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Principle, structure and optimization of piston type energy recovery device: a comprehensive review by designer

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ABSTRACT

With the continuous development and the diversified applications of membrane desalination technology, goals such as lower energy consumption, higher efficiency, more flexible parallel combination forms and miniaturization have been presented for the piston type energy recovery device (ERD). To reach the above goals, this article will analyze the optimization direction of piston type ERD from the perspective of design and application. First, it is to study the function of the reduced drive energy consumption on improving the energy recovery ratio; second, it is to introduce the function of optimized signal control mode and time control mode on the ERDs' operational stability and flexibility and to analyze the optimal parallel combination form of double-cylinder and single-cylinder piston type ERDs; finally, it is to evaluate the feasibility of the miniaturization design about piston type ERD and to introduce the operating characteristics of miniaturized piston type ERD coupled in seawater desalination system.

Keywords: Energy recovery device; Energy recovery ratio; Parallel form; Miniaturization design

1. Introduction

In a seawater desalination project, energy recovery device (ERD) can reduce the energy consumption of high pressure (HP) pump and water production cost of system greatly by recycling the pressure energy of HP brine; therefore, it is listed as the first three key technologies with HP pump and the membrane module [1–3]. ERD adopted positive displacement principle can realize pressure energy conversion process by one step, thereby, its energy recovery efficiency is as high as 95% and it is widely used [4–6]. Positive displacement ERD can be divided into isobaric one and differential ones, and the isobaric ones is wildly applied including the piston type and rotary type. This paper focuses on the piston type ERD which has been widely used in large scale RO desalination projects [7,8], due to its exceptional efficiency, operational flexibility and high availability [9–11].

Typical product of the piston type ERD is the dual work exchanger energy recovery (DWEER) [12,13]. The features of DWEER are that each switcher corresponds to the two hydraulic cylinders, pressurization process and depressurization process are alternated in two hydraulic cylinders, and the maximum capacity of single device is 500 m^3/h [14,15]. Good reliability is one prominent feature of piston type ERD. The latest target for such device is to further improve energy recovery ratio, thus to reduce the water production cost of the system [16,17]. Therefore, the first task of this article is to explore the method of improving the energy recovery ratio from the perspective of the designer on the basis of introducing working principle and structural characteristics of piston type ERD briefly.

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Piston type ERD meets the capacity of seawater desalination project by parallel combination. The corresponding programmable logic controller (PLC) system plays an important role in maintaining the continuity of energy recovery process, and it commonly includes signal control mode and time control mode [18]. The important operational indexes of piston type ERD under parallel condition are the stability and flexibility; however the above two control modes are difficult to ensure these two indexes at the same time, so the control modes should be optimized. The latest development of piston type ERD is to make each switcher connect with one hydraulic cylinder and thus make the pressurization process and depressurization process relatively independent. The representative product using this connection way is the SalTecN [19].

This new connecting way is a good direction and worth researching since it changes the devices' parallel combination form and affects the number of hydraulic cylinders per capacity, the fluctuation of flowrate and pressure during the switch process, the operational flexibility, etc. [20]. Therefore, the second task of this article is to research the method for optimizing the control mode, to study the function of optimized control mode on improving the operational stability and flexibility and to explore the combination optimum form of double-cylinder ERD and single-cylinder ERD which is more stable, more space-saving and more flexible.

The technology of piston type ERD applied in the large desalination project is relatively mature and there are a lot of engineering applications and research reports. But less research and applications of piston type ERD in the compact seawater desalination system, such as the container type, have been reported. The compact seawater desalination system with relatively small capacity can be applied in the island, scenic spots, ships, etc., and its market demand is increasing. If this compact desalination system does not use ERD, its energy consumption per unit product water is up to 9 kW/m^3. Due to the advantages of the fine operational flexibility, piston type ERD is very suitable for the above conditions. So the third task of this article is to evaluate the feasibility of piston type ERDs' miniaturization design and to introduce the characteristics of miniaturized piston type ERD coupled in the compact seawater desalination system.

2. Principle and advantage of piston type ERD

The piston type ERD mainly consists of three parts: a switcher, hydraulic cylinders and check valve nests as shown in Fig. 1. One switcher connecting with two hydraulic cylinders is called double-cylinder ERD, and one switcher connecting with one hydraulic cylinder is called single-cylinder ERD. The ERD in Fig. 1 belongs to the double-cylinder type. The switcher is the core component of the device, whose function is to guide the HP brine and the depressurized brine to flow in and out of the hydraulic cylinders periodically. The hydraulic cylinder is the place for the energy recovery process. The check valve nest comprised of several parallel check valves directs the low pressure (LP) seawater and pressurized seawater to flow in and out of the cylinders, respectively [21–23]. A booster pump is needed to raise the seawater pressure out of ERD to the membrane pressure requirement. This pump is an important component in the ERD systems.

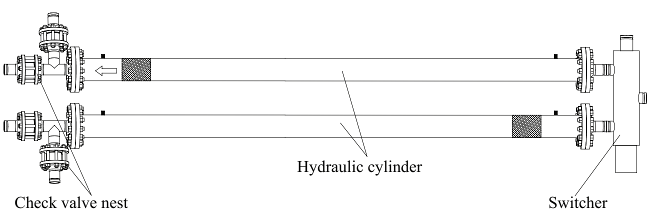

Fig. 1. Double-cylinder piston type ERD with different working strokes.

The switcher has two working strokes, the forward stroke and backward stroke, corresponding to the pressurization process of hydraulic cylinder or the depressurization process. During the end of the pressurization process and depressurization process, PLC control system will send order to the drive device of the switcher for completing the switch of working strokes and entering the next pressurization process or depressurization process. The pressurization process or depressurization process can be carried out continuously through the circulation of the above process. However, in order to realize the continuity of energy recovery process, both the pressurization process and depressurization process should be carried out continuously, so at least two hydraulic cylinders are needed and either the double-cylinder ERD or the single-cylinder ERD (as shown in Fig. 2) is feasible.

The movements of switcher are associated with the pressurization process and depressurization process controlled by the PLC, and the PLC control mode includes signal control mode and time control mode [20]. The signal control mode judges the progress of pressurization process and depressurization process by monitoring the position information of piston in the hydraulic cylinder through magnetic sensors. The pressurization process and depressurization process will be determined completed when the piston passes the magnetic sensor fixed at the end of hydraulic cylinder. For double-cylinder ERD, the movement order can depend on the signal either from the single piston or two pistons. The switch time set in the time control mode is usually a fixed value based on the calculation and experimental data of pressurization process, depressurization process and switch process, namely the time interval between two adjacent switch processes is fixed.

The working principle determines that the piston type ERD has the following advantages. First, there is

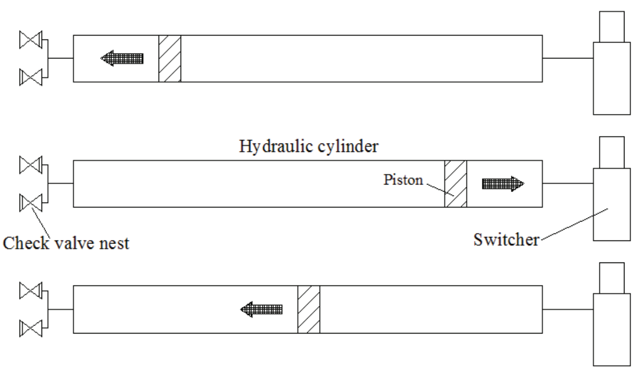

Fig. 2. Parallel combination of single-cylinder piston type ERD.

no high-speed rotating components inside ERD, so the ERD belongs to slow machinery – it has low precision requirements for processing and assembling, and owns exceptional reliability and service life. Second, the switch process is associated with the pressurization process and depressurization process through the control mode, especially the signal control model, so good operational flexibility is ensured and the phenomenon of overflow is avoided. The overflow refers to, respectively, the HP brine or LP seawater flowing out of cylinder. Third, the free piston in cylinder is used to prevent the salinity mixing between the brine and the seawater streams, avoiding the additional energy consumption due to the mixing.

But intermittent switch process of the piston type ERD also brings the following problems. First, the flow will be cut off temporally during the switch process, which will cause pressure increasing and water hammer phenomenon in pipeline, bring noise and vibration while affecting the operational stability. Second, in order to complete the switch process in a short time, the switcher should be started and stopped rapidly, so the drive power needed to actuate the switcher is relatively high which will affect the energy recovery ratio.

3. Structural characteristics and functions

Under the circumstance of meeting above working principles, the structural characteristics of each component, especially the switcher, have important influence on operational performance of piston type ERD. In order to extend the advantages and to solve the problems brought by the intermittent switch, designers and engineers have proposed many innovative structures. Several typical structures will be introduced in the following sections.

3.1. Structural characteristics and functions of switcher

As the core component of piston type ERD, the switcher is the unique active component to ensure the continuity of energy recovery process, so its structural characteristics and functions play an important role in improving the operational performance.

3.1.1. Fluid overlapping

Fluid overlapping can be divided into HP overlapping and LP overlapping as shown in Fig. 3 and the HP overlapping will be introduced by the following example [18]. The switcher with HP overlapping structure owns the following function: during the switch process, the pressurization process in one hydraulic cylinder has not completed, but the depressurization process in the other hydraulic cylinder has switched into the pressurization process; namely the pressurization process is switched continuously during the switch process, so the HP fluid can maintain continuous flow and thus avoid or reduce pressure and flow fluctuation. The function of LP overlapping is to maintain the continuous flow of LP fluid during the switch process and avoid or reduce pressure and flow fluctuation of LP fluid. But a single set of device cannot realize the HP overlapping and LP overlapping simultaneously, namely a flow spike and a flow deficit are hardly avoided at the same time. The HP fluid connects

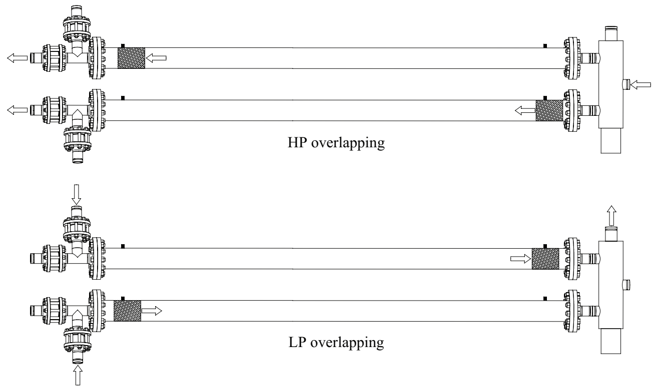

Fig. 3. Working principle of HP overlapping and LP overlapping.

with the membrane module directly whose operational performance is more important, so the HP overlapping is commonly used in the switcher.

3.1.2. Performance optimization of LP fluid

Due to the fact that LP overlapping is hardly used, the pressure increasing in the pipeline of LP seawater and water hammer in the pipeline of depressurized brine caused by the switch process can be resolved by the following solutions:

- To install a pressure valve on the pipeline of LP seawater; its effect is to discharge the additional fluid when the pressure in the pipeline exceeds the set value; this way is simple and costs less, but it will waste a part of the LP fluid.
- To install a buffer tank on the pipeline of LP seawater; its effect is to store the additional fluid temporally and direct the fluid into the pipeline again after the switch.
- The water hammer phenomenon is caused by the vacuum area because of fluid inertia during the cutoff of depressurized brine. The vacuum area results in the fluid flowing backward and hitting pipeline, producing noise and vibration. The solution is to compensate some fluid into the pipeline, avoiding the formation of vacuum or reducing the vacuum degree. Therefore, the liquid discharged from the pressure valve of LP seawater can be directed for the pipeline of depressurized brine, and the air can also be used.

3.1.3. Seal form

There are motive seal form and static seal form inside the switcher. The motive seal form plays a leading role during the switch process and the static seal form plays a leading role during the pressurization process and depressurization process. In different types of ERDs, the seal forms are not identical and the contact seal and medium seal are commonly used, since the static seal form works in most of the time and the switcher does not rotate in high speed, so its sealing effect is good and requirements on water quality are relatively low [19]. What's more, with the development and application of new seal technology, the energy recovery efficiency (>98%) and leakage rate (close to zero) of piston type ERDs are approaching the limit [18].

3.2. Structural characteristics of hydraulic cylinder

The hydraulic cylinder is the place for the energy exchange and accounts for the biggest volume in the device. When the capacity is constant, the size of cylinder is related to the switch frequency. The length of hydraulic cylinder is inversely proportional to the switch frequency, the higher the switch frequency, the smaller the length of hydraulic cylinder. This is consistent with the principle of rotary type ERD realizing the dramatic reduction of channels' length through high frequency rotation. But for piston type ERD, the switch frequency not only affects the stability of pressure exchanging process and the maintenance period of the switcher and check valve but also increases the external energy consumption for driving the switcher, such as electrical actuator or hydraulic pumps. So its switch frequency is relatively low, usually at around 6–10 times per minute. In order to further reduce the length of hydraulic cylinder, its diameter can be increased obviously and is generally several times of the pipe.

Due to the reciprocating motion of piston inside the hydraulic cylinder, the requirement of cylindricity and roughness for the cylinder is high, so the hydraulic cylinder made of metal material confronts the following problems: high manufacturing cost, heavy weight and time-consuming installation process. In order to reduce the manufacturing requirements of hydraulic cylinder due to the existence of the piston, the mixture section of seawater and brine can be regarded as the liquid piston, but the progress of energy recovery process cannot be detected by the magnetic signal. The pressure vessels made of fiber reinforced plastic (FRP), namely membrane shell, owns good cylindricity and roughness determined by its molding process which meets the reciprocating motion requirements of piston. What's more, the FRP pressure vessel also owns the following advantages: low cost, light weight, standard interface type and convenient installation process, which resolve the problems of metal hydraulic cylinder well, so the FRP pressure vessel is a good way to substitute the metal hydraulic cylinder and has been applied in the desalination project [19,24].

Based on the above structural characteristics, a single set of piston type ERD can reach large capacity from aspects of device size and basic operating performance. So the processing load of membrane stack, even the largest one, in the desalination project can be reached through 3–5 sets of piston type ERDs in parallel. From the aspects of structure and principle, the miniaturization design of piston type ERD is also feasible, but it need to be analyzed and tested in detail.

4. Relationship between drive power and efficiency

According to the introduction in section 3.1, the energy recovery efficiency η of piston type ERD has nearly approached the highest level from the view point of energy exchanging and is hard to be improved continuously. In order to reduce water production cost, the feasible method is to explore the way of enhancing energy recovery ratio η1. Energy recovery rate recovery ratio refers to the ratio of energy flowing in and out of ERD, Eq. (1). Compared with the energy recovery efficiency, energy recovery rate recovery ratio can reflect the effect of ERDs' energy conversion better. To study the ERDs' energy recovery ratio, energy balance for the whole ERD should be researched considering the power consumption. The power consumption mainly refers to the drive power of the switcher. The relationship among the drive power, energy recovery efficiency and energy recovery rate recovery ratio will be analyzed through the energy calculation.

$$\eta 1 = (E_{out} - E_{consume})/E_{in} \quad (1)$$

For the piston type ERD, the drive power of switcher can be used to substitute the power consumption $E_{consume}$. The energy flowing into ERD E_{in} refers to the pressure energy of HP brine and LP seawater, and the energy flowing out of ERD E_{out} refers to the pressure energy of pressurized seawater and depressurized brine. The ratio of E_{out} and E_{in} is the energy recovery efficiency η. In order to facilitate calculation, the ratio of $E_{consume}$ and E_{in} can be expressed by n, Eq. (2). Take the above values into Eq. (1), achieving:

$$n = E_{consume}/E_{in} \quad (2)$$

$$\eta 1 = \eta - n \quad (3)$$

η is the energy recovery efficiency, %; η1 is the energy recovery ratio, %; n is the ratio of $E_{consume}$ and E_{in}, %; E_{in} is the energy flowing in ERD; E_{out} is the energy flowing out of ERD; $E_{consume}$ is the power consumption of ERD.

Through these equations, it can be obtained that the ratio n should be reduced in order to ensure the relative high energy recovery ratio in the case of constant energy recovery efficiency, namely the drive power of switcher should be reduced. In order to show the requirement of energy recovery efficiency and ratio n for reaching certain energy recovery ratio in a more visually appealing manner, three representative energy recovery ratio points will be analyzed, for example, according to above equations. As shown in Table 1, the energy recovery efficiency is fixed for the certain device under the ideal and real conditions, so the value range of ratio n should be limited in order to ensure the different level of energy recovery ratio. For example, in the ideal condition, the energy recovery efficiency is close to 100%, and the ratio n should be less than 2% in order to ensure the energy recovery ratio higher than 98%. However, in the real operating condition, the energy recovery efficiency basically will not be higher than 99%, and in order to make the energy recovery ratio higher than 98% in this condition, the ratio n should be less than 1% which is quite low.

The representative product of rotary type ERD adopts water driven mode and does not consume external drive energy, so its measured energy recovery efficiency is

Table 1
Relationship among n, η and η_1

n/%		η_1/%		
		90	95	98
η/%	100	10	5	2
	99	9	4	1

the energy recovery ratio which is as high as 98%. Given the lubricant liquid consumption and resistance loss, its ratio *n* is less than 1%, indicating that it is feasible to reduce the ratio *n* to 1%. The water driven mode refers that the ERD is driven by the HP liquid inside the ERD without external drive power.

According to the value range of ratio *n* and operating parameters of piston type ERD, the upper limit drive power *W* of the switcher can be calculated by Eq. (4). Taking the device with capacity of 50 m^3/h, pressure of 6.5 MPa, *n* of 1% as an example, the upper limit drive power is 0.9 kW. The obtained drive power is the average power and the upper limit drive power in other operating conditions where the pressure is the same, which is shown in Table 2. The switcher of piston type ERD commonly adopts reciprocating motion and the drive power of its external drive device is commonly higher than that of PX device, which can be summarized as the following three reasons:

(1) Due to the intermittent switch process, a large part of the drive power is wasted in the form of idle work.
(2) Considering the energy transfer process of external drive device, the mechanical efficiency is generally less than 80%.
(3) Certain drive power is used to overcome frictional resistance of contacting surface and pressure differential force.

$$W = nQP/(3.6) \tag{4}$$

W is the drive power of switcher; *n* is the ratio of $E_{consume}$ and E_{in}, %; *Q* is the flowrate of HP seawater; *P* is the pressure of HP seawater.

For instance, the external drive devices' power of a piston type reciprocating-switcher ERD with capacity of 30 m^3/h is 7 kW, so its ratio *n* exceeds 10% and energy recovery ratio is less than 90% according to the above analysis. However, after the application of water driven mode, its drive power and ratio *n* have reduced to 0.677 kW and 1.25%, respectively, and the energy recovery ratio has been raised to 95.75% [25]. This proves the importance of reducing the drive power on the improvement of the energy recovery ratio.

For the piston type ERD driven by external device, such as oil hydraulic actuator, it is hard to further reduce its drive power; what's more, under different operating conditions, the ratio *n* changes greatly due to the influence of mechanical efficiency, power of cooling device, etc. Especially for the small and medium-sized devices, the ratio *n* is relatively bigger and it is difficult to reach the value in Table 2, such as the 0.09 kW under capacity of 5 m^3/h. However, for the piston type ERD adopting water driven mode, the drive power is proportional to the capacity, since the drive device meets requirement as long as the force equilibrium is achieved structurally between the drive device and load device so it does not need any cooling device. Therefore, the ratio basically remains constant under different conditions for the water driven mode.

Table 2
Requirements of the drive power under different operating conditions

W (kW)		Flowrate (m^3/h)			
		5	30	50	500
n/%	1	0.09	0.54	0.9	9
	2	0.18	1.08	1.8	18

To sum up, the drive power affects the energy recovery ratio directly and should be reduced in order to ensure the relative higher energy recovery ratio and lower water production cost. And the water driven mode can reduce the drive power obviously and is an effective way to reduce the energy consumption and increase the energy recovery ratio.

5. Study of control mode and parallel combination

In seawater desalination project, the control mode and parallel combination form have prominent effect on the number of hydraulic cylinder per unit capacity, operational stability, operational flexibility and so on, but great difference exists in terms of the parallel combination form between the double-cylinder ERD and single-cylinder ERD. Therefore, the key point of this section is to study the control modes of piston type ERD and the parallel combination forms of double-cylinder ERD and single-cylinder ERD.

5.1. Signal control mode and time control mode

As mentioned in section 2, the two commonly used control modes of piston type ERD are signal control modes and time control mode. Signal control mode determines the switch process based on the actual progresses of pressurization process and depressurization process in the cylinder and thus it owns exceptional flexibility. The time control mode determines the switch process through the switch time, so the control process is simple, accurate and easy to realize the coordination of parallel devices.

Except realizing the increase of capacity, the other important function of parallel combination is to reduce the pressure and flow fluctuation problems caused by the intermittent switch. To achieve this function, the switch process of the parallel multiple devices should be completed in turn, so that the devices under pressurization process and depressurization process can share the flowrate of the device under switch process, avoiding the cutoff of flowrate and substantially reducing fluctuation of pressure and flowrate. However, if several devices carry out the switch process at the same time, the fluctuation of pressure and flowrate will get worse.

If the signal control mode is adopted, the time of pressurization process and depressurization process among parallel devices will have slight difference and change due to the influence of proto pipe flow distribution, switch speed, resistance and leakage. So even the switch process of parallel multiple devices is completed successively in the start-up phase, the phenomenon of several devices performing the switch process simultaneously will appear with the continuous operation and affect the operational stability. Therefore, the simple application of the signal control mode in the parallel multiple devices is unable to connect each set of devices for resolving the fluctuation problems and difficulty for the popularization and engineering application.

Due to the advantage of operational flexibility, the signal control mode should be optimized for the application in the parallel combination form. The parallel multiple devices should be connected and the optimized way is listed below:

(1) Add judgment magnetic sensors in front of the normal magnetic sensors, as shown in Fig. 4.
(2) The PLC control system will record the information of the piston passing through the judgment magnetic sensor. The signal control mode is carried out according to the previous principle if no other pistons passing through the judgment magnetic sensor when the recorded piston reaches the normal magnetic sensor.
(3) If there are other pistons passing through the judgment magnetic sensor when the recorded piston reaches the normal magnetic sensor, the PLC control system will direct the devices to perform the switch process at a certain time interval according to the sequence of passing through the judgment magnetic sensor and the time interval is slightly longer than the switch process.

This optimized signal control mode connects each device and resolves the problem of several devices performing the switch process simultaneously on the premise of remaining the advantage of operational flexibility.

Compared with the signal control mode, time control mode can make each device in parallel complete the switch process orderly according to the pre-written procedure strictly, so the problem of several devices performing the switch process simultaneously will not exist and the time control mode is more suitable for parallel operation basing on this point. However, the switch time of the time control mode is usually fixed and thus the operational flexibility is not good; what's more, the volume utilization rate of hydraulic cylinder is relative low, since the switch time is set short for avoiding the piston hitting the end of hydraulic cylinder and the phenomenon of overflow.

In order to improve the impact of this kind of unfavorable factors, the time control mode should be optimized through setting the switch time as variable value which connects with the capacity of the device. So the real-time flowrate will be transported into the PLC control system when the device is not operating under the rated conditions, and then the PLC will adjust the switch time basing on its relationship with the flowrate. Therefore, the operational flexibility and volume utilization rate of optimized time control mode can be improved significantly.

This suggests that both the two control modes can be applied in parallel combination of piston type ERDs and the more suitable control mode can be chosen depending on the operating conditions. Of course, the two control modes can also be contained in one PLC control system and be switched to the working state automatically according to the requirements, making the device own certain ability of emergency disposal.

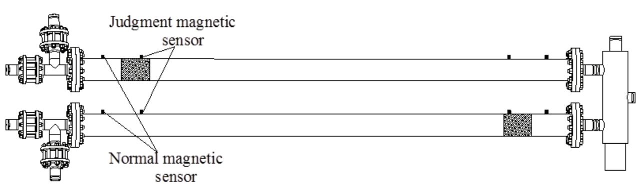

Fig. 4. Position of judgment magnetic sensor.

5.2. Parallel combination form of double-cylinder ERD

Single set of double-cylinder piston type ERD can realize the pressurization process and depressurization process at the same time and its parallel combination form is relatively simple. The number of parallel devices is generally more than or equal to the number of three sets, which is determined according to the ratio of total operating load and the capacity of single set device and then the import and export pipelines are linked together. The pressurization process and depressurization process of double-cylinder piston type ERD are switched simultaneously, and the energy recovery process is relatively independent of the parallel devices. Both the two control modes are suitable for this parallel combination form.

5.3. Parallel combination form of single-cylinder ERD

In addition to the simple and flexible installation process of parallel devices, the more important breakthrough of single-cylinder piston type ERD is that the connection type gets rid off the restriction of one pressurization process and depressurization process forming one recycle, so that the parallel combination form of a single-cylinder ERD is more flexible.

The parallel flexibility of single-cylinder piston type ERD is reflected by the fact that the number of parallel hydraulic cylinders can be either odd number or even number and the number of hydraulic cylinders for pressurization process is not consistent with that for depressurization process. Taking the seven parallel hydraulic cylinders, for example, the number of hydraulic cylinders for pressurization process and depressurization process can be four to three, or three to four. Under this parallel combination form, the capacity equals that of three to four sets of double-cylinder ERDs, so this form can save one hydraulic cylinder under its maximum capacity compared with the double-cylinder ERD. The number of hydraulic cylinders for pressurization process and depressurization process can also be three to three, and the rest hydraulic cylinder is under waiting state to better resolve the flow and pressure fluctuation during the switch process; or the rest hydraulic cylinders are in standby state for working under emergency or online maintenance condition. The parallel combination form of single-cylinder piston type ERD under other scales is similar with this form, and the time for HP discharge and LP discharge can be substantially different.

Since the parallel combination of single-cylinder piston type ERD is relatively strict with the time of pressurization process and depressurization process, so the time control mode is more applicable. From the above analysis, it can be shown that the parallel combination form of double-cylinder ERD is one kind of the parallel combination form of single-cylinder ERD; namely the number of parallel hydraulic cylinders is even number and the number of hydraulic cylinders for the pressurization process is equal to the number of hydraulic cylinders for the depressurization process. Above all, the parallel combination form of single-cylinder piston type ERD is one important direction for future research and application.

6. Miniaturization design and application of piston type ERD

In addition to the development of the large-scale desalination project, desalination system also has the following development trends and characteristics. First, the requirements for the small desalination system, especially the container type, are increasing. Second, with the development of membrane technology, the operating pressure is gradually reducing. Third, with the diversification of application field, especially in the seawater softening and brackish water desalination, the operating pressure is far less than that of seawater desalination and usually consistent with the working pressure of the nanofiltration membrane [26]. What's more, the pretreatment process of above desalination system is relatively simple and its flow fluctuation is relatively large with the change of external conditions. Due to the advantages of the fine operational flexibility, piston type ERD is very suitable for the above conditions. However, the related researches and reports are much less, so the study about miniaturization design and application of piston type ERD is necessary and the miniaturization design and application of piston type ERD are necessary.

6.1. Feasibility analysis

First, from the perspective of design, there is almost no limit for the miniaturization design of piston type ERD and the capacity can be can be infinitely small in theory. The best proof is the Clark pump which is integrated with HP pump, ERD and booster pump and whose capacity is suitable for the system far smaller than that of container type. The Clark pump belongs to differential ERD and realizes the pressure increase gradually until to the membrane requirements. The structure and working principle of Clark pump are very similar to the piston type ERD. Second, the operation of piston type ERD is, basically, not affected by the operating pressure, so it can be better applied in the brackish water and nanofiltration desalination system. Finally, in addition to the slight change of pressure loss, the energy recovery efficiency is, basically, not affected by the miniaturization design or the operating pressure.

Due to the influence of capacity, control system and installation space, single set of piston type ERD is more suitable for the small desalination system than the parallel devices. Although single set of piston type ERD has certain pressure and flow fluctuation during the switch process, the fluctuation can be reduced to the range of the desalination allowance through implementing the structure and the plan proposed in section 3.1. Through adopting the signal control mode or the optimized time control mode, the operational flexibility leads the ERD to be able to adapt to the changes of pressure and flow in the desalination system. To sum up, the miniaturization design and application of the piston type ERD are feasible from the aspects of structure, operating condition and operational performance.

6.2. Characteristics of piston type ERD coupled in start-up process of small desalination system

The typical characteristics of small water desalination system is that the system will start and stop at any time according to the demand and at each start-up process the initial position of piston of piston type ERD is different, such as working strokes of the switcher, the position of piston in the hydraulic cylinder. The initial position of piston of piston type ERD should not affect the start-up process, namely the start-up process can be completed automatically and does not need manual adjustment. This not only greatly reduces the operating cost of ERD but also enables the ERD to own the function of the remote control. Automatic start-up process can be realized by optimizing the control system and the shutdown process can be realized in the same way. The optimized control system can also realize the function of dealing with the emergency condition to ensure the continuous operation and to achieve unattended state.

During the start-up process, the LP pump will be operated first to wash and fill the desalination system. Then the HP pump should be started to raise the operating pressure to rated value; of course, this rated pressure value can be realized by either one step or step by step using the frequency converter; the flow of the system equals to the flow of HP pump in this process. The piston type ERD and booster pump will be started finally to realize the energy recovery and increase the flowrate to the rated value, completing the start-up process. Since the flowrate of HP pump and water production rate of membrane module are fixed, the flowrate of desalination system will be automatically adjusted to the design value with the continuous operation of piston type ERD during the start-up process.

6.3. Self-pressurization

Making the ERD own the function of booster pump can not only save the investment cost of booster pump but also simplify the complex pipeline connection and reduce the footprint, so this way is very suitable for the small desalination system whose footprint is limited. Due to the structural characteristics, the piston type ERD cannot couple with the centrifugal pump or vane pump through sharing the same drive motor and the common way for realizing the self-pressurization is to adopt the principle of differential pressure. Of course, the piston type ERD can realize the energy recovery by means of flowrate increment through changing the area difference, namely the flowrate of pressurized seawater is larger than that of HP brine. The area difference can be realized by a piston with rod in the unilateral or separate cylinders with different diameter.

In addition, the structure and operation process of miniaturized piston type ERD are consistent with that of large-scale desalination project. And the advantages and detailed performance parameters need further research.

7. Conclusion

In this paper, the piston type ERD is researched and introduced from the perspective of design and application, it concludes that the current important way for improving the energy recovery rate recovery ratio is to reduce the drive consumption and the water driven mode can reduce the drive consumption significantly; the optimized signal control mode and time control mode enhance the operational stability and flexibility of the parallel devices and the single-cylinder piston type ERD owns more flexible parallel combination forms; the piston type ERD has the feasibility of miniaturization design and application from the perspective of structural design, operating condition and performance analysis. Thus, this article provides information about the optimization design of the piston type ERD.

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Symbols

ERD	—	Energy recovery device
PLC	—	Programmable logic controller
LP	—	Low pressure
HP	—	High pressure
η	—	Energy recovery efficiency, %
η1	—	Energy recovery ratio, %
n	—	Ratio of $E_{consume}$ and E_{in}, %
E_{in}	—	Energy flowing in ERD
E_{out}	—	Energy flowing out of ERD
$E_{consume}$	—	Power consumption of ERD

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