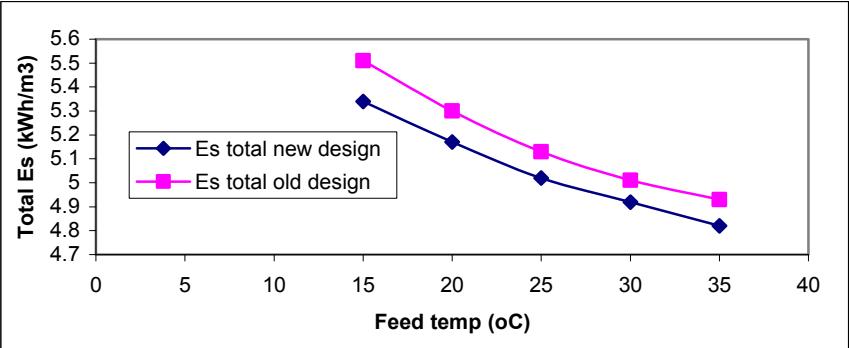
Figure 10: Effect of feed temperature on 2nd pass BWRO energy consumption.

5 Cost of energy

In this study the cost of energy per kWh (Eu) was estimated to be USD 0.05 \$/kWh and the plant capacity is 100000 m³/day. The cost of energy can be calculated from:

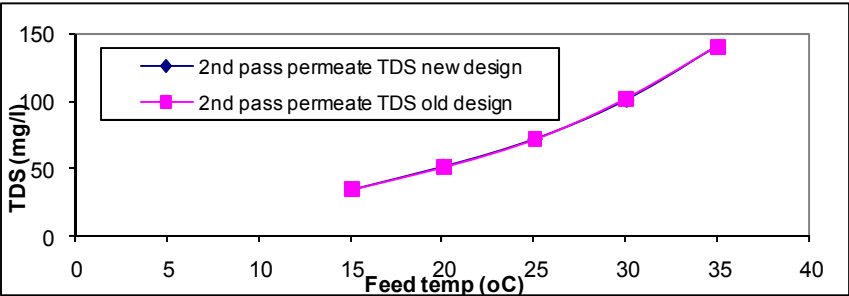
$$\text{Energy Cost} = \text{Plant Capacity (m}^3\text{/d)} * Eu (\$/\text{kWh}) * \text{Time (days)} * Es (\text{kWh}/\text{m}^3)$$





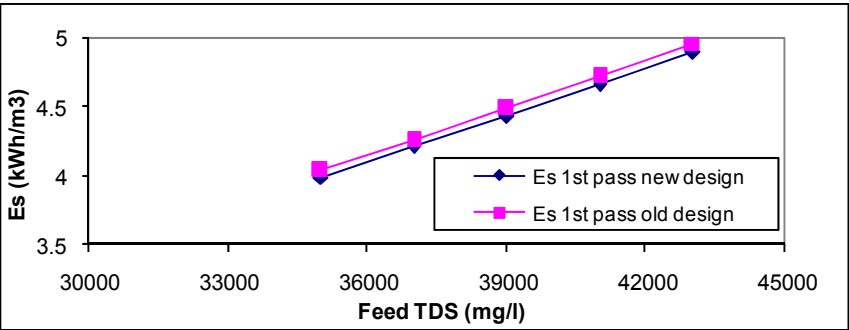
Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, feed TDS 41000 ppm.

Figure 11: Effect of feed temperature on the overall energy consumption.



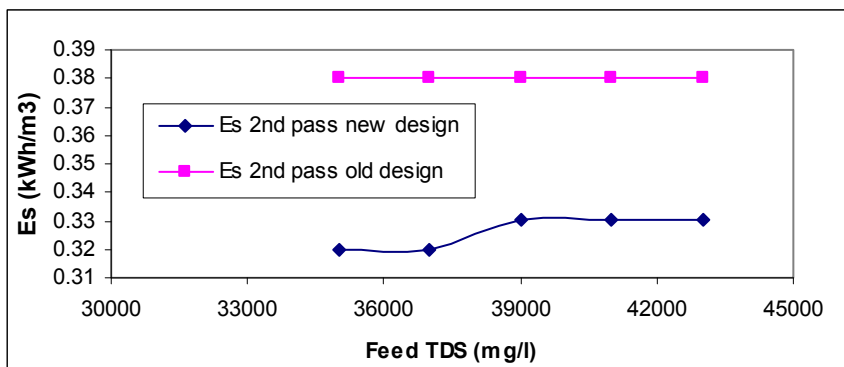
Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, feed TDS 41000 ppm.

Figure 12: Temperature effect on permeate TDS in conventional and new designs.



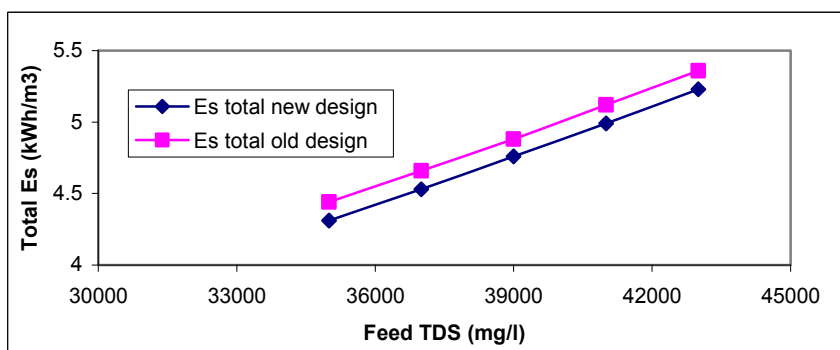
Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, %R, temp 25 °C.

Figure 13: Effect of feed salinity of 1st pass specific power consumption.



Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, %R, temp 25 °C.

Figure 14: Effect of feed salinity on 2nd pass specific power consumption.



Testing condition: feed flow 24.3 m³/h, %R 1st pass 50%, %R, temp 25 °C.

Figure 15: Effect of feed salinity on total specific power consumption.

Table 4: Annual energy cost for desalination.

Salinity (mg/l)	Conventional Design Cost (\$/year)	New Design Cost (\$/year)	Difference (Conventional-New) (\$/year)
35000	8103000	7865750	237250
37000	8504500	8267250	237250
39000	8906000	8687000	219000
41000	9344000	9106750	237250
43000	9782000	9544750	237250
45000	10256500	9982750	273750

The cost of energy in the conventional and new RO designs were calculated for different feed water TDS using the same specific energy values obtained from ROSA. The results are listed in table 6 for comparison purpose. According to these results, the new design was more energy efficient than the old design.

References

- [1] N. Hilal, H. Al-Zoubi, N.A. Darwish, A.W. Mohamma, M. Abu Arabi, A comprehensive review of nanofiltration membranes: Treatment, pretreatment, modelling, and atomic force microscopy, *Desalination*, Volume 170 (2004), 281-308
- [2] E. El-Zanati, K.M. El-Khatib, Integrated membrane-based desalination system *Desalination*, volume 205 (2007), 15-25
- [3] S. A. Avlonitis, Operational water cost and productivity improvements for small-size RO desalination plants, *Desalination*, Volume 142 (2002), 295-304
- [4] C. Fritzmann, J. Löwenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination, *Desalination*, Volume 216 (2007), 1-76
- [5] Ioannis C. Karagiannis, Petros G. Soldatos, Water desalination cost literature: review and assessment, *Desalination*, Volume 223 (2008), 448-456
- [6] Mohammad Abdul-Kareem Al-Sofi, Seawater desalination — SWCC experience and vision, *Desalination*, Volume 135 (2001), 121-139
- [7] Mahmoud Abdel-Jawad, Essam E. F. El-Sayed, Sadeq Ebrahim, Ahmad Al-Saffar, Mohamed Safar, Mohamed Tabtabaei, Ghada Al-Nuwaibit, Fifteen years of R&D program in seawater desalination at KISR part II. RO system performance, *Desalination*, Volume 135 (2001), 155-167
- [8] I. El Saliby, Y. Okour, H.K. Shon, J. Kandasamy, In S. Kim *Desalination plants in Australia, review and facts*, *Desalination*, Volume 247 (2009), 1-14
- [9] K. Chinu, A.H. Johir, S. Vigneswaran, H.K. Shon, Jaya Kandasamy, Assessment of pretreatment to microfiltration for desalination in terms of fouling index and molecular weight distribution, *Desalination*, Volume 250 (2010), 644-647
- [10] P. Palomar, I.J. Losada *Desalination in Spain: Recent developments and recommendations*, *Desalination*, Volume 255 (2010), 97-106

