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Development and stand tests of reciprocating-switcher energy recovery device for SWRO desalination system

Daiwang Song[a,b,c], Yue Wang[a,b,c,*], Naiyuan Lu[a,b,c], Hui Liu[a,b,c], Enle Xu[a,b,c], Shichang Xu[a,b,c]

[a]*Chemical Engineering Research Center, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, P.R. China*
[b]*Tianjin Key Laboratory of Membrane Science and Desalination Technology, Tianjin 300072, P.R. China*
[c]*Collaborative Innovation Center of Chemical Science and Engineering, Tianjin 300072, P.R. China, Tel. +86 22 27404347; Emails: songdw123@126.com (D. Song); tdwy75@tju.edu.cn (Y. Wang); lunaiyuan1987@163.com (N. Lu); liuhui1988qidan@163.com (H. Liu); xel360@126.com (E. Xu); xushichang@sina.com (S. Xu)*

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ABSTRACT

In this paper, a novel piston exchanger—reciprocating-switcher energy recovery device (RS-ERD) was introduced and developed. The RS-ERD adopts the unique open/close plate design, which not only ensures a perfect sealing effect and high efficiency of the device, but also favors avoiding the destruction of micro-particles in the liquid occasionally. For proving the operating performances of the RS-ERD, an emulating RO-ERD desalination platform was established and the testing conditions were regulated as ERD capacity of 30 m^3/h and operating pressure of 6.5 MPa. The experimental results indicate that the operating stability of the RS-ERD is good. The leakage ratio of the device is lower than 1.7% and the energy recovery efficiency is above 98%, which can satisfy the industrial requirements of the SWRO plant.

Keywords: Seawater reverse osmosis (SWRO); Desalination; Energy recovery device (ERD); Operating performance

1. Introduction

Reverse osmosis (RO) technology owns a great market share in desalination engineering projects for the advantages of low investment, low energy consumption, and short construction period [1–3]. Currently, the most effective and practical way to achieve low energy consumption is to introduce the energy recovery devices (ERDs) into the RO desalination system [4,5]. According to the type of energy conversions, the ERDs can be generally classified into two major categories: the centrifugal type and the isobaric type [6].

For the centrifugal type ERDs (including the mechanical assisted pumping and the hydraulically driven pumping in series), the pressure energy in the high-pressure (HP) brine is first transformed into mechanical energy and then into the pressure energy of raw seawater. The “two-step” energy transmission makes great energy losses, which limits the devices’ efficiency in the range of 50–80%. For this reason, their market share is gradually reduced although the applications are relatively earlier [7,8]. For the isobaric type

*Corresponding author.

ERDs, the pressure energy in the HP brine is directly transferred to the raw seawater, which promotes the devices' energy recovery efficiency up to 95% or even higher [9,10]. Therefore, the isobaric type ERDs, including the piston exchanger as double work exchanger (DWEER) and rotary exchanger as PX, have attracted worldwide attentions for both the research and industrial applications [11–13].

In our previous papers, an isobaric type ERD called fluid-switcher energy recovery device (FS-ERD) was introduced and investigated [14,15]. The application has identified that the FS-ERD may be out of order resulted by micro-particles occasionally due to precision coordination of the fluid switcher's rotor and the shell, although the device is compact in structure and its efficiency can be as high as 95% [15]. So continuous improvements and contributions have been made to the ERD in recent years and a novel reciprocating-switcher energy recovery device (RS-ERD) is developed. The RS-ERD belongs to the piston exchanger and follows similar working principle as DWEER, but with unique structure and short journey of the RS.

In this paper, the working principle and structural characteristics of the RS-ERD are introduced and explained. Operating performances of the RS-ERD, including the pressure and flow stabilities of the device are experimentally evaluated through an emulating RO desalination platform under the ERD capacity of 30 m^3/h and operating pressure of 6.5 MPa. As a consequence, the internal leakage ratio and the energy recovery efficiency of the device are assessed and compared with commercial products.

2. Description of the RS-ERD

2.1. The operating principle

The RS-ERD mainly consists of three parts: a reciprocating switcher (RS), two water hydraulic cylinders, and a check valve nest, as shown in Fig. 1. The RS is the core component of the RS-ERD, whose role is to guide the HP brine and the depressurized brine to flow in and out of the hydraulic cylinders periodically, and also to keep the continuity and stability of pressure exchange in cylinders. The check valve nest comprised of four parallel check valves directs the raw seawater and pressurized seawater to flow in and out of the cylinders, respectively. The free piston in each cylinder is used to prevent the salinity mixing between the brine and the seawater streams.

More concretely, when the RS lies in the forward position, pressurization process is carried out in water hydraulic cylinder one, where the HP brine transfers

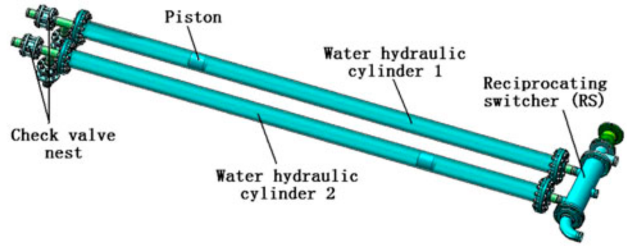

Fig. 1. Basic components of RS-ERD.

the pressure energy to the raw seawater and pushes the pressurized seawater out of the check valve nest. Simultaneously, the depressurization process is implemented in water hydraulic cylinder two, where the raw seawater fills the water hydraulic cylinder and discharges the depressurized brine out of the RS. When both the pressurization process in cylinder one and the depressurization process in cylinder two are accomplished, the RS changes to the backward position and at this time, the cylinder one is alternated to depressurization process and cylinder two to the pressurization process. By repeating the above steps and following the control loops presented in Fig. 2, the RS-ERD achieves the efficient recovery of pressure energy from HP brine stream. Fig. 3 gives the scene of RS-ERD prototype in the experiments with clear features of the RS presented.

2.2. Characteristics of the RS-ERD

As the most innovative aspect of the RS-ERD, the unique structures of the RS bring more working advantages for the device. The RS is comprised of two

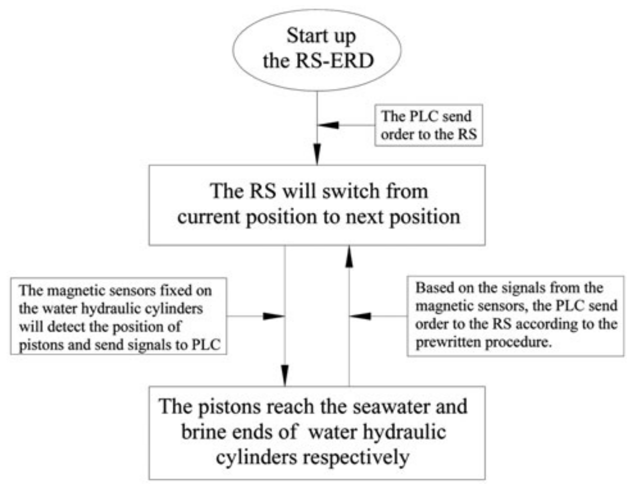

Fig. 2. The control loops for RS-ERD device.

Fig. 3. The prototype of RS-ERD device.

parts, the oil hydraulic actuator and the switcher, as shown in Fig. 4. There are four valve plates (two HP plates, two LP plates) inside the switcher, all of which adopt metallic sealing structure similar to lift check valves. The unique structure provides little opportunity for micro-particles in the liquid to stay in the sealing area of the plate, which does benefit for the protection of sealing surface and ensures a leakage-free operation of the device.

Also, the two HP valve plates are fixed on the rod shaft, while the other two LP valve plates can slide back and forth along the shaft. The sliding movement of the LP plates facilitates the earlier closure of the LP plates than the HP plates, and also makes it possible for the overlapping of pressurization process in two cylinders during the position switch of the hydraulic actuator. Additionally, the pressing force required by LP valve plates for sealing comes from the pressure difference between HP brine and depressurized brine, which favors the sealing adaption of the plates on the changes of operating pressure. Moreover, the flow cross-sectional area needed inside RS can be formed through a relative short-distance movement of each plate, which reduces the journey and switch time of the actuator. No special materials are used in RS-ERD and almost all of its components can be manufactured by lathe, therefore, the RS-ERD can be setup economically.

For evaluating the performance of the RS-ERD, an emulating RO-ERD desalination system is established whose flow diagram is shown in Fig. 5. In the figure, the main components for the system are incorporated, including the HP pump (Danfoss, PAH80), the booster pump (Sulzer, ZF50-3315), and the supply pump (Grundfos, CR32-3-2), except the RO membranes. Instead, the pressure differential of the RO membranes is simulated by a shut-off valve and is controlled below the hydraulic head of the booster pump (2.5 bar). A PLC controller with manual and automatic operating modes is configured to achieve the integral control of the system. To startup the system, the RS-ERD, the supply pump, and the booster pump should be launched in order. When the system reaches the steady stage, the HP pump should be brought into operation accompanying the adjusting of operating pressure through the bypass valve.

Tap water is selected as the testing medium for convenience, and the words “seawater” and “brine” are used in this article just for easy description. Flow meters and pressure gauges with a precision of ±0.5% are also installed in the main pipelines of the RS-ERD. The monitoring data is displayed and saved in real time through the acquisition software (see Fig. 6).

3. Performance tests of the RS-ERD

3.1. Pressure characteristics of the cylinder seawater end

In order to investigate the pressure characteristics in cylinders, two pressure gauges are set on the cylinder seawater ends and the corresponding pressure curves are shown in Fig. 7. There are two rectangular waves corresponding to the pressure variations in the two cylinders, respectively. The upper section of the wave represents the instant pressure of the pressurization process, the lower section referring to the depressurization process. It can be seen from the figure that the pressure curves for the

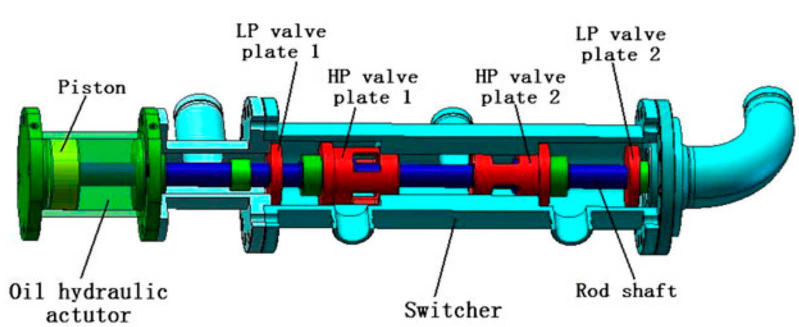

Fig. 4. Structure diagram of the RS.

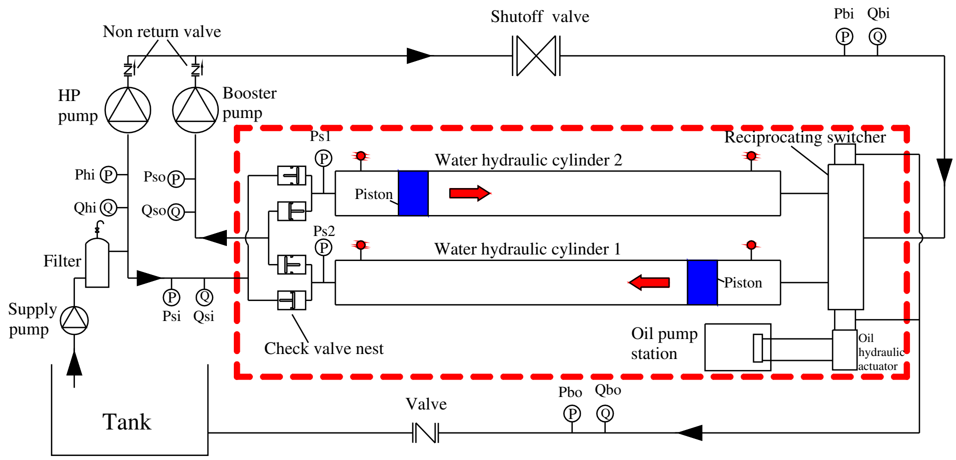

Fig. 5. The flow diagram of RS-ERD test stand.

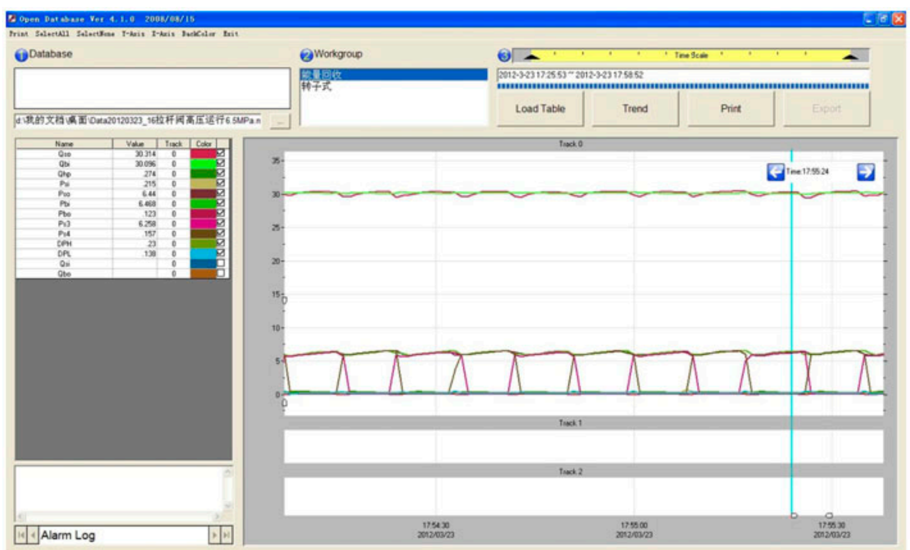

Fig. 6. The data acquisition system of RS-ERD.

upper section and the lower section are almost parallel to the x-coordinate, indicating that the pressurization process and depressurization process maintain stable during the tests.

Also, there exists overlap in the upper section of pressure curves, meaning that the pressurization process is underway simultaneously in two cylinders. The overlapping phenomenon arises from the unique structure of the RS and it is very useful for ensuring the continuities of the HP brine stream, and thus the pressurized seawater stream. Besides, it can be found from the figure that the plateau pressure of the pressurized seawater stream is slightly lower than that of HP brine stream(6.5 MPa), but is quite higher than that of the raw seawater, indicating that the pressure energy of the HP brine has been efficiently transferred to the raw seawater.

3.2. Characteristics of the seawater and brine flows

The RS-ERD device is incorporated into the RO desalination system by accepting the HP brine from the RO modules and pumping the pressurized seawater as HP feed to the RO modules. So the stability of HP streams in and out of the RS-ERD is of great importance for safe operation of the RO desalination system. Therefore, characteristics of the HP brine and

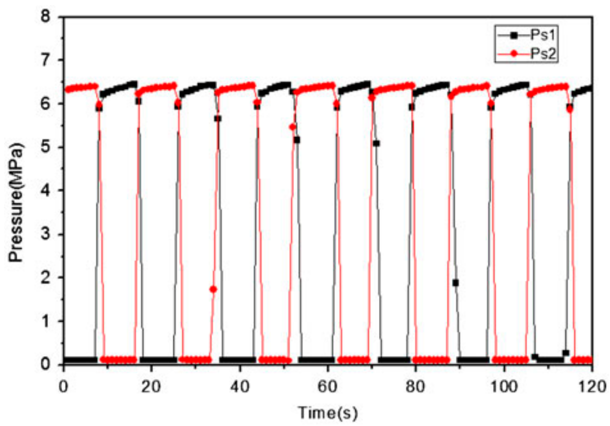

Fig. 7. The pressure curve of the hydraulic cylinder seawater end with time.

pressurized seawater are mainly described and discussed in this section.

Fig. 8 shows the flow and pressure curves of the HP brine. It can be seen that the flow curve of HP brine keeps steady (30 m^3/h) which benefits from the overlapping function of the RS described in the above section. However, the pressure curve of the HP brine presents downward fluctuations periodically, which corresponds to the occasion of the RS switch process. The fluctuations are caused by the sudden increase of another cylinder incorporated in the pressurization process, even though the flow curve of the brine stream remains continuous and the same. Although the downward fluctuation is transient and not as harmful as the upward fluctuation to the RO system, further efforts should be made to resolve the phenomenon.

The pressurized seawater is another HP stream related to the RS-ERD, which has a balanced flow with the HP brine stream. Fig. 9 presents the corresponding flow and pressure curves of the pressurized seawater. It indicates that the pressurized seawater flow remains mainly constant except for the transient downward fluctuations (about 1 m^3/h) during the switch process. Though the pressurized seawater is pumped directly by the HP brine and should have the same flow characteristic as the HP brine stream, the flow stability of the pressurized seawater is evidently influenced by the response time and pressure difference required by the check valve nest. Referring to the pressure characteristic of the pressurized seawater flow, the pressure curve is almost consistent with that of the HP brine (in Fig. 8), meaning that the influence of the check valve nest on the pressure is not obvious.

3.3. Evaluation of the internal leakage and the efficiency

For the RS-ERD, the internal leakage is an important parameter which reflects the sealing performance, and thus influences the energy recovery efficiency of the device. Internal leakage is actually the flow from the HP brine to the depressurized brine through the LP valve plates of the RS, which cannot be measured directly during the operation. According to the mass balance of the flow diagram in Fig. 5, Eqs. (1) and (2) can be obtained. By analyzing the equations, the internal leakage (Ql) theoretically equals the supplied flow into the system through the HP pump (Qhp) since the flows of Qsi and Qbi equal to the flows of Qso and Qbo respectively.

$$\mathrm{Qbi} = \mathrm{Qso} + \mathrm{Qhi} \tag{1}$$

$$\mathrm{Qbo} = \mathrm{Qsi} + \mathrm{Ql} \tag{2}$$

Fig. 10 illustrates the supplied flow curve of the HP pump at the RS-ERD capacity of 30 m^3/h and working

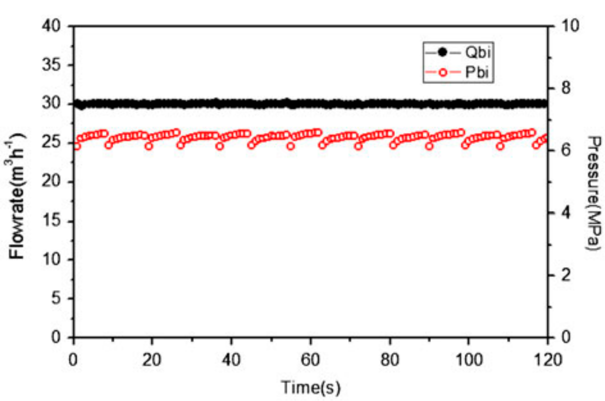

Fig. 8. The flow and pressure curve of the HP brine stream with time.

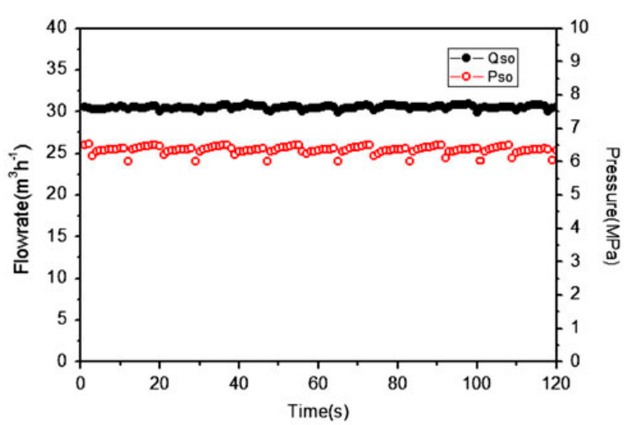

Fig. 9. The flow and pressure curve of the pressurized seawater stream with time.

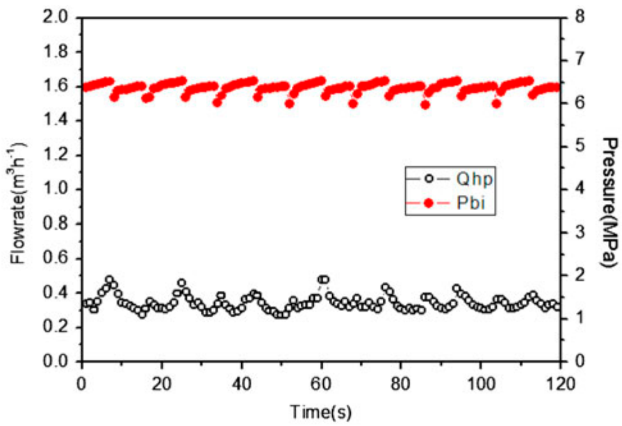

Fig. 10. The flow curve of HP pump with time.

pressure of 6.5 MPa. It indicates that the flow of HP pump presents upward fluctuations periodically and varies between 0.3 and 0.5 m^3/h. The obtained highest leakage of the RS-ERD is only about 0.5 m^3/h, namely the maximal leakage ratio (the ratio of the internal leakage to the capacity of the device) is less than 1.7%, which is superior to the practical level of the some commercial ERD products [16].

The advantages of the RS-ERD lie not only in its low internal leakage ratio, but also in its high-energy recovery efficiency. The efficiency of the RS-ERD is commonly defined as the ratio of the total energy exported from the RS-ERD to the total energy imported to the device, and can be expressed as [17]:

$$\eta = \frac{\mathrm{Qso} \cdot \mathrm{Pso} + \mathrm{Qbo} \cdot \mathrm{Pbo}}{\mathrm{Qsi} \cdot \mathrm{Psi} + \mathrm{Qbi} \cdot \mathrm{Pbi}} \quad (3)$$

Based on the experimental data of the RS-ERD in its steady operation, the average efficiency is calculated to be above 98% by Eq. (3). The high efficiency benefits mainly from both the isobaric principle and the minor leakage rate mentioned above.

4. Conclusions

An innovative isobaric type RS-ERD for SWRO desalination system is described and developed. As the core component of the RS-ERD, the unique structure of the RS owns advantages of excellent sealing effect, short actuator journey, and simple structure. Under the testing conditions of working capacity 30 m^3/h and operating pressure 6.5 MPa, outstanding performances of the RS-ERD are obtained, including its stable operating characteristics, minor leakage ratio of 1.7%, and high-energy recovery efficiency of 98%. Application of the RS-ERD in the desalination industries is promising.

Acknowledgments

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Abbreviations

Psi	—	pressure of the raw seawater, MPa
Pso	—	pressure of the pressurized seawater, MPa
Pbi	—	pressure of the high-pressure brine, MPa
Pbo	—	pressure of the depressurized brine, MPa
Ps1	—	pressure of the seawater in water hydraulic cylinder 1, MPa
Ps2	—	pressure of the seawater in water hydraulic cylinder 2, MPa
Qsi	—	flow rate of the raw seawater, m^3/h
Qso	—	flow rate of the pressurized seawater, m^3/h
Qbi	—	flow rate of the high-pressure brine, m^3/h
Qbo	—	flow rate of the depressurized brine, m^3/h
Ql	—	the internal leakage of RS, m^3/h
Qhi	—	the flow of HP pump, m^3/h
η	—	energy recovery efficiency, %

References

[1] Y.M. Kim, S.J. Kim, Y.S. Kim, S. Lee, I.S. Kim, J.H. Kim, Overview of systems engineering approaches for a large-scale seawater desalination plant with a reverse osmosis network, Desalination 238 (2009) 312–332.
[2] Y. Lu, A. Liao, Y. Hu, The design of reverse osmosis systems with multiple-feed and multiple-product, Desalination 307 (2012) 42–50.
[3] L. Malaeb, G.M. Ayoub, Reverse osmosis technology for water treatment: State of the art review, Desalination 267 (2011) 1–8.
[4] S. Bross, W. Kochanowski, SWRO core hydraulic module—the right concept decides in terms of energy consumption and reliability part II. advanced pressure exchanger design, Desalination 165 (2004) 351–361.
[5] A. Subramani, M. Badruzzaman, J. Oppenheimer, J.G. Jacangelo, Energy minimization strategies and renewable energy utilization for desalination: A review, Water Res. 45 (2011) 1907–1920.
[6] S. Avlonitis, K. Kouroumbas, N. Vlachakis, Energy consumption and membrane replacement cost for seawater RO desalination plants, Desalination 157 (2003) 151–158.
[7] M. Hajeeh, A. Al-Othman, E. El-Sayed, S. Al-Fuliaj, On performance measures of reverse osmosis plants, Desalination 144 (2002) 335–340.
[8] S. Avlonitis, Operational water cost and productivity improvements for small-size RO desalination plants, Desalination 142 (2002) 295–304.

[9] X. Wang, Y. Wang, J. Wang, S. Xu, Y. Wang, S. Wang, Comparative study on stand-alone and parallel operating schemes of energy recovery device for SWRO system, Desalination 254 (2010) 170–174.
[10] B. Peñate, L. García-Rodríguez, Energy optimisation of existing SWRO (seawater reverse osmosis) plants with ERT (energy recovery turbines): Technical and thermoeconomic assessment, Energy 36 (2011) 613–626.
[11] R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices, Desalination 203 (2007) 168–175.
[12] O.M. Al-Hawaj, The design aspects of rotary work exchanger for SWRO, Desalin. Water Treat. 8 (2009) 131–138.
[13] B. Schneider, Selection, operation and control of a work exchanger energy recovery system based on the Singapore project, Desalination 184 (2005) 197–210.
[14] J. Sun, Y. Wang, S. Xu, S. Wang, Energy recovery device with a fluid switcher for seawater reverse osmosis system, Chinese J. Chem. Eng. 16 (2008) 329–332.
[15] Z. Wang, Y. Wang, Y. Zhang, B. Qi, S. Xu, S. Wang, Pilot tests of fluid-switcher energy recovery device for seawater reverse osmosis desalination system, Desalin. Water Treat. 48 (2012) 310–314.
[16] R.L. Stover, B. Andrews, Isobaric Energy Recovery Devices—Past, Present and Future, IDAWC/PER11-103. IDA World Congress, Perth, Western Australia, September 4–9, 2011.
[17] S. Bross, W. Kochanowski, SWRO core hydraulic system: Extension of the SalTec DT to higher flows and lower energy consumption, Desalination 203 (2007) 160–167.