Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.1003980

57 (2016) 5385–5390
March

Design and performance of a new zero-wastewater small-size reverse osmosis desalination system

Tarek Qasim[a,*], Ahmed Abu-Haifa[a], Mohsen Abu-Haifa[b]

[a]*Industrial Engineering Department, Jordan University of Science and Technology, Irbid 22110, Jordan, Tel. +962 79504661; emails: tqqasim@just.edu.jo (T. Qasim), ahabuhaifa@just.edu.jo (A. Abu-Haifa)*
[b]*Petra Company for Water Treatment Systems, P. O. Box 420, Al-Hassan Industrial Area, Ramtha 21110, Jordan, Tel. +962 02 7391531/+962 02 7391532; email: tqqasim@just.edu.jo*

Received 9 August 2014; Accepted 29 December 2014

ABSTRACT

A modified reverse osmosis (RO) system with zero wastewater was developed, and its performance was tested against allowable limits of total dissolved solids (TDS) in Jordan. New components were added to the typical single- and double-membrane RO systems used in private homes to re-direct the amount of saline water rejects to drainage. Instead, this water is mixed with input water from the source. Then, the mixed water is used for domestic household purposes other than drinking. The TDS values of output fresh water and mixed water were tested and found to be within safe limits. The new components can be fitted to existing systems with a small amount of extra space. The reuse of saline water after mixing does not require human interaction, and the system can be fully utilized for safe and continuous operation. The newly modified system produced huge water savings relative to existing systems. The implementation of modified RO plants could save a country like Jordan, 18 million cubic meters of supplied input water annually, based on 500,000 RO units operating in Jordanian homes, with 100% water recovery.

Keywords: Reverse osmosis; Zero waste water; Control unit; Jordan

1. Introduction

Recently, portable reverse osmosis (RO) desalination systems have become widely used in private homes, industrial settings, and remote areas as a means of providing safe drinking water. Several studies have concentrated on the quality of water produced by RO units in terms of salt concentrations or biocompatibility, but the amount of wastewater that these systems reject to drainage has yet to be addressed. This problem must be solved to meet the increasing demand for fresh water. With limited water resources for domestic use, saving water has becomes a general concern for individuals in many parts of the world [1]. Avlonitis studied the water cost per cubic meter for small-size RO desalination plants in remote parts of Greek islands for three years with the purpose of improving the productivity using new technology, such as data acquisition, automation, and remote operation. He concluded that running the low-cost RO plants can improve labor productivity directly [2]. Lee et al. evaluated agricultural drainage water in terms of feedwater quality by choosing a suitable membrane to control salt rejection and biofouling potential.

*Corresponding author.

The initial results suggested that a long-term pilot plant would be feasible [3]. Several studies have concentrated on water quality and water treatment for drinking water using chemical absorbents [4,5]. The variation of sea water temperature and seasonal fouling effect was studied to find the optimal operation of RO systems using sea water [6,7]. Both temperature and seasonal changes affected scaling and biofouling to some degree. To evaluate the small RO units used in private homes in Jordan, Al-Jayyousi and Mohsen conducted a study comparing the water quality of RO units sold commercially to bottled and tap water. They concluded that the RO systems produce water within allowable limits of total dissolved solids (TDS) and pH and do so at a reasonable price [8]. A research project funded by Middle East Desalination Research Center conducted in the Middle East and North Africa region to develop zero-waste small home-use RO units that use water softeners to demineralize the water from municipal systems. This may render the RO units used in private homes more efficient [1].

Several pilot RO projects use solar energy to save power. Such systems can be used in remote areas where energy supplies are limited or not available. Zhang et al. utilized a combination of solar energy and a RO system to treat the feedwater boilers. They showed energy savings and an environmentally friendly system which meet steam-boiler water quality standards [9]. Most of the research done on RO system optimization has focused on the performance of individual components of the system to enhance water quality [10–12]. Several studies of RO systems have addressed issues of particular concerns. Here, their data were collected and evaluated, and recommendations were developed.

The issue of the low recovery rate of RO plants is still a major concern. In this paper, a newly modified RO system was developed, built at Petra for Water Treatment Systems Company, and tested at Jordan University of Science and Technology (JUST) and in private homes in Jordan. The purpose of the present work was to establish the new system that can reuse rejected water to drainage (RWD) automatically, without human interaction, while maintaining the allowable limits of TDS and water quality adequate for domestic use. A saline water tank was added to the typical commercial RO system. A series of relay valves was placed inside the feeder and discharge control unit to manage and redirect the flow, resulting in zero wastewater from the newly modified RO system. The modified RO system is shown in Fig. 1 with a connecting diagram. Analyses of the quality of water supplied from the system, fresh water for drinking (FW), and rejected water mixtures (RWM) meant for household use were below the allowable limits and safe to use.

2. Typical small RO system

In a typical commercially available RO system, salt water is rejected and connected to drain. The recovery of this plant was very low and depended on several factors, such as filter quality and maintenance, the membrane used, and especially the amount of fresh water required for drinking by the user. It is estimated that 3–9 L of water rejected to drainage (RWD) were wasted for each liter of fresh water (FW) produced. This amount of rejected water could cost a country like Jordan, 18 million cubic meters of supplied input water (IW) annually, based on an estimates that a single five-person household would require 25 L of fresh drinking water each day and an average rate of water to drainage of four liter per one liter of fresh water. It is estimated that 500,000 RO plants are operating in private homes in Jordan [13].

3. New RO model developments

A new, modified RO system is presented in Fig. 1. In addition to the components found in typical RO plants sold commercially, two one-way high-pressure valves shown in Fig. 1 ((6) and (12)) have been added to prevent the pressurized water inside both tanks from returning to the membrane. One valve is for fresh water supplied to the fresh water tank, and the other valve is for salt water supplied to the newly added saline water tank. These both direct the flow to the desired tank. The function of the low-pressure cut-off switch in Fig. 1(2) is to switch the pump off, when the flow from the input water supply (IW) becomes low. A saline water tank similar to the fresh water tank was added to the system to supply private homes with mixtures of salt water and supplied municipal input suitable for cleaning and other non-drinking purposes. Both tanks are meant to be pre-pressurized to 8 psi. The TDS of the domestic cleaning water may increase slightly but remains within acceptable limits for its intended use. To control the flow and distribution of supplied input water for filtration, filtered salt water, and mixtures of rejected salt water and municipal input water, a feeder and discharge unit (control unit) consisting of a series of pressurized relay valves was placed in the system as shown in Fig. 1(1).

Most households use more water for cleaning than for drinking, so the salt water tank will be empty more often than the fresh water tank. When the salt

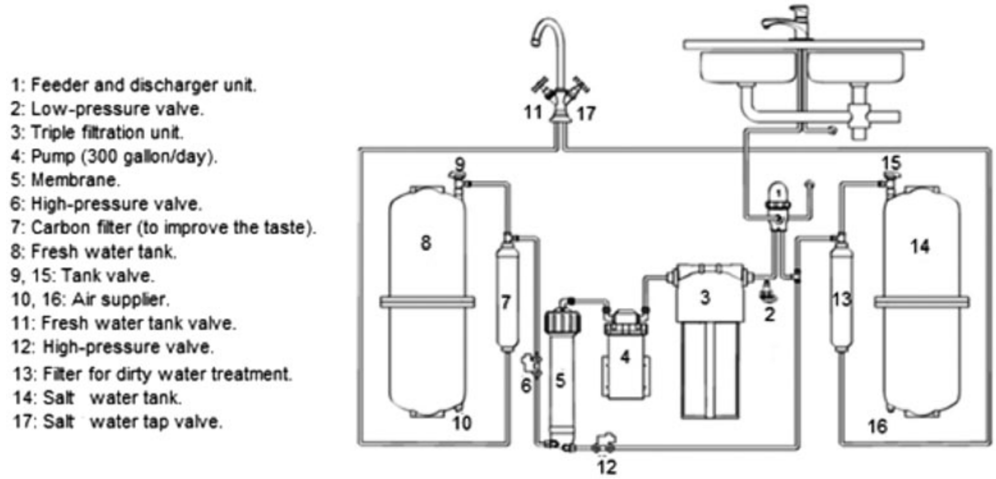

Fig. 1. The new RO system which was built at Petra Company for Water Treatment Systems, Jordan.

water tank becomes full, the system (pump) shuts down. It restarts once the water from saline water tank is removed. This does not affect the use of fresh water from the pressurized fresh water tank. In this fashion, no wastewater is produced by this modified RO system. More importantly, the quality of the fresh drinking water and the mixed cleaning water was within acceptable limits of TDS, as listed by American and Jordanian standards, and safe to use [14]. This new, self-sufficiently modified system eliminates the need for direct human interaction, such as collecting rejected water. The added components of the new RO plant do not require much extra space and can fit under a typical sink, as is the case with typical RO systems.

4. Testing procedure

Feeder and discharge units have two main parts, as shown in Fig. 2. The upper component is used for mixing the salt water after filtration (water that would be rejected by a typical RO units) with supplied fresh water. Then, the mixture is available for general household cleaning and other non-drinking purposes. The lower component is used for feeding the supplied municipal input water into the RO system and upper component. The saline water rejected after filtration is sent to the upper mixing component. The main feature of the supply and discharge unit is that it does not allow the drained salt water back into the RO unit. This leads to a high salt concentration in the filter and the membrane. This salt concentration can reduce the life time of the RO system.

Fig. 2(A) shows the feeder and discharge unit, and Fig. 2(B) is a photograph of major parts inside the feeder and discharge unit, which consists of two check valves, an O-ring, and several fittings. The dash lines show the water flow through the unit. To assess the unit after assembly, it was fitted with a typical commercially available RO system and used in private homes and at the JUST laboratory for seven days. The fresh drinking water produced by the system and the general purpose mixed water were collected and analyzed in terms of volume flow rate and TDS and compared to water collected from a typical RO plant without a feeder or discharge control unit.

5. Results and discussion

To test the quality of water intended for specific purposes, such as drinking and cleaning, the water output of the modified RO system was tested against typical RO systems at the Chemical Engineering Laboratory of JUST with a double-membrane RO system over the course of several days. Table 1 shows the results of the two systems during a one-week trial. For the system without a control unit (typical system), the amount of water rejected to drainage RWD (useless water) averaged 8.88 L per L of fresh water (FW) produced. This is very high, bringing Jordan's wastewater estimates to 36 million m^3 each year. However, using the double-membrane unit shown in Table 1, the TDS limits for the input water (IW) from source, the fresh drinking water (FW), and the salt water (SW) after filtration were all acceptable and below 500 ppm.

For the system tested with the new feeder and discharge control unit installed, the mixed water

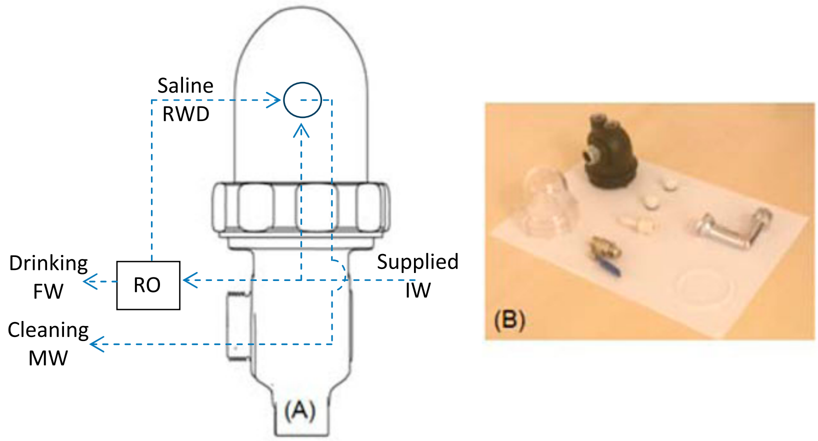

Fig. 2. Feeder and discharge unit: (A) external view showing the upper mixing and lower feeder units; (B) photograph of the major parts.

Table 1
Double-membrane RO systems with and without control unit tested at JUST

Period	Control unit	IW TDS [ppm]	FW TDS [ppm]	SW TDS [ppm]	MW TDS [ppm]	Volume of FW [L]	Volume of RWD [L]	Volume of RWM [L]	Flow rate of FW [L/min]	Flow rate of SW [L/min]	Flow rate of MW [L/min]
Day 1	NO	288	6.6	421	–	1	9	–	1/1.83	1/0.20	–
Day 2	NO	287	6.7	420	–	1	8.9	–	1/1.85	1/0.20	–
Day 3	NO	287	6.6	420	–	1	9	–	1/1.85	1/0.20	–
Day 4	NO	297	6.6	425	–	1	8.85	–	1/1.93	1/0.21	–
Day 5	NO	290	6.7	422	–	1	8.5	–	1/1.85	1/0.21	–
Day 6	NO	292	6.6	421	–	1	8.9	–	1/1.90	1/0.20	–
Day 7	NO	290	6.7	422	–	1	9	–	1/1.91	1/0.21	–
Average		**290.14**	**6.64**	**421.57**		**1.00**	**8.88**		**1/1.87**	**1/0.20**	
Day 1	YES	290	7.8	420	371	1	0	2	1/1.52	1/0.61	1/0.41
Day 2	YES	290	7.3	416	373	1	0	2	1/1.52	1/0.61	1/0.41
Day 3	YES	293	7.4	414	377	1	0	2	1/1.52	1/0.61	1/0.41
Day 4	YES	293	7.2	410	380	1	0	2	1/1.52	1/0.61	1/0.41
Day 5	YES	293	7.3	411	379	1	0	2	1/1.52	1/0.61	1/0.41
Day 6	YES	297	7.2	385	345	1	0	2.2	1/1.46	1/0.68	1/0.28
Day 7	YES	297	7.2	429	335	1	0	2.4	1/1.35	1/0.41	1/0.20
Average		**293.29**	**7.34**	**412.14**	**365.71**	**1.00**	**0.00**	**2.09**	**1/1.49**	**1/0.59**	**1/0.36**

IW: Input water from source.
FW: Fresh/drinking water after filtration.
SW: Saline water after filtration.
MW: IW + SW for domestic use through the control unit.
RWD: Water rejected to drainage (useless water).
RWM: Water to rejected feeder and discharge unit for domestic use.

(MW) can be used for non-drinking domestic purposes (cleaning). This mixture contains input water from source (IW) and salt water (SW) left over from filtration. The TDS values of the mixed water for domestic use (MW) were above the TDS value of input water (IW) from the source but still within acceptable limits. For example, they posed no harm to human hands such as rash or chemical burn. The main feature of the new feeder and discharge control unit is that no water is rejected to drainage (RWD); it shows 100% water recovery. Results showed that the RWM rate used in these tests was 2 L for each L of

Table 2
Single-membrane RO system with and without control unit tested in a private home

Period	Control unit	IW TDS [ppm]	FW TDS [ppm]	SW TDS [ppm]	MW TDS [ppm]	Volume of FW [L]	Volume of RWD [L]	Volume of RWM [L]	Flow rate of FW [L/min]	Flow rate of SW [L/min]	Flow rate of MW [L/min]
Day 1	NO	375	45	520	–	1	4	–	1/8.50	1/3.2	–
Day 2	NO	377	46	520	–	1	3.8	–	1/9.00	1/3.0	–
Day 3	NO	372	42	510	–	1	4	–	1/9.00	1/3.1	–
Average		**374.67**	**44.33**	**516.67**		**1.00**	**3.93**		**1/8.83**	**1/3.1**	
Day 1	YES	375	59	518	390	1	0	2.5	1/5.50	1/2.2	1/0.41
Day 2	YES	377	63	520	389	1	0	2.5	1/7.85	1/2.8	1/0.36
Day 3	YES	360	58	516	390	1	0	2.5	1/7.00	1/2.7	1/.40
Average		**370.67**	**60.00**	**518.00**	**389.67**	**1.00**	**0.00**	**2.50**	**1/6.78**	**1/2.57**	**1/0.39**

Table 3
Impurities in water produced by typical and modified RO systems

Water Supplied*	Control unit	PH	Temp. [˚C]	Salinity [ppm]	TDS [ppm]	Cond. [µs]	Mg [ppm]	Ca [ppm]	Na [ppm]	Zn [ppm]	Cu [ppm]
IW	YES	7.76	25	0.3	291	586	20.30	22.70	13.34	0.54	0.45
FW	YES	6.10	25	0.0	0.4	540	0.00	0.50	0.08	0.00	0.00
SW	YES	7.81	25	0.5	460	948	23.23	25.70	26.26	0.67	0.00
RWM	YES	7.79	25	0.3	340	696	21.36	24.70	21.18	0.59	0.00
FW	NO	6.00	25	0.0	0.2	586	0.00	0.00	0.00	0.02	0.00
RWD	NO	7.77	25	0.3	320	660	22.40	24.30	19.96	0.57	0.00

*The abbreviations in this column are the same as those used in Table 1.

fresh drinking water produced. In this way, more cleaning water was made available for general household use. These tests were repeated for several weeks. Results of one typical week are presented.

Another, single-membrane RO system was fitted and tested at a private home. The home was equipped with typical single-membrane RO system. Data from the existing unit were collected, and then the system was modified. A feeder, mixing unit, salt water tank, and valves were added. Then, the before and after data were compared. Note that the TDS of the salt water sent to drainage (SWD) was above 500 ppm before mixing. After the salt water was mixed with the water from the source, the TDS value was below 400 ppm. This level is safe, and the water can be used for cleaning purposes as shown in Table 2. Less water per L of fresh water produced was rejected to drainage by the system without a control unit than by the double-membrane system (3.9 L), but this is still too much waste. The performance of the newly modified system showed significant water saving whether it was used with single- or double-membrane system.

Water quality was tested against Jordanian standards for impurities in input water from the municipal source, fresh drinking water, and the filtered salt water. The rejected water mixed for domestic use is shown in Table 3. The allowable limits in Jordanian standards are 500 ppm TDS and 6.5–9.0 pH, respectively [8]. All values obtained were within limits for the intended use of the water.

6. Conclusions

The modified RO system, which is meant for domestic use, showed significant water savings without affecting the quality of either drinking or cleaning water. Conservatively, there are an estimated 500,000 RO units operating in private homes in Jordan. The new modifications can fit into existing typical RO systems with only a little extra space needed for the new parts. With limited water resources and the low quality of municipal water, the use of RO systems is increasing in both domestic and commercial settings. Typical RO systems have very low recovery rates. This results huge amounts of water rejected to drainage. The newly modified RO system produces no wastewater. It reduces the user's water bill and conserves the country's water resources. The new design of RO system has been registered in 12 countries for intellectual property rights through Abu-Ghazaleh Intellectual Property Group, which is indicative of the novelty of the new system and its importance to the water conservation. Currently, a new, space-saving filtration system is under development. It will allow the use of the three or more filters into one unit. This will save space and make the new units more efficient.

Acknowledgments

This work was supported by a grant from the Ul-Urdonia Lil-Ebda/South Business Incubator. We would like to thank Dr Nezar Samarah of Jordan University of Science and Technology for discussing intellectual property rights with us.

Conflicts of interest

There are no conflicts of interest.

References

[1] Watermark newsletter of the Middle East Desalination Research Centre, 28 (2009) 1–12.

[2] S.A. Avlonitis, Operational water cost and productivity improvements for small-size RO desalination plants, Desalination 142 (2002) 295–304.

[3] R.-W. Lee, J. Glater, Y. Cohen, C. Martin, K. Kovac, M. Milobar, D. Bartel, Low-pressure RO membrane desalination of agricultural drainage water, Desalination 155 (2003) 109–120.

[4] L. Zaleschi, C. Sáez, P. Cañizares, I. Cretescu, M.A. Rodrigo, Electrochemical coagulation of treated wastewaters for reuse, Desalin. Water Treat. 51(16–18) (2013) 3381–3388.

[5] M. Hammad Khana, M. Tariqa, F. Bashira, T. Shafiqa, R.A. Khana, J. Jung, Arsenic removal from drinking water with conventional and modified adsorbents: The factorial design of experiments, Desalin. Water Treat. 51(37–39) (2013) 7304–7310.

[6] K. Sassi, I. Mujtaba, Optimal operation of RO system with daily variation of freshwater demand and seawater temperature, Comput. Aided Chem. Eng. 30 (2012) 817–821.

[7] H.L. Young, C. Huang, J.C. Te Lin, Seasonal fouling on seawater desalination RO membrane, Desalination 250 (2010) 548–552.

[8] O. Al-Jayyousi, M. Mohsen, Evaluation of small home use reverse osmosis units in Jordan, Desalination 139 (2001) 237–247.

[9] X.Q. Zhang, J.F. Xu, M.X. Du, Y. Zhang, Boiler-water treatment by reverse osmosis employing solar energy, Adv. Mater. Res. 374–377 (2011) 1021–1024.

[10] M. Al-hajlia, A. Ajbara, E. Alia, K. Alhumaizi, Optimization-based periodic forcing of RO desalination process for improved performance, Desalin. Water Treat. 51(37–39) (2013) 6961–6969.

[11] A. Mostafa, A. El-Aassar, Improvement of reverse osmosis performance of polyamide thin-film composite membranes using TiO2 nanoparticles, Desalin. Water Treat. 52 (2013) 22–24. Available from: http://www.tandfonline.com/doi/abs/10.1080/19443994.2014.940206?journalCode=tdwt20#preview.

[12] Y. Fang, S.J. Duranceau, Comparison of nonhomogeneous and homogeneous mass transfer in reverse osmosis membrane processes, Desalin. Water Treat. 51 (34–36) (2013) 6444–6458.

[13] Annual report, Water Authority of Jordan, Ministry of Water and Irrigation. Amman, Jordan, 2009.

[14] Standard Methods for the Examination of Water and Wastewater, fifteenth ed., American Public Health Association, American Water Works Association, and Water Pollution Control Federation, Washington, DC, 1981.