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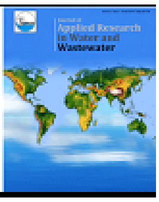

An investigation on boiler feed water treatment using reverse osmosis and ion exchange by WAVE software

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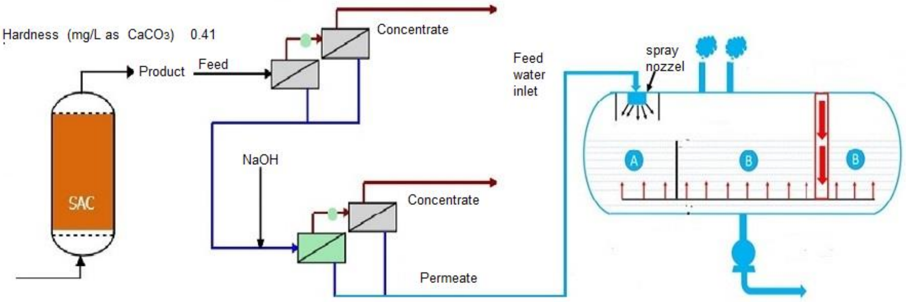
GRAPHICAL ABSTRACT

Inlet water



Parameters	Value	Unit
Total hardness	<0.5	mg/L as $CaCO_3$
pH value	8.8	-
TDS	1.27	As mg/L
Silica	0	mg/L as SiO_2

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ABSTRACT

Although during the last two decades many studies have proved the effectiveness of the reverse osmosis system and this system has been used as a suitable and efficient method to treat drinking and industrial water and to desalinate the seawater, salt water, as well as sewage, it has some shortcomings, including sensitivity to ions, microorganisms, and organic matter in feed water causing problems such as scaling, fouling, as well as biofouling. Acidification of the permeate and its low pH are also other drawbacks of this system. This study is designed based on a two-pass reverse osmosis system, and each pass includes two stages (to provide higher system recovery). Moreover, ion exchange resin and AMBERPACK tank are used as pre-treatments considering the common problems of reverse osmosis system. Such fouling has been done to provide the required quality. It should be noted that by using the exchange resin system instead of the acid injection system, the TDS rate changed from 3.15 to 1.27 mg/L, which is equivalent to 59.68 % improvement, the LSI parameter, which in previous cases indicated severe fouling, ideally changed to -1.35 and -2.01. Also, the working pressure decreased from 13.7 bar to 12.5 bar, which indicates an 8.76 % improvement in working conditions.

1. Introduction

The availability of proper quality water is a basic need for most aspects of life and a key element of life for all human societies. Proper quality water leads to excellent health, human survival, as well as the development and expansion of industries. By providing the required water with proper quality that can be used in industry and boilers, problems such as corrosion, fouling, and premature failure of industrial equipment that need feed water will be significantly reduced. However, according to the UN Report 2019, at least two billion people on Earth do not have access to safe drinking water. The crisis is also present in Europe and North America, but it is much more severe in African countries (WHO and UNICEF 2021). The water crisis is also severe in Iran and it is getting worst day by day. The Washington Post noted last July that Iran is moving toward a large-scale water crisis. According to the latest report of the International Institute of Water Management, Iran's groundwater reserves will reach dangerous and irreversible levels by 2025 (WHO and UNICEF 2021). A study took advantage of the experiments performed using the FILMTEC SW30 membrane and considered the feed water supply pressure, feed temperature, and salt concentration to predict the performance of the reverse osmosis system (Abbas and Al-Bastaki. 2005). Then another study examined the performance of the membrane in the RO system and also improved its performance in terms of fouling (sedimentation) considering the flux of

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membranes (Amiri and Samiei. 2007). The next investigation introduced the RO reverse osmosis system as the most advanced technology for water treatment and desalination. It also introduced MSF thermal processes and multi-effect distillation (MED) and compared them with the RO system. Finally, it addressed the principles of the process, membranes, and membrane modules (Fritzmann et al. 2007). Some other researchers studied the factors affecting the design of large-scale desalination plants in which seawater is treated and desalinated using pre-treatment systems and RO networks as well as post-treatment systems. Then, they reviewed the system models with the minimum required cost and they predicted the performance of the models based on SWRO technology (Kim et al. 2009). Moreover, a reverse osmosis system was designed by taking a wide range of salinity and seawater temperature into account and the results showed that salinity and water temperature affect the design of the RO system according to the capital and operational costs required to satisfy freshwater quality (Sassi and Mujtaba. 2012). Researchers also investigated seawater temperature and the boron removal rate according to pH and they optimized the reverse osmosis system by using a framework which was based on the MINLP model, an SW system (seawater modules), and a BW system (membrane modules), and by examining the effect of seasonal changes (Sassi and Mujtaba. 2013). Then the researchers used the reverse osmosis system to recycle materials in water. Moreover, they studied how to dispose of contaminants resulting from water treatment (concentrate) (Sung & Berrin. 2015). Another study reported that over the past two decades, reverse osmosis technology has made significant progress; therefore, the cost of filtration and water treatment (desalination) is reduced (Carter. 2015). Other researchers followed four work stages to ensure 95 % recovery and optimal water quality for drinking (Stillwell and Webber. 2016). The next researcher who utilized the reverse osmosis method performed simulations with the use of Hydranautics software to purify the Persian Gulf water to produce drinking water in Bandar Abbas. For this purpose, she used the RO system at 1.2MPa pressure and obtained the following parameters: SO_4^{2-} = 88.49 %, TDS = 61.42 %, CL^- = 70.34 % and Na^+ = 50.85 % (Aghababaei. 2017). Another study examined the energy consumption in desalination operations and during the analysis, the researchers found out that the effect of factors such as water quality and initial treatment operations on the amount of this energy is more than 86 % of the energy consumption in water treatment through reverse osmosis method. The results of this analysis can be a great help in predicting the amount of energy used for water treatment and desalination (Arola et al. 2019). Another study investigated water treatment and desalination using reverse osmosis. The study and simulation were performed using ROSA _ 72 software and raw groundwater with TDS of 1570-2910 mg/L was desalinated turned into the drinking water with TDS of 39.41 mg/L. In this study, the pressure was 7.91 bar, the membrane area was 2.6 m^2, and water recovery was 15 % (Abbasa and Rand Rafea. 2021). The present study examined surface water treatment with the characteristics obtained from the experiments performed through reverse osmosis to reach the feed water required for industrial boilers using the WAVE software. In this method, BW modules are used to reach the desired water quality. Moreover, some additives such as hydrochloric acid (HCl) and sodium hydroxide (NaOH) are added to prevent fouling, the results of adding these additives are listed in Table 4. In addition, ion exchange (IX) pretreatment system is used to reach the required water quality according to IS standard: 10392-1982 . Finally, the results of using each of these three methods (i.e. RO, RO + acid + NaOH, and IX) as pretreatment are compared; moreover, the results of adding NaOH to reduce water acidity and using RO as the final treatment are displayed.

2. Methods and procedure

This paper examines the methods of supplying boiler feed water using water application value engine (WAVE) software. First, a brief explanation regarding IX and RO systems are provided and it is attempted to achieve the desired result by using the reverse osmosis system, otherwise, other systems such as IX will be used. Reverse Osmosis Method: In this method, water passes through a semi-permeable membrane from higher to lower concentrations when the pressure increases, but this membrane does not let the ions and minerals present in the water pass. This method can be used to treat all kinds of waters, including seawater, brackish water, and wastewater. Most of the treatment systems all over the world, use the RO method. This method is widely used because these systems show high levels of scalability. Therefore, the capacity of the system can be increased or decreased simply by increasing or decreasing the number of filters (modules). On the other hand, these systems consume lower energy compared to other systems, especially distillation systems. Another advantage that can be mentioned is the wide operating range of TDS: 50-50000 mg/L.

Ion exchange systems

This purification method can be used to remove calcium, magnesium, barium, and strontium compounds (i.e. the compounds that cause scaling in the system), and sodium is added to the system instead. In the post-treatment stage, the pharmaceutical industry is also used to reach the water with a very high percentage of purity.

Fig. 1. Sodium resins.

As shown in Fig. 2, sodium ions cover the surface of these granules. When feed water containing calcium and magnesium compounds meets these granules, calcium and magnesium ions replace sodium ions and sodium ions are released (the calcium and magnesium trade places with sodium ions) and the sodium that enters the water can be easily removed by the RO system. When the surface of these granules is covered with calcium and magnesium ions, the performance of this system practically decreases.

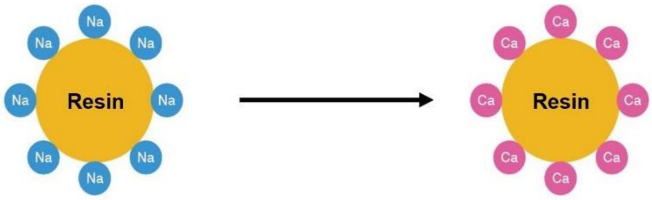

Fig. 2. A schematic diagram of IX resin.

In this study, the amount of the boiler feed water is set as 600m^3/day. Moreover, some laboratory examinations are performed. Table 1 shows the values of the parameters and compounds obtained for surface feed water: According to the study, boiler feed water must have the characteristics presented in Table 2.

First, the characteristics of FILMTEC modules were specified using conventional modules, HIGH REJECTION, and ECO, and a reverse osmosis system was designed. In this study and in a two-pass RO system, the water purified in the first pass is used as the water feed to the second pass, and here to determine the amount of RO2 membrane flux, the type of RO permeate feed water is set as:

SDI <1
Max element recovery = 30 %
Design flux = 36 ~ 43 LMH

Considering the effective surface area of the desired element (BW30-400 equals 37 m^2), the required number of elements was obtained from the following equation (FILMTEC Reverse Osmosis Membranes Technical Manual. 2021).

$$N_E = \frac{Q_p}{f \times S_E} \tag{1}$$

If flux = 36 LMH → NE=16
If flux = 43 LMH → NE=18

Based on the initial assumption, 18 modules can be operated by default in three PVs with a capacity of 6 elements. The water recovery should be high so that the quality of the input feed to the RO2 stage will be at the desired level and less water will be consumed. For this purpose, this system is designed with a water recovery of 85 %. At this water recovery level, the amount of the water that has been purified at the first pass can be calculated as follows.

QP=600 (m^3/d)/0.85=706 m^3/d

Therefore, the production capacity of RO1 is calculated to be 706 m^3/d. Now to calculate the number of required elements according to the type of water, the flux is set as 20-27 LMH.

If flux = 20 LMH → NE=40
If flux = 27 LMH → NE=29

If the maximum number of required elements is set as 40, then ten PVs with a capacity of 4 elements can be used by default. Considering that the water recovery for the first RO equals 75 %, the system structure is as follows (FILMTEC Reverse Osmosis Membranes Technical Manual, 2021).

$$R = \left[\frac{1}{(1-Y)}\right]^{\frac{1}{n}} \tag{2}$$

R = (1/(1-0.75))(1/2)=2

$$N_v(1) = N_v \Big/ \left(1 + (R^{-1})\right) \tag{3}$$

NV1=10/(1+(2-1))=6.67=7
NV2=10-7=3

Therefore, in RO1, the number of PVs in the first stage equals 7 and the number of PVs in the second stage equals 3 by default. Likewise, in RO2, the number of PVs equals approximately two in the first stage and one in the second stage. Fig. 3 is a schematic diagram displaying the PVs of these two states.

Table 1. Characteristics of feed water.

Parameter	Unit	Value
Electrical conductivity (EC)	dS/m	1.20
pH	---	7.58
Total dissolved solids (TDS)	mg/L	768
Non-carbonate alkalinity	meq/L	0.30
Carbonate ion concentration /CO_3^{2-}/	meq/L	0.0
Bicarbonate ion concentration /HCO_3^-/	meq/L	2.70
Chloride ion concentration /Cl^-/	meq/L	1.60
Sulfate ion concentration /SO_4^{2-}/	meq/L	8.71
Calcium ion concentration /Ca^{2+}/	meq/L	5.17
Magnesium ion concentration /Mg^{2+}/	meq/L	2.59
Sodium ion concentration /Na^+/	meq/L	5.51
Potassium ion concentration /K^+/	meq/L	0.04
SAR	$(mmol/L)^{0.5}$	2.79
SSP	%	41.50
Total hardness (TH)	mg/L	386.17
Residual sodium carbonate (RSC)	meq/L	-4.76
Mg_{HAZ}	%	33.37
[Ca]/[Mg]	---	1.99

Table 2. Feed water characteristics as per IS:10392-1982.

Parameters	Up to 20 Kg/cm^2	21 Kg/cm^2 to 39 Kg/cm^2	40 Kg/cm^2 to 59 Kg/cm^2	Unit
Total hardness	<10	<1.0	<0.5	mg/L as $CaCO_3$
pH value	8.5-9.5	8.5-9.5	8.5-9.5	-
Dissolved oxygen	0.1	0.02	0.01	mg/L
Silica	-	5	0.5	mg/L as SiO_2

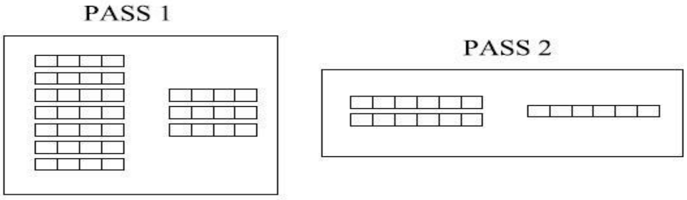

Fig. 3. A schematic diagram of the initial arrangement of the modules.

The required initial information was entered into the WAVE software and further calculations and simulations were performed using this software. Then, the mistakes made by the software were eliminated and the outputs of the software were examined to optimize the water and reach the required water quality. It should be noted that the WAVE software is one of the tools used to design industrial reverse osmosis (RO) desalination plants. This software is manufactured by Dupont company. The WAVE simulator software simultaneously design and analyze different parts of a system such as ix and uf. This software is based on chemical-mechanical analysis. The software inputs can be the number of filters, layout, temperature, type of inlet water and etc., and its output will be final water analysis, final layout, system operating pressure and etc. In this study, version 1.77a of this software was used.

3. Results and discussion

The initial data were entered into the WAVE software. Considering the BW30-400 module, the following results were obtained. As can be seen, Concentrate Flow Rate <Minimum limit errors were observed in PASS1 in stages one and two and in modules 3 and 4. Also, element recovery> maximum limit errors can be seen in PASS1, in the first stage of modules 2, 3, and 4. To eliminate these errors, the number of modules increased to up to 6 modules in PASS1 PVs, and the amount of pressure between step one and step two of PASS1 increased by 3 bar. In this way, the errors were corrected. It should be noted when a pressure control valve was placed to control the concentrate permeate and the water pressure of the concentrate was increased by 3 bar, a similar result was obtained and the relevant errors were eliminated. The results of the outlet water are shown in Table 3.

According to the results, pH and langelier saturation index (LSI) errors are evident. The amount of LSI parameter indicates improper performance in the modules, which will cause premature scaling in the first PASS module, and the acidity of the permeate will cause corrosion of boiler systems. Therefore, to solve these problems, the following different tests were performed using several modules, and the results obtained were the same for all modules. To reduce the amount of LSI and solve the scaling problem, the acidity should be increased to pH 6 by increasing the amount of HCl although then TDS of the permeate equals 2.12 mg/L, and its acidity increases to pH=4.6. pH of water feed to PASS2 reaches 10 during treatment stages when NaOH is added, but the quality of the permeate decreases significantly. On the other hand, when LSI increases in PASS2, the previous problem emerges again leading to scaling (rapid clogging and poor performance). Characteristics of the water after adding HCl to PASS1 and NaOH to PASS2 are as follows Table 4.

Table 3. The permeate of the two-PASS RO system.

Ion	NH_4^+	K^+	Na^+	Mg^{+2}	Ca^{+2}	Sr^{+2}	Ba^{+2}	CO_3^{-2}	HCO_3^-
mg/L	0.00	0.00	0.12	0.00	0.01	0.00	0.00	0.00	0.54
Ion	**NO_3^-**	**F^-**	**CL^-**	**Br^{-1}**	**SO_4^{-2}**	**PO_4^{-3}**	**SiO_2**	**Boron**	**CO_2**
mg/L	0.00	0.00	0.06	0.00	0.08	0.00	0.00	0.00	5.20
Parameter	**TDS**	**pH**	**LSI**	**P_{MAX}, bar**	**-**	**-**	**-**	**-**	**-**
mg/L	0.82	5.3	1.58	13.4	-	-	-	-	-

Table 4. The permeate from a two-PASS RO system after adding hydrochloric acid and sodium hydroxide

Ion	NH_4^+	K^+	Na^+	Mg^{+2}	Ca^{+2}	Sr^{+2}	Ba^{+2}	CO_3^{-2}	HCO_3^-
mg/L	0.00	0.00	1.05	0.00	0.00	0.00	0.00	0.11	1.71
Ion	**NO_3^-**	**F^-**	**CL^-**	**Br^-**	**SO_4^{-2}**	**PO_4^{-3}**	**SiO_2**	**Boron**	**CO_2**
mg/L	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00
Parameter	**TDS**	**pH**	**LSI**	**P_{MAX}, bar**	**-**	**-**	**-**	**-**	**-**
mg/L	3.15	9.1	1.5	13.7	-	-	-	-	-

Taking into account all these cases, a purifying and softening station called ion exchange (IX) system was set up to soften the water and heighten the recovery up to 97.7 %. Water hardness reduces significantly when the AMBERPACK system was used in this softener (a purification tank was used and the operation was bottom-up) and AMBERLITE HPR 1100 NA resin with sodium base was used and the hardness of the permeate of this stage was as follows: hardness (mg/L $CaCO_3$) = 0.4. The permeate of this system feeds the reverse osmosis system described before and after the errors of the software were corrected, the following output was obtained. Software output after setting up the IX treatment plant before RO treatment system by adding 3bar pressure between stage one and two in both PASSes and adding NAOH to increase the pH of the feed water to PASS2 up to 10.5 (Fig. 4 and Table 5).

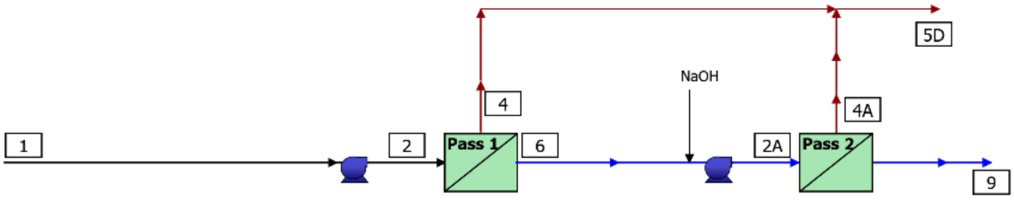

Fig. 4. A schematic diagram of a two-PASS RO system.

Table 5. Operating conditions of two-PASS RO system equipped with ion exchange.

Position	Description	Flow, m^3/d	TDS, mg/L	Pressure, bar	Position	Description	Flow, m^3/d	TDS, mg/L	Pressure, bar
1	Raw feed to RO system	941.7	915.5	0.0	2A	Net feed to PASS 2	705.8	39.12	11.9
2	Net feed TO PASS 1	941.4	915.7	6.0	4A	Total concentrate from PASS 2	105.9	248.7	12.2
4	Total concentrate from PASS 1	235.4	3618	8.1	5D	Net concentrate from RO system	341.4	2568	-
6	Total permeate from PASS 1	706.2	12.83	0.0	-	-	-	-	-
9	Net product from RO system	600.2	1.27	0.0	-	-	-	-	-

Table 6. Characteristics of the permeate from the two-PASS RO system equipped with ion exchange.

Ion	NH_4^+	K^+	Na^+	Mg^{+2}	Ca^{+2}	Sr^{+2}	Ba^{+2}	CO_3^{-2}	HCO_3^-
mg/L	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.02	0.52
Ion	**NO_3^-**	**F^-**	**CL^-**	**Br^{-1}**	**SO_4^{-2}**	**PO_4^{-3}**	**SiO_2**	**Boron**	**CO_2**
mg/L	0.00	0.00	0.00	0.00	0.013	0.00	0.00	0.00	0.00
Parameter	**TDS**	**pH**	**LSI IN SEC PASS**	**P_{MAX} ,bar**	**-**	**-**	**-**	**-**	**-**
mg/L	1.27	8.8	-2.01	12.5	-	-	-	-	-

Table 7. Design errors displayed by WAVE software.

Design warning	Limit	Value	Pass	Stage	Element	Product
Concentrate flow rate<minimum limit, m^3/d	81.8	77.2	1	1	6	BW30-400
Element recovery<maximum limit, %	15.0	15.6	1	1	5	BW30-400
Element recovery<maximum limit, %	15.0	17.7	1	1	6	BW30-400

Table 8. Hardness and pH of permeate from the ion exchange system.

Parameter	Amount	Required average	Required end point	Estimated average
pH @ 25 ºC	7.57	-	-	7.58
Hardness, mg/L $CaCO_3$	365.60	1	1.50	0.41

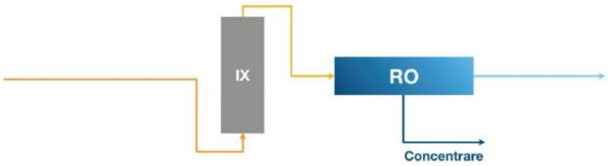

Fig. 5. A schematic diagram of ion exchange and reverse osmosis systems.

Table 9. A comparison of the characteristics of the permeate from the systems mentioned in the first column.

System	**NH_4^+**	**K^+**	**Na^+**	**Mg^{+2}**	**Ca^{+2}**	**Sr^{+2}**	**Ba^{+2}**	**CO_3^{-2}**	**HCO_3^-**
Double RO	0.00	0.00	0.12	0.00	0.01	0.00	0.00	0.00	0.54
Double RO + HCl+NaOH	0.00	0.00	1.05	0.00	0.00	0.00	0.00	0.11	1.71
IX+RO+NaOH	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.02	0.52
System	**NO_3^-**	**F^-**	**CL^-**	**Br^{-1}**	**SO_4^{-2}**	**PO_4^{-3}**	**SiO_2**	**Boron**	**CO_2**
Double RO	0.00	0.00	0.06	0.00	0.08	0.00	0.00	0.00	5.20
Double RO + HCl+NaOH	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.00
IX+RO+NaOH	0.00	0.00	0.00	0.00	0.013	0.00	0.00	0.00	0.00
System	**TDS**	**pH**	**LSI IN PASS 1**	**LSI IN PASS 2**	**P_{MAX}, bar**				
Double RO	0.82	5.3	1.58	-2.86	13.4				
Double RO + HCl+NaOH	3.15	9.1	-0.19	1.5	13.7				
IX+RO+NaOH	1.27	8.8	-1.35	-2.01	12.5				

4. Conclusions

Since the boilers have some problems, first their performance was examined, and then the problem of boiler feed water was taken into consideration. In this regard, standards have been set for boiler feed water. This study tried to reach a kind of water that is suitable for these devices and does not cause scaling or corrosion in boilers and tanks. In this regard, reverse osmosis (RO) systems and ion exchange filtration system were used and the life span and potential shortcomings of RO systems were taken into consideration to meet the required standards for boiler feed water. Double RO systems with two pass and two stages and sodium resin treatment system were used and the following results were obtained in each stage. To correct the errors of the WAVE software, two methods were used and both of them showed the same results:

- The pressure increased to 5 bar between two stages in PASS1;
- The concentration of water pressure increased when a pressure control valve was inserted and as a result, the permeate pressure increased up to 5 bar;
- When the amount of acid injection is increased to prevent fouling and to reduce the LSI parameter, TDS of permeate and also the acidity of the water increase. When an ion exchange system is used, the treated water has better acidity because the ion exchange system protects the TDS rate, controls the LSI parameter, and improves the characteristics of the permeate. Moreover, when some NaOH is added and the alkalinity of water feed to PASS2 is heightened, an appropriate pH in the RO system will be reached. When the ion exchange system was used as pre-treatment, the hardness was significantly reduced to 0.41 and the following results were obtained.

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