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Reverse osmosis design with IMS design software to produce drinking water in Bandar Abbas, Iran

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ABSTRACT

Reverse osmosis (RO) has proven to be an efficient technique for desalination of seawater, brackish water, and reclaimed wastewater. However, the performance of RO desalination is sensitive to its design parameters and operating conditions. The purpose of this study was to model the removal of total dissolved solids (TDS) and Rejection of different ions are reported, from water to the city of Bandar Abbas. The main purpose of this research was modeling and simulation of desalination of blended water by RO. In this study, a design method based on a simulation technique has been developed for optimizing RO desalination systems. The design is made with the use of Hydranautics design software version 2011. In this paper main focus is on the design part with software. The desalinated water obtained from reverse osmosis at a pressure of 1.2 MPa showed rejections of approximately 88.49 % for SO_4^{2-}, 61.42 % for TDS, 70.34 for Cl^- and 50.85 for Na^+. It shows that software gives accurate design with least possible error and user friendly so the world while accepted. Blended water was proposed to optimize the produce drinking water with a recovery rate of 95 %. Reverse osmosis is an excellent alternative for the supply of water in Bandar Abbas.

1. Introduction

Availability of fresh potable water is a fundamental need for most aspects of life and key element for all societies. Safe drinking water, excellent sanitation and hygiene are important for good health, human survival and development (WHO. 2006), However, about 1 billion people around the world have no access to safe, clean drinking water sources; 2.5 billion people have no access to improved sanitation facilities (UNICEF and WHO. 2012). The most widely used methods for desalination include thermal and membrane processes. Membrane based desalination processes, such as Reverse osmosis (RO) and Electro dialysis (ED) are barrier technologies for producing potable water from brackish water (Kim et al. 2009). Techniques used for water desalination depend on specific requirements (TDS of feed water), in many cases more research is needed to conclude on the right technique to be applied, on the process parameters. Membrane based water desalination techniques have become reliable for providing potable drinking water (Strathman 1992). Membrane based desalination processes, such as RO and ED are barrier technologies for producing drinkable water (TDS: b500 ppm) from brackish water (Malaeb and Ayoub 2011).

Reverse Osmosis (RO) is a method which is used around the globe to produce fresh water. This technology is typically used to desalinate seawater or brackish water. Reverse osmosis (RO) is a membrane process technique, which is more popular compared to the conventional thermal process technology. One of the biggest advantages of the RO system is its low energy consumption compared to all other desalination systems (Fritzmann et al. 2007; Li 2011; Voros et al. 1998). Over the last decades, the membrane technology has experienced significant advancement that reduces the cost of filtration and enhances the quality of drinking water. As a consequence, this technology can be considered as the lowest cost technology for water desalination (Carter 2015) in comparison to others existing technologies, such as thermal desalination (multistage flash desalination, MSF; multi-effect distillation, MED) (Moonkhum et al. 2010). As a result, a number of researchers in the past decades developed several mathematical models of a RO desalination process in order to explain the separation technique and to carry out model based optimization to enhance the efficiency of the production process (Kamal et al. 2012, 2013). The global applications of RO technology for seawater desalination are projected to grow from a capacity of 40 to 100 million m^3 per day from 2008 to 2015 (Schiermeier 2008).

The fresh water production rate is dependent on the salt concentration in the feed water and on membrane properties such as the selectivity and the permeability. Several investigators studied the influence of spacers on the membrane performance for desalination processes. Karode and Kumar (2001) conducted three-dimensional flow simulations and experiments to examine flow characteristics in a feed channel containing different types of commercial spacers. Since the success of an RO system largely depends on the system design and operation condition, the availability of reliable RO models is essential for efficient design and operation (Abbas and Al-Bastaki 2005). Although the membrane makers have developed computer models to help possible customers to design an RO plant, they mainly focus on the performance analysis of some RO modules rather than the optimization of RO process in terms of energy consumption and product water quality. In optimum case initial reduction of TDS below 2000 ppm and further desalination by RO for best water recovery was considered.

Two fouling mechanisms are generally observed for membrane processes: surface fouling and fouling in pores. However, RO membranes do not have distinguishable pores; these are considered to be essentially non-porous. Thus, the main fouling mechanism for RO membranes is surface fouling. Surface fouling can occur from a variety of contaminants, including suspended particulate matter (inorganic or organic), dissolved organic matter, dissolved solids, and biogenic material (Amiri and Samiei 2007).

In addition, fouling can develop unevenly through a membrane module or element and can occur between the membrane sheets of a module, where spacers are located to create space for the concentrate stream (Tran et al. 2007). Dindarlu, Alipoor and Farshidfar studied on Chemical quality of drinking water in Bandar Abbas (Dindarlu et al. 2006). The present study was simulation model of RO systems for improved quality of drinking water in city of Bandar Abbas (Aghababaei).

This study demonstrates how the application of a simple experimental plan combined with statistical analysis can be used to

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define the operating envelope of IMS membrane unit operations for minimizing fouling at large pilot scale.

2. Materials and methods

Groundwater and surface water are considered to be the sole natural waters resource in the study area. The main purpose of this research was modeling and simulation of desalination of blended water by RO in Bandar Abbas. Reverse Osmosis System Analysis (IMS design) (Hydranautics 2011), which is a sophisticated reverse osmosis (RO) design program that predict performances based on types of membranes. IMS design is a comprehensive software design program that allows the user to design a membrane system using Hydranautics membranes (Hydranautics 2011). It tracks RO system performance and specifically designed to be a user-friendly interface for RO system operators. To assure the highest standards of data integrity, normalization program is in compliance with ASTM Standard D 4516-85, Standard Practice for standardizing reverse osmosis performance data (Mehta and Patel 2012). The lab scale RO with a small pretreatment of RO downy membrane filter was installed, the dematerialized water was allowed to pass through it (Michael 2003). Drinking water resources of Bandar Abbas include two surface and groundwater. A pilot-scale cross-flow RO filtration system was used in this investigation. The pilot system comprises four in parts. The flow in a RO membrane system for desalination shows (Fig. 1). The feed solution was delivered from the feed reservoir to the first stage by a pump; the concentrate of the first stage was transferred to the second and third stage followed by the fourth stage. Four ESPA1 (Hydronautics, Oceanside, CA, USA) (2011) spiral wound elements were used. ESPA1 reverse osmosis elements offer the highest productivity while maintaining excellent salt rejection (99.4% (99.2% minimum)). It has the highest flow rates available to meet the water demands of desalinator. Application Data in ESPA1 was maximum applied pressure 600 psig, maximum operating temperature 113 °F (45 °C) and maximum feed water SDI (15 min) 5. Table 1 shown characterization of applied RO in this study.

Membrane rejection was calculated by relating the concentration of each compound in permeate and in feed water as where reported as a dimensionless number (Favaretto 2014).

$$\text{Salt Rejection} = [1 - \frac{C_p}{C_a}] \tag{1}$$

Flux (J) is volume of permeate (V) collected per unit membrane area (A) per unit time (t); flux is related directly to driving force and total resistance offered by the membrane as well as the interfacial region adjacent to it, which is calculated as:

$$J = \frac{V}{At} \tag{2}$$

Table 1. RO system components configuration.

Parameter	Value
HP pump flow	12505.3 gpm (Hydranautics 2011)
Feed pressure	0.98 MPa
Fouling factor	0.93
Permeate flow	11880 gpm
Raw water flow	12505.3 gpm (Hydranautics 2011)
Average flux rate	15.9 gfd

In order to evaluate the performance of reverse osmosis systems, raw and treated water experiments results were analyzed by descriptive statistics and the results in terms of mean values, standard deviation and removal efficiency were reported. The average life of RO membranes is one year.

The ability of a given membrane to withstand extended exposure to mono chloramine, other oxidants or any other non-standard chemical should be thoroughly investigated to ensure long-term membrane viability. Six to twelve months or more of pilot operation may be required for any integrity losses to become evident. The membrane warranty should reflect anticipated pretreatment methods, including addition of oxidants.

3. Results and discussion

Main aim was to design the plant for treatment for water. After application of reverse osmosis, the water was coming in the range of reusable quality. So for RO design was suggested using Hydranautics design software (Hydranautics 2011). The results of the modeling parameters measured in city of Bandar Abbas are shown in Table 2. Testing pilot reclamation plants are based on the Integrated Membrane System (IMS) (Hydranautics 2011) approach and RO membranes. Management models provide an effective means of rapidly testing and evaluating different scenarios for a given set of conditions (Bick and Oron 2000). Good resistance to fouling and scaling and high recovery operation are important in most brackish water desalination, industrial water treatment and water reuse applications. During the design and operation of RO processes, the recovery ratio is one of the consequential factors affecting the effectiveness of desalination. RO systems provide new or enhanced means for addressing these challenges. Cross flow supplied by a circulation pump washes the membranes and reduces the effects of scaling and fouling. As the salinity throughout the RO process cycles from just above the feed water salinity to that of the most concentrated brine, biofilm formation and scale precipitation can be disrupted. Greater than 99% recovery is possible by control panel setting using the same equipment, cutting brine waste production in half or more.

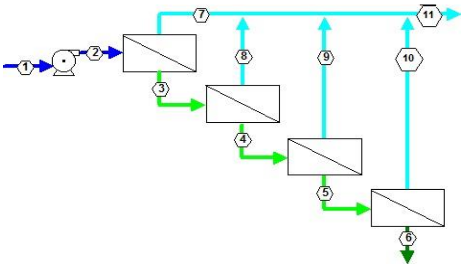

Fig.1. Schematic diagram of the RO system.

Over 95 % recovery operation has been demonstrated in the field. Studies have shown that recovery rates that produce high degrees of super-saturation of sparingly-soluble salts can be achieved in batch RO processes without the use of scale inhibitors. Specifically, recovery rates of over 95 % have been achieved and maintained from water sources with high concentrations of silica and calcium sulfate. Furthermore, scale depositions can be dissolved by batch cycling, making sustained run times at high recovery rates possible even with source waters with high levels of sparingly soluble salts (Sarkar et al. 2008). where C_p is concentration of a particular component of permeate and C_a is retentate concentration. RO membranes achieve NaCl rejections of 98–99.8 % (Bartels et al. 2005). Membrane manufacturers offer high salt rejection membranes for RO plants; the membranes do not retain the initial salt rejection throughout the membrane's lifetime (up to seven years with effective pretreatment). Normal membrane aging causes the salt passage (salt passage % = 100- R_s) to increase approximately 10 % per year (Wilf and Klinko 2001), and other factors, such as temperature, salinity, target recovery, and cleaning methods, can also affect salt passage. The desalinated water obtained from reverse osmosis at a pressure of 1.2 MPa showed rejections 88.49% for SO_4^{2-}, 61.42 % for TDS, 70.34 for Cl^- and 50.85 for Na^+.

Pressure was adjusted to a value greater than osmotic pressure by means of the restricting needle valve. The features of the resulting process configuration will be high yields, elevated removal of contaminants, and reliable operation. The higher average fluxes and pressure vessel configurations employed in RO can save substantial capital costs. For the case study systems, the conventional RO system would cost up to 16 % more than the high-flux RO system. Desalination is a general term for the process of removing salt from water to produce fresh water. Fresh water is defined as containing less than 1000 mg/L of salts or total dissolved solids (TDS) (Sandia 2003). Above 1000 mg/L, properties such as taste, color, corrosion propensity, and odor can be adversely affected. Many countries have adopted national drinking water standards for specific contaminants, as well as for total dissolved solids (TDS), but the standard limits vary from country to country or from region to region within the same country. In Table 2, for TDS, WHO (2011) has a drinking water taste threshold 250 mg TDS/L and the ISIRI (1978) has secondary standards of 200 mg chloride/L and 500 mg TDS/L. As shown in the Table 2, the most problems in terms of Physico-Chemical quality of drinking water were an increase in the rate

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of Chloride, sulfate, Sodium and TDS, above the maximum level recommended. However, Table 2 reveals that SO_4^{2-}, Cl^-, Na^+ and TDS does not comply with WHO guidelines and ISIRI for potability. No health-based guideline value has been developed for TDS and sulfate concentrations, but both chemical parameters can have effects on the acceptability of drinking water by consumers. The presence of sulfate in drinking water can cause a strong taste, and very high levels can have a laxative effect on unaccustomed consumers (WHO 2011). Water with high dissolved solids is of inferior palatability, an d highly mineralized water has restricted industrial applications (APHA 2005). A TDS level of less than about 500 mg·L^{-1} is generally considered to be good; drinking water becomes increasingly unpalatable at TDS levels greater than approximately 1000 mg·L^{-1} (WHO 2011). All analytical methods followed the World Health Organization (WHO 2011). The major scaling salts (Ca^{2+}, CO_3^{2-}, Mg^{2+}) showed reductions higher. Hydrated sulfate ions are very large molecules, as such, they do not exhibit preferential desalination like the other divalent ions. Another limiting parameter of an RO system design with a shorter combined element length is the concentration polarization factor (CPF). The CPF expresses an excess of dissolved ion concentration at the membrane surface. Because the concentration polarization phenomenon is inevitable in the RO process sparingly soluble salts ($CaSO_4$, $CaCO_3$, etc.) may concentrate within the membrane element beyond their solubility limit, and precipitate on the membrane leading to higher operating pressure.

Table 2. Quality of the Blended water (Feed) treated in the integrated membrane system 2011 (mg/L) (Hydranautics 2011).

Ion	**Raw water mg/l**	**Feed water mg/l**	**Permeate mg/l**	**Concentrae mg/l**	**WHO recommendation**	**Iranian standard**
Ca^{+2}	70.95	70.95	8.505	1256.40	-	75
Mg^{+2}	26.94	26.94	3.227	476.7	-	50
Na^+	270.30	270.30	132.832	3134.2	200	250
CO_3^{-2}	0.90	0.90	0.031	17.400	-	-
HCO_3^-	239.5	239.5	191.777	1146.2	-	-
SO_4^{-2}	261.13	261.13	30.048	4651.1	250	200
Cl^-	304.19	304.19	90.223	4367.800	250	200
F^-	1.03	1.03	0.673	7.900	1.5	1.5
NO_3^-	1.21	1.21	0.2	1.255	50	10
TDS	1188.50	1188.50	458.5	15057.80	1000	500
pH	7.66	7.66	7.56	8.24	6.5 ≤ pH ≤ 8.5	6.5 ≤ pH ≤ 8.5

Table 3 shows design of four-stage RO system with hydranautics version 2011 (Hydranautics 2011) in Fig. 1, the design and the practical operational conditions of the process units. This information is crucial for the conception, design, scale up and optimization of the RO unit. To explain these higher values, correlations between input and output are sought, it may be attributed to a statistical fluctuation. Removing either the calcium or the sulfate from the water supply is one way to prevent calcium sulfate scaling in the process.

Table 3. Design of four stage RO system with hydranautics version 2011 (Hydranautics 2011).

Number	**Flow Gpm**	**Pressure Psi**	**TDS Ppm**
1	2505.3	0	1188.5
2	12505	177.7	1188.5
3	2087.1	155.1	6936.0
4	765.2	147.2	1576.9
5	656.1	138.1	15746.2
6	625.3	124.6	15057.8
7	10418	0.0	37.1
8	1321.8	0.0	1826.5
9	109.1	0.0	15856.6
10	30.9	0.0	29695.9
11	11880	0.0	458.5

Knowing the membrane permeability, the local permeate flux can be calculated based on the local pressure. Subsequently, the overall permeate flux can also be calculated. In fact, the simulated permeate flux only deviated slightly from the observed value at the applied pressure of 1MPa (Fig. 2).

Flux rate is important in a RO system because it governs the cross flow rate and mass transport rate through the membrane. There is an optimum ratio of cross flow to permeate flow to keep the membrane surface clean, and the energy consumption at a minimum. Furthermore, if the cross flow becomes too low, the concentration polarization at the membrane surface becomes high. This causes the apparent ion and contaminant concentration at the surface of the membrane to be much higher than the incoming feed. Beta value is the measure that is used to determine the degree of concentration polarization. A beta value of 1.2, or 20 % higher concentration at the membrane surface, is considered to be the maximum beta value that is typically allowed.

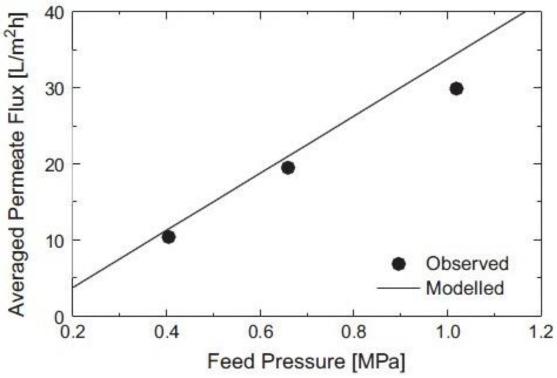


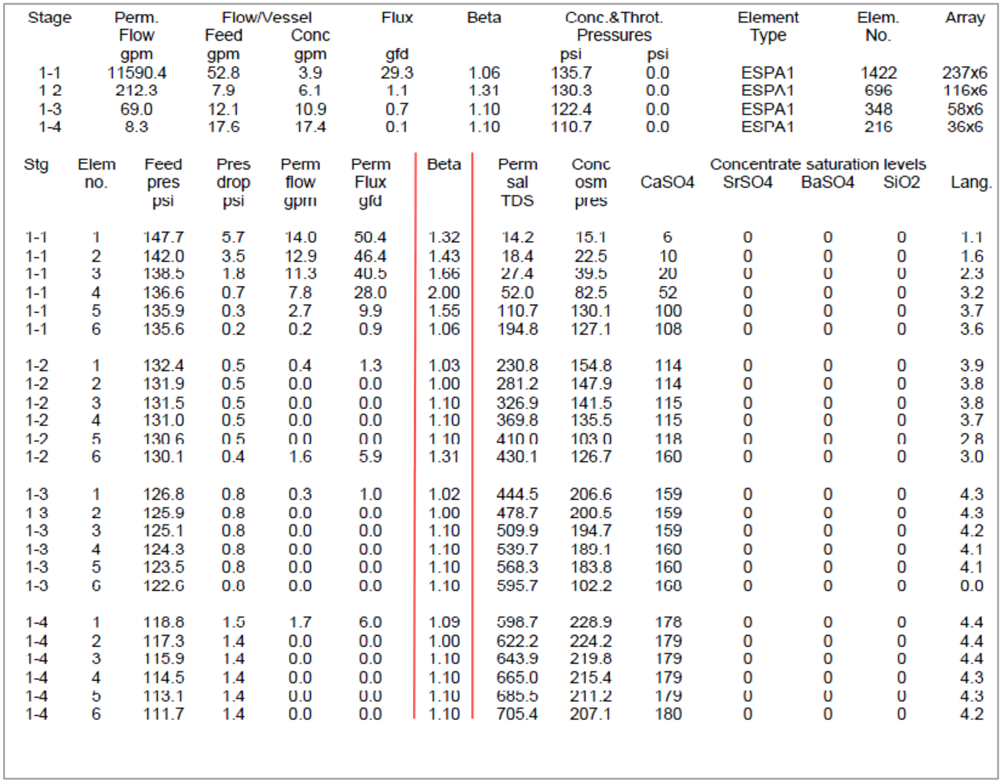
Fig. 2. Observed and modeled overall permeate flux as a function of the feed pressure at the RO system.

4. Conclusions

This study gave a brief description of the water supply in Bandar Abbas, showing that the city could implement desalination to meet drinking water. The groundwater and surface are a potential source for water harvesting, but the total dissolved solids, sulfate, chloride and sodium concentrations exceed the limits for drinking water without additional treatment. Reverse osmosis has been shown to be an efficient method for improving the quality of water from the Blended water with the quality required for drinking water. Performances of RO systems were separately evaluated for water desalination. The RO produced permeate with TDS of 458.5 mg/L at the time of sampling.

According to the results, the removal efficiencies of TDS, Sodium, Chloride and Sulfate in RO were 61.42 %, 50.85 %, 70.34 %, 88.49%. The pump efficiency is 83 %. The results indicated that the pretreatment through RO proved to be effective and reliable by removing both suspended solids and turbidity. Membrane lifetime and permeate flux, however, are primarily affected by the phenomena of concentration polarization and fouling at the membrane surface. For efficient and dependable water supply to areas like Bandar Abbas, at which potable water is scarce, RO desalination plants offer the practical option. Some variations in the quality of the feed water were taken into account in the IMS design, but generally it has had many unforeseen problems in operation and maintenance. It has been observed that this software is user-friendly and gives accurate design with possible micro details. It can save time for lab experiments. So for design of RO system in the field. The results showed the quality of feed water; and pretreatment plays an extremely important role in performance and operational problems such as fouling of RO systems.

Table 4. Projected individual element performance for RO System.



Stage	Perm. Flow gpm	Flow/Vessel Feed gpm	Conc gpm	Flux gfd	Beta	Conc.&Throt. Pressures psi	psi	Element Type	Elem. No.	Array
1-1	11590.4	52.8	3.9	29.3	1.06	135.7	0.0	ESPA1	1422	237x6
1 2	212.3	7.9	6.1	1.1	1.31	130.3	0.0	ESPA1	696	116x6
1-3	69.0	12.1	10.9	0.7	1.10	122.4	0.0	ESPA1	348	58x6
1-4	8.3	17.6	17.4	0.1	1.10	110.7	0.0	ESPA1	216	36x6

Stg	Elem no.	Feed pres psi	Pres drop psi	Perm flow gpm	Perm Flux gfd	Beta	Perm sal TDS	Conc osm pres	CaSO4	Concentrate saturation levels SrSO4	BaSO4	SiO2	Lang.
1-1	1	147.7	5.7	14.0	50.4	1.32	14.2	15.1	6	0	0	0	1.1
1-1	2	142.0	3.5	12.9	46.4	1.43	18.4	22.5	10	0	0	0	1.6
1-1	3	138.5	1.8	11.3	40.5	1.66	27.4	39.5	20	0	0	0	2.3
1-1	4	136.6	0.7	7.8	28.0	2.00	52.0	82.5	52	0	0	0	3.2
1-1	5	135.9	0.3	2.7	9.9	1.55	110.7	130.1	100	0	0	0	3.7
1-1	6	135.6	0.2	0.2	0.9	1.06	194.8	127.1	108	0	0	0	3.6
1-2	1	132.4	0.5	0.4	1.3	1.03	230.8	154.8	114	0	0	0	3.9
1-2	2	131.9	0.5	0.0	0.0	1.00	281.2	147.9	114	0	0	0	3.8
1-2	3	131.5	0.5	0.0	0.0	1.10	326.9	141.5	115	0	0	0	3.8
1-2	4	131.0	0.5	0.0	0.0	1.10	369.8	135.5	115	0	0	0	3.7
1-2	5	130.6	0.5	0.0	0.0	1.10	410.0	103.0	118	0	0	0	2.8
1-2	6	130.1	0.4	1.6	5.9	1.31	430.1	126.7	160	0	0	0	3.0
1-3	1	126.8	0.8	0.3	1.0	1.02	444.5	206.6	159	0	0	0	4.3
1 3	2	125.9	0.8	0.0	0.0	1.00	478.7	200.5	159	0	0	0	4.3
1-3	3	125.1	0.8	0.0	0.0	1.10	509.9	194.7	159	0	0	0	4.2
1-3	4	124.3	0.8	0.0	0.0	1.10	539.7	189.1	160	0	0	0	4.1
1-3	5	123.5	0.8	0.0	0.0	1.10	568.3	183.8	160	0	0	0	4.1
1-3	6	122.6	0.8	0.0	0.0	1.10	595.7	102.2	160	0	0	0	0.0
1-4	1	118.8	1.5	1.7	6.0	1.09	598.7	228.9	178	0	0	0	4.4
1-4	2	117.3	1.4	0.0	0.0	1.00	622.2	224.2	179	0	0	0	4.4
1-4	3	115.9	1.4	0.0	0.0	1.10	643.9	219.8	179	0	0	0	4.4
1-4	4	114.5	1.4	0.0	0.0	1.10	665.0	215.4	179	0	0	0	4.3
1-4	5	113.1	1.4	0.0	0.0	1.10	685.5	211.2	179	0	0	0	4.3
1-4	6	111.7	1.4	0.0	0.0	1.10	705.4	207.1	180	0	0	0	4.2

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