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Experimental Investigation of Energy Consumption and Performance of Reverse Osmosis Desalination using Design of Experiments Method

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A B S T R A C T

To control the quality of reverse osmosis (RO) product water and reduce operational costs and environmental impacts by increasing the system's energy efficiency, it is necessary to identify the influence of process parameters on energy consumption and permeate water quality. This paper introduces a case study focused on the application of Design of Experiments (DOE) method in an industrial-scale RO desalination plant. In this study, energy consumption and permeate water salinity are formulated in terms of system design (the number of membranes and system recovery rate) and flow parameters (feed water flow rate, alkalinity, thermal effects, and salinity). Findings indicate that energy consumption decreases by increasing feed water temperature and the number of membranes. Moreover, increasing feed water flow rate and alkalinity leads to higher quality permeate water (lower salinity), whereas, increasing the number of membranes and system recovery rate and higher feed water temperature and salinity, increases the salinity of permeate water. The findings provide insight into the RO process features and can help designers and operators achieve a higher energy efficiency and better performance in the design and operation of RO units and the presented solution can be built into systems for comprehensive techno-economic evaluation of RO-based processes to consider changes in effective parameters.

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1. INTRODUCTION

Less than 3% of the earth's 1.35 billion cubic kilometres of water is fresh and it is very unevenly distributed across the planet [1]. The growth in population and in the standard of living in developing countries coupled with inefficient use of water and pollution of available water resources has added to the fresh water crisis [2]. To achieve adequate quality requirements and to overcome the extreme global shortage of water resources, desalination of seawater and brackish water is applied nowadays for both domestic and industrial purposes [3, 4], in addition to laboratory-scale experimenting [5, 6].

Reverse Osmosis (RO) is a membrane-based purification process in which pressure is applied on saline water to overcome its osmotic pressure in order to pass water molecules through a semipermeable membrane and remove larger ions and molecules. RO is now a universal water desalination technology, accounting for 65% of the worldwide installed desalination capacity in 2013 [2], due to its ease of operation and maintenance, economic competitiveness, and environmental friendliness compared to traditional desalination methods [7-9].

Although reverse osmosis is the leading desalination technology, there are concerns over its potential environmental impacts, mainly related to the system's energy efficiency, recovery rate, or volume of concentrated brine water produced during desalination. Energy efficiency is a key measure to reduce fossil fuel consumption and thereby greenhouse gas emissions [10]. Recovery rate is a parameter specifying both capital and O&M costs of the RO system [11]. However, energy is the most important concern for desalination plants, especially when designed for use

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with renewable energy sources [12]. Although RO is recognized as the most energy-efficient seawater desalination method [13], but it is yet much more energy-intensive than conventional freshwater treatment technologies [14].

To implement effective control over RO plants, it is essential to systematically identify the influence of design and operational parameters on the performance, cost and environmental impacts of RO systems. Many researchers have studied the effects of some of these parameters on the process performance, energy efficiency, environmental impacts, and costs. For example, Ludwig et al. [15] studied the effect of hydrostatic pressure on the permeate water flux of reverse osmosis membranes for different salinities and found that water flux increases non-linearly with respect to the increasing concentration difference over the membrane. Al-mutaz and Al-ghunaimi [16] presented relations, also in the scale of membranes, for the osmotic pressure of the saline solution, permeate flow rate and salinity, recovery rate and specific energy consumption in terms of temperature, total dissolved solids (TDS), membrane geometry and permeability, hydraulic and osmotic pressure differential across the membrane. Agashichev and Lootah [11] presented a model to investigate the influence of feed concentration, flow rate and temperature on permeate recovery and energy consumption of a RO system and showed that an increase of temperature will improve permeate recovery and decrease net energy consumption. Geraldes et al. [17] presented a mathematical model of a two-stage SWRO desalination unit with spiral-wound modules based on mass and momentum equations. Vince et al. [18] used a multi-objective optimization method to study the design of RO process and specify optimal solutions between economic costs, technical performance and environmental impacts. Zirakrad et al. [19] conducted a study on the performance of RO potable water desalination plants regarding the quality of the permeate water. Recently, Jiang et al. [13] presented a mathematical model to optimize the operational cost of a SWRO system under variable operating conditions, including feed temperature, seawater salinity, electricity price and freshwater demand. Gholami et al. [20], Moradi et al. [21], and Ghoreyshi et al. [22] have focused on improving the performance of various membrane-based purification techniques.

Each of the previous studies have played role in improving the understanding of the effect of a number of design and/or operational factors on energy efficiency, performance, environmental impact, or costs of RO systems, through theoretical analyses and experimental investigations. However, in processes where two or more factors take part, the effect of one factor on the performance is usually studied by keeping other factors constant. However, the effect of the factor being studied on the performance may not be the same at all levels of the other factors, which indicates an interaction between the factors. Therefore, when interactions may be present, in order to avoid misleading conclusions, it is necessary to plan the experiments so that the effects of a factor is estimated at several levels of the other factors, yielding conclusions that are valid over a range of experimental conditions [23].

Statistical design of experiments (DoE) refers to the process of planning experiments so that appropriate data are collected and analysed by statistical methods, resulting in valid and objective conclusions [23]. DoE is a collection of mathematical and statistical techniques for reducing the number of experiments in order to find the effect of parameters (factors) affecting a response in a process [24]. A number of previous researches have been conducted using DoE to find the effective parameters of various desalination techniques. Kazemian et al. [25] used DoE method for thermodynamic optimization of MED plants, and to find the effective parameters on the flow rate of distilled water. Madaeni and Koocheki [26] studied a pilot-scale wastewater treatment using RO elements by applying the Taguchi approach in experiments involving multiple factors affecting membrane flux, namely, pressure, temperature and concentration.

To the knowledge of the authors, no previous study has thoroughly considered the joint effect of all time-dependent operational and design factors on the performance, costs, and environmental aspects of an industrial-scale RO water desalination plant. Therefore, in the present work, energy efficiency (the specific energy consumption) and performance (quality of permeate water) are formulated in terms of all important RO system design and operational parameters through DoE method, in an industrial-scale RO plant. To this end, factorial design is used to study the effect of operational factors including feed fluid flow rate, salinity, thermal effects, alkalinity, and also design parameters including the number of membranes and system recovery rate on the system's response. Based on the DoE analysis, regression models are presented to quantify the effects of these parameters on energy consumption and permeate water quality. The presented solution can be built into systems for comprehensive techno-economic evaluation of RO-based processes where changes in operation parameters are to be considered, in order to enhance the understanding of the RO process and its optimal control.

2. METHODOLOGY

Reverse osmosis has proven to be capable of producing a permeate product which is convenient for both industrial and municipal use [27]. The effects of important design and operational parameters on energy efficiency and permeate water quality of an industrial-scale RO desalination plant was investigated in this paper. The water treatment plant is owned by the direct reduction iron plant (DRI) of Sirjan Jahan Steel Complex (SJSCO), located at a mean altitude of 1700 meters above sea level in Kerman province, Iran.

It is worth mentioning that the focus of this research was placed on the RO system, so the input and output of the system was considered without studying the upstream, especially pre-treatment and chemical dosing. Detailed investigation of RO pre-treatment technologies has been presented by Jamaly et al. [28] and Bakr et al. [7] to avoid fouling of membranes [29].

The RO industrial water treatment plant under study comprises of four separate 60 m^3/h units, for which the total maximum flow of the system permeate water is 240m^3/h (5760 cubic meters per day) and includes the following equipment, a schematic block diagram of which is shown in Figure 1:

1- Raw feed water storage tank
2- Pre-treatment systems
3- Chemical dosing system
4- Reverse osmosis units
5- Post treatment systems
6- Permeate water storage tank

The influence of parameters including feed water flow rate, salinity, temperature, pH, system recovery rate and the number of membranes on energy efficiency and permeate water quality was studied. The selection of the effective design and operational parameters was based on previous research findings [3, 18, 26, 30].

Feed, permeate and concentrate water flow rates were measured online, using Georg Fischer® 2537 Paddlewheel online flow meters and recycle flow rate was monitored using Georg Fischer® SK series variable area rotameters. Feed water flow rate was adjusted by controlling the flow rate of feed pumps. In order to set feed water salinity at the desired values in different experiments, the value of TDS (total dissolved solids) was adjusted using a blending line and reject concentrate water recycling, wherever necessary.

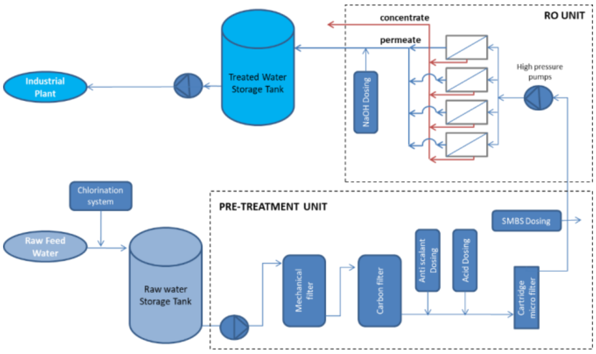


Figure 1. Schematic block diagram of RO plant

Feed water salinity and permeate water quality measurements were conducted using Georg Fischer® Signet 2850 online electrical conductivity (EC) meters. Temperature variations were monitored using Wika HART® TIF50 field temperature transmitter. The alkalinity or acidity was set by dosing adequate amounts of acidic or basic solutions to the feed water. The potential of Hydrogen (pH) was monitored online using Georg Fischer® 2750 DryLoc pH/ORP Transmitter. In accordance with the variations of recovery rate in different experiments, the feed water flow rate to the unit was adjusted with the amount of permeate water and the percentage of concentrate recycling, during pre-tests. To evaluate the effect of the number of membranes in the system a parallel arrangement of pressure vessels with six membranes per vessel was used, which enabled the addition or isolation of parts of the vessels in each test system. Instruments were calibrated at multiple staged prior to and during the experiments. All 4-20 mA electric signals were transferred to the control room human-machine interface (HMI). To ensure the effectiveness of membranes and cartridge filters, the membranes and cartridge filters were checked on a regular basis and replaced whenever necessary.

DoE analysis was performed on k=6 parameters at two levels to study their direct effects and also their interactions on the desired responses. The maximum and minimum range of variations of each parameter used to construct a test table is shown in Table 1.

Tests were performed to find the impact of the test parameters on specific energy consumption and permeate salinity. In order to collect reliable data, each test was performed for up to 2 hours on different days of the year, in order to satisfy conditions of equilibrium. It should be mentioned that the significant parameters were quantified based on the p-value, a value less than 0.5 indicating significance [23]. DoE analysis was performed on the data to illustrate the effect of the selected parameters on permeate water salinity and specific energy consumption and regression analyses were performed on these test results to quantify the effects of these parameters on the performance.

TABLE 1. Parameters and their levels for 2^k factorial model of responses

Factors	Variable	Parameters	Level 1 (-1)	Level 2 (+1)
A	m_f	Feed water flow rate (m^3/h)	25	75
B	X_f	Salinity of feed water (mg/L)	3000	10000
C	pH	Potential of Hydrogen	6	8
D	n	No. of membranes	30	60
E	T_f	Feed water temperature (^0C)	15	25
F	η	System recovery rate (%)	60	80

3. RESULTS AND DISCUSSION

3. 1. Permeate Water Salinity (Quality)

Results of DoE analysis of changing each of the variables from the average value (Level 0) to the minimum value (Level -1) and the maximum value (Level +1) are shown in Figure 2 which clearly indicate that the effect of the selected parameters on permeate water salinity are significant. It can be predicted that changes in the variables with a steeper positive slope have a higher direct relation with permeate water salinity, namely, X_f, n, T_f, and η, in order of significance; changes in variables with a steeper negative slope have a higher inverse effect on salinity, mf and pH, in order of significance.

Then, a 2^k factorial test table is designed to study the response of the first objective function (permeate water salinity) on the variations of these parameters. Results of the analysis of variance of the factorial tests are shown in Table 2.

Regarding permeate water salinity, the significant terms ($\alpha<0.05$) for this response are all the main effect terms and the two-factor interactions between feed water flow rate and salinity (AB), flow rate and temperature (AE), flow rate and recovery rate (AF), salinity and alkalinity (BC), and salinity and recovery rate (BF).

Next, a regression analysis has been performed on these test results to quantify the effects of the six parameters on permeate water salinity, based on DoE analysis:

$$\mathrm{Ln}(X_P)= -1.865094 + (0.071680 \times m_f) - (0.000242 \times X_f) - (0.300104 \times pH) + (0.154419 \times n) + (0.422240 \times T_f) - (0.006917 \times \eta) + (0.000007 \times m_f \times X_f) - (0.005397 \times m_f \times pH) - (0.000367 \times m_f \times n) - (0.006519 \times m_f \times T_f) - (0.000636 \times m_f \times \eta) - (0.000018 \times X_f \times pH) + (0.000013 \times X_f \times n) - (0.000001 \times X_f \times \eta) - (0.009181 \times pH \times n) + (0.012344 \times pH \times T_f) + (0.013635 \times pH \times \eta) - (0.010823 \times n \times T_f) - (0.000829 \times n \times \eta) + (0.001267 \times T_f \times \eta) \quad (1)$$

The regression function is composed of the effective parameters and their interactions, using which the predictive two-factor contour plots of the responses to each parameter can be plotted. According to Equation (1), the related variables and constants are used to plot contours, which are shown in Figure 3, to identify the effect of RO process parameters. on salinity Xp.

Contour line plots of permeate water salinity against variations of feed water salinity and flow rate (Figure 3 a) indicate that for increased flow rates, permeate water salinity increases with feed water salinity at a lower rate than for lower flow rates. The contour of Figure 3b shows that a more pronounced improvement in permeate water salinity is obtained by increasing the pH at higher feed water flow rates than at low flow rates.

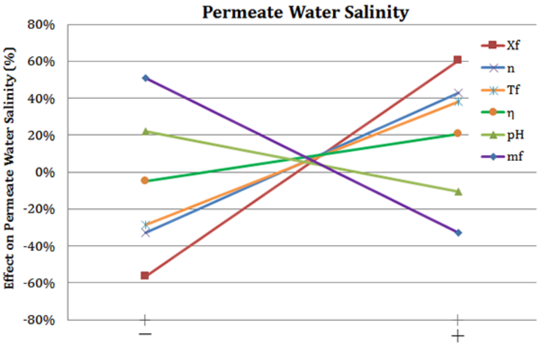
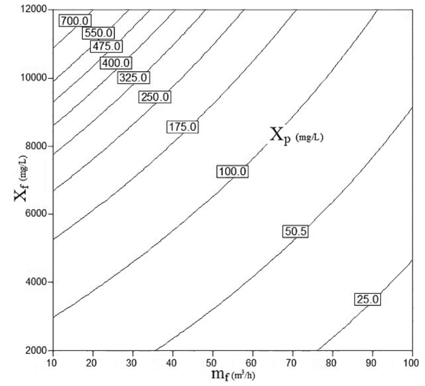


Figure 2. Response of DoE analysis for permeate water salinity

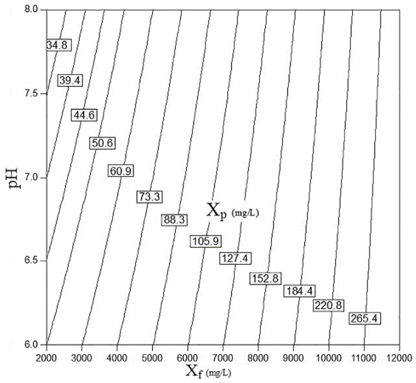
TABLE 2. Analysis of variance of 2k factorial model for permeate water salinity

Source	Sum of Squares	Mean Squares	F Value	p-value
Model	70.3529	2.2694	26.3104	< 0.0001
A (m_f)	19.1740	19.1740	222.2896	< 0.0001
B (X_f)	32.3189	32.3189	374.6829	< 0.0001
C (pH)	1.4860	1.4860	17.2281	0.0002
D (n)	7.2735	7.2735	84.3244	< 0.0001
E (T_f)	4.2159	4.2159	48.8767	< 0.0001
F (η)	0.8114	0.8114	9.4073	0.0044
AB (m_f, X_f)	0.3385	0.3385	3.9239	0.0563
AC (m_f, pH)	0.0030	0.0030	0.0352	0.8525
AD (m_f, n)	0.0002	0.0002	0.0025	0.9605
AE (m_f, T_f)	0.2829	0.2829	3.2799	0.0795
AF (m_f, η)	0.0250	0.0250	0.2896	0.0594
BC (X_f, pH)	0.2597	0.2597	3.0108	0.0923
BD (X_f, n)	0.2105	0.2105	2.4401	0.1281
BF (X_f, η)	0.4202	0.4202	4.8714	0.0346
CD (pH, n)	0.0000	0.0000	0.0001	0.9911
CE (pH, T_f)	0.2343	0.2343	2.7164	0.1091
CF (pH. η)	0.0016	0.0016	0.0184	0.8930
DE (n, T_f)	0.2242	0.2242	2.5990	0.1167
DF (n, η)	0.0022	0.0022	0.0258	0.8735
EF (T_f, η)	0.2159	0.2159	2.5028	0.1235
ABC (m_f, X_f, pH)	0.2544	0.2544	2.9495	0.0956
ABD (m_f, X_f, n)	0.3423	0.3423	3.9678	0.0550
ABF (m_f, X_f, η)	0.2640	0.2640	3.0604	0.0898
ACE (m_f, pH, T_f)	0.2404	0.2404	2.7868	0.1048
AEF (m_f, T_f, η)	0.2673	0.2673	3.0984	0.0879
BCD (X_f, pH, n)	0.2473	0.2473	2.8670	0.1001
BCF (X_f, pH, η)	0.2533	0.2533	2.9363	0.0963
BDF (X_f, n, η)	0.2443	0.2443	2.8318	0.1021
CDE (pH, n, T_f)	0.2555	0.2555	2.9622	0.0949
CEF (pH, T_f, η)	0.2464	0.2464	2.8568	0.1007
DEF (n, T_f, η)	0.2400	0.2400	2.7819	0.1051



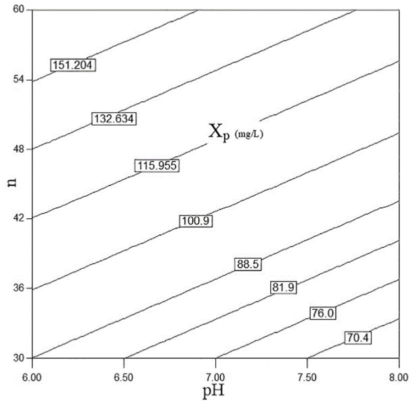
pH=7, n=42, T_f=20ºC, η=70%

a



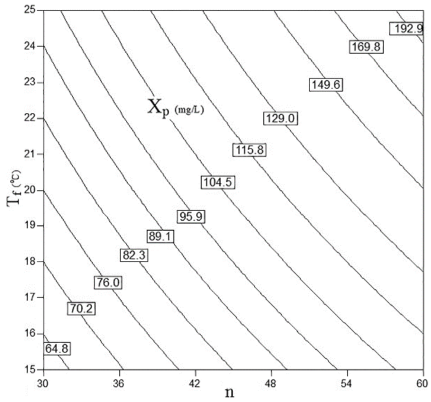
m_f=50m^3/h, n=42, T_f=20ºC, η=70%

b



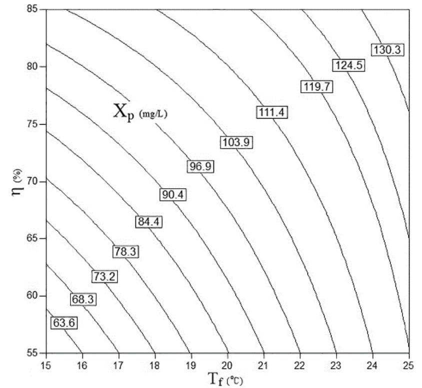
m_f=50m^3/h, X_f=6500mg/L, T_f=20ºC, η=70%

c



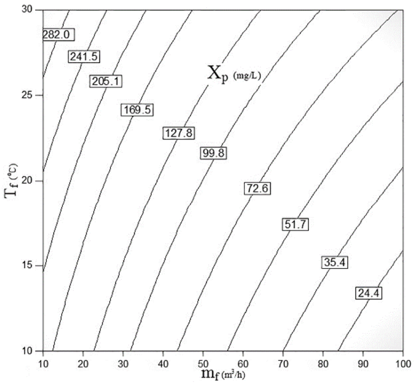
m_f=50m$_3$/h, X_f=6500mg/L, pH=7, η=70%

d



m_f=50m^3/h, X_f=6500mg/L, pH=7, n=42

e



m_f=50m^3/h, X_f=6500mg/L, pH=7, n=42, η=70%

f

Figure 3. Contour line plots of permeate water salinity Xp against variations of a) feed water salinity and flow rate, b) feed water salinity and alkalinity, c) number of membranes and feed water alkalinity, d) number of membranes and feed water temperature, e) system recovery rate and feed water temperature, and f) feed water temperature and flow rate, (other variables kept constant at the values mentioned below each figure)

However, Figure 3c indicates that decreasing the number of membranes makes better improvements in permeate water salinity for low pH values than at higher pH values. It can be observed from Figure 3d that decreased feed water temperature leads to a more significant improvement when a larger number of membranes are used. Figure 3e indicates that increase in system recovery rate results in better improvements at low feed water temperatures than higher temperatures. Finally, Figure 3.f implies that decreasing feed water temperature leads to a more significant improvement in permeate water salinity at higher flow rates than low feed water flow rates. As illustrated by the results, increasing the flow rate (m_f) and alkalinity (pH) of inlet stream, while other variables kept constant, leads to lower salinity of permeate water. This is due to the fact that by increasing the input flow rate and keeping other variables constant, the amount of water passing through the membrane at constant pressure increases. On the other hand, to maintain the recovery rate of the system, water production will increase and as a result will lead to a reduction in the salinity of permeate water. By increasing the alkalinity to an acceptable level, characterized by membrane performance, the pressure increases, which will ultimately reduce the salinity of permeate water. Moreover, increasing the number of membranes (n) reduces the salt concentration of permeate water as long as it does not interfere with production performance, and suitable wetness of cellulosic sheets is achieved (over time, the production of permeate water reduces significantly). On the other hand, results indicate that the salinity of permeate water is increased by increasing the salinity (X_f) or temperature (T_f) of feed water and/or the system recovery rate (η). These findings are in accordance with the results of previous research, introducing temperature as an important parameters affecting membrane performance [16].

Finally, in order to demonstrate the accuracy of the results predicted by these contours, comparisons are done with the results obtained directly from experimental data. As seen in Table 3, within the range of performed tests these results are very close while out of the range of performed tests the accordance between results is acceptable.

3. 2. Energy Efficiency (Cost)

The same approach is adopted for the energy efficiency. The results of the factorial design for specific energy consumption, based on changing each of the variables from the average value (Level 0) to the minimum (Level -1) and maximum (Level +1) values are shown in Figure 4. It can be predicted that changes in the variables with a steeper positive slope have a higher direct relation with power consumption, namely, X_f, m_f and η, in order of significance; changes in variables with a steeper negative slope have a higher inverse effect on energy efficiency, n, Tf, and pH, in order of significance. The analysis of variance of specific energy consumption is presented in Table 4.

Regarding the energy efficiency, the significant terms ($\alpha<0.05$) for this response are all the main effect terms and the two-factor interactions between feed water flow rate and salinity (AB), flow rate and number of membranes (AD), flow rate and temperature (AE), salinity and number of membranes (BD), salinity and temperature (BE), salinity and recovery rate (BF), and number of membranes and temperature (DE). The estimated regression model representation of the six-factor experiments resulting from DoE analysis for specific energy consumption (φ) is as follows:

$$\begin{aligned}\mathrm{Ln}(\varphi) = &-0.542835 + (0.024143 \times m_f) - (0.000031 \times X_f) \\ &+ (0.005150 \times pH) - (0.013148 \times n) - (0.005209 \times T_f) - (0.006331 \times \eta) - (0.000001 \times m_f \times X_f) \\ &- (0.000137 \times m_f \times n) - (0.000355 \times m_f \times T_f) + (0.000204 \times m_f \times \eta) + (0.000001 \times X_f \times n) \\ &+ (0.000001 \times X_f \times T_f) + (0.000002 \times X_f \times \eta) - (0.000501 \times n \times T_f) + (0.000100 \times n \times \eta) \\ &- (0.000072 \times T_f \times \eta)\end{aligned} \tag{2}$$

TABLE 3. Percentage of error in permeate water salinity

	Prediction	Actual	Error %
In the range	87.06	87.35	0.33
Out of range	819.5	924.33	11.34

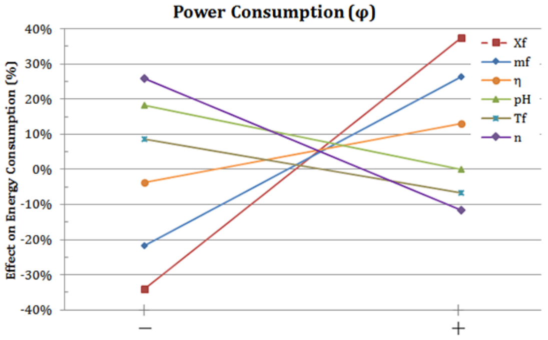


Figure 4. Response of DoE analysis for energy consumption

TABLE 4. Analysis of variance of 2^k factorial model for specific energy consumption

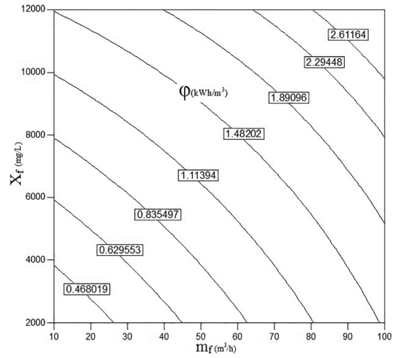
Source	Sum of Squares	Mean Squares	F Value	p-value
Model	19.9769	0.9513	2769.4865	< 0.0001
A (m_f)	5.5272	5.5272	16091.5074	< 0.0001
B (X_f)	9.9053	9.9053	28837.5457	< 0.0001
C (pH)	0.0017	0.0017	4.9415	0.0317
D (n)	2.4276	2.4276	7067.4069	< 0.0001
E (T_f)	0.5125	0.5125	1492.1908	< 0.0001
F (η)	0.5414	0.5414	1576.1668	< 0.0001
AB (m_f, X_f)	0.3166	0.3166	921.8662	< 0.0001
AD (m_f, n)	0.3578	0.3578	1041.5880	< 0.0001
AE (m_f, T_f)	0.0760	0.0760	221.2949	< 0.0001
AF (m_f, η)	0.0005	0.0005	1.5980	0.2132
BD (X_f, n)	0.0954	0.0954	277.8116	< 0.0001
BE (X_f, T_f)	0.0450	0.0450	131.0765	< 0.0001
BF (X_f, η)	0.1091	0.1091	317.4993	< 0.0001
DE (n, T_f)	0.0331	0.0331	96.4896	< 0.0001
DF (n, η)	0.0002	0.0002	0.6782	0.4148
EF (T_f, η)	0.0000	0.0000	0.0142	0.9056
ADE (m_f, n, T_f)	0.0134	0.0134	39.1470	< 0.0001
ADF (m_f, n, η)	0.0086	0.0086	25.0553	< 0.0001
AEF (m_f, T_f, η)	0.0015	0.0015	4.2673	0.0451
BDF (X_f, n, η)	0.0025	0.0025	7.3366	0.0097
DEF (n, T_f, η)	0.0013	0.0013	3.7340	0.0601

To show the accuracy of the regression equation, comparisons are done in the same procedure as for permeate water salinity and the percentage of error is shown in Table 5. With regard to Equation (2), the related variables and constants are used to plot contours to identify the effect of RO process parameter on specific energy consumption φ, the results of which are shown in Figure 5.

Contour line plots of specific energy consumption versus feed water salinity and flow rate (Figure 5a) indicate that for increased flow rates, energy consumption increases with salinity at a higher rate than for lower flow rates.

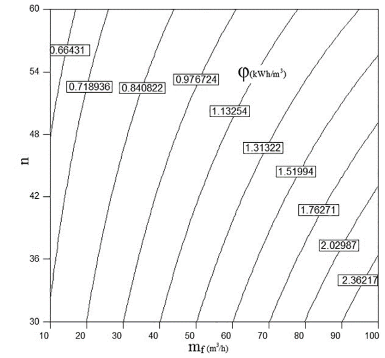
TABLE 5. Percentage of error for specific energy consumption

	Prediction	Actual	Error %
In the range	0.75	0.69	8.24
Out of range	1.92	2.34	17.69



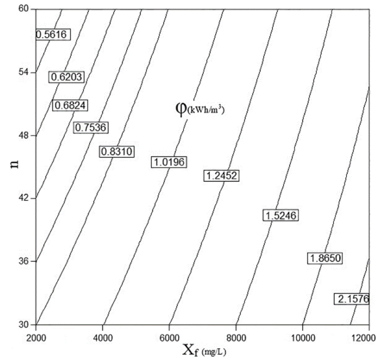
pH=7, n=42, T_f=20ºC, η=70%

a



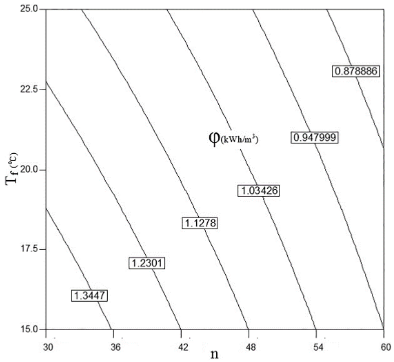
X_f=6500 mg/L, pH=7, T_f=20ºC, η=70%

b



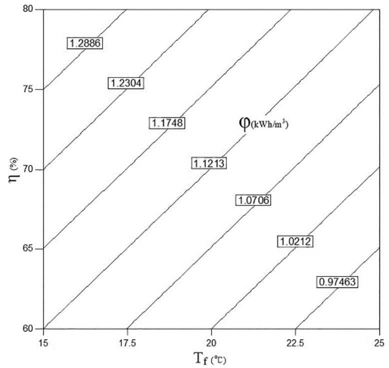
pH=7, m_f=50 m^3/h, T_f=20ºC, η=70%

c



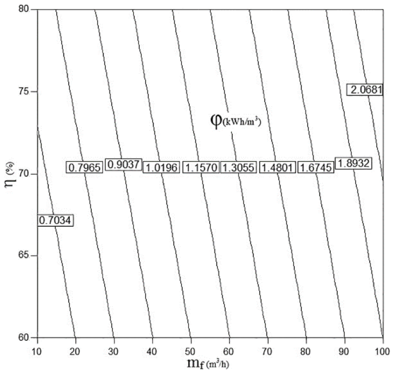
pH=7, m_f=50 m^3/h, pH=7, η=70%

d



pH=7, m_f=50 m^3/h, n=42, X_f=6500 mg/L

e



pH=7, X_f=6500 mg/L, T_f=20ºC, n=42

f

Figure 5. Contour line plots of specific energy consumption φ against variations of a) feed water salinity and flow rate, b) feed water flow rate and number of membranes, c) number of membranes and feed water salinity, d) number of membranes and feed water temperature, e) system recovery rate and feed water temperature, and f) feed water flow rate and system recovery rate, (other variables kept constant at the values mentioned below each figure)

The contour of Figure 5b shows that much more pronounced energy efficiency improvements are obtained by increasing the number of membranes at higher feed water flow rates than at low flow rates. However, Figure 5c indicates that increasing the number of membranes makes similar improvements in energy efficiency for high and low feed water salinity values. It can be observed from Figure 5.d that increased feed water temperature leads to a more significant improvement when smaller number of membranes are used. Figure 5e indicates that increase in system recovery rate results in slightly better improvements at low water temperatures. Finally, Figure 5f implies that increasing system recovery rate leads to a more significant energy consumption improvement at higher flow rates than low feed water flow rates.

Results clearly indicate that energy efficiency improves by increasing feed water temperature (T_f) and the number of membranes (n) which is in accordance with previous results [31, 32]. Previous research has also concluded that temperature is an important parameters affecting membrane performance; increasing feed water temperature for constant permeate flow, decreases the required applied feed pressure, and hence, specific energy consumption [16]. However, results of variance analysis (Figure 4 and Table 4) illustrate that changes in the alkalinity (pH) do not have a significant impact on specific energy consumption.

On the other hand, increasing feed water flow rate (m_f) and salinity (X_f) and also the recovery rate (η) of the system increases the specific energy consumption. Although previous studies have also concluded that increasing the recovery rate of the system in the range of 60-80% increases the value of specific energy consumption [3, 31], the analysis of variance (Table 4) shows that recovery rate affects the specific energy consumption less significantly compared to feed water flow rate and salinity, and can be considered as a factor having a lower degree of importance.

4. CONCLUSION

In order to shed light on the effects of feed water flow rate, salinity, thermal variations, alkalinity, number of membranes and system recovery rate on energy efficiency and the quality of permeate water of the system, method of Design of Experiment (DoE) has been adopted for the case of an industrial RO desalination plant. It is shown that permeate water salinity increases by increasing salinity or temperature of feed water and the number of membranes and system recovery rate. On the other hand, increasing the flow rate and alkalinity of the inlet stream leads to higher quality (lower salinity) of permeate water. Feed water flow rate, salinity and temperature along with the number of membranes are the most important factors to monitor and control in order to achieve optimal performance. Energy efficiency is improved by increasing feed water temperature and the number of membranes. Specific energy consumption is increased by increasing feed water salinity or flow rate and system recovery rate. Therefore, to promote the adoption of a more sustainable, cost-effective and environmentally friendly desalination operation, parameters such as feed water flow rate, salinity, temperature and system recovery rate should be optimized over other parameters.

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Experimental Investigation of Energy Consumption and Performance of Reverse Osmosis Desalination using Design of Experiments Method

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چکیده

به منظور کنترل کیفیت آب تولیدی به روش اسمز معکوس (RO) و کاهش هزینه‌های عملیاتی و اثرات زیست محیطی از طریق افزایش بهره‌وری انرژی، مطالعه تأثیر پارامترهای فرایند بر مصرف انرژی و کیفیت آب ضروری است. این مقاله، مطالعه‌ای موردی با هدف استفاده از روش طراحی آزمایش (DOE) در یک واحد تصفیه آب RO است. در این مطالعه، مصرف انرژی و شوری آب تولیدی بر حسب پارامترهای طراحی سیستم (تعداد ممبران (غشاء)ها و درصد بازیابی آب) و پارامترهای جریان (دبی، قلیاییت، دما و شوری آب خام ورودی) فرمول‌بندی شده است. یافته‌ها نشان می‌دهد که مصرف انرژی با افزایش دمای آب ورودی و تعداد غشاءها کاهش می‌یابد. به‌علاوه، افزایش دبی و قلیاییت آب ورودی باعث افزایش کیفیت آب تولیدی (شوری پایین‌تر) می‌شود، در حالی که افزایش تعداد غشاءها و درصد بازیابی آب، افزایش دما و شوری آب خام، باعث افزایش شوری آب تولیدی می‌شود. یافته‌های این تحقیق، اطلاعات مفیدی در مورد ویژگی‌های فرایند RO ارائه می‌دهند و به طراحان و کاربرها برای دست‌یابی به افزایش بهره‌وری انرژی و عملکرد بهتر در طراحی و کارکرد واحدهای RO کمک می‌کند. راه حل ارائه شده را می‌توان در سیستم‌های جامع برای ارزیابی فنی و اقتصادی فرایندهای مبتنی بر RO برای در نظر گرفتن تغییرات در پارامترهای موثر به کار بست.

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