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Leakage and permeability characteristics of seawater with different concentrations at the distribution windows of variable motor pumps for seawater desalination

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ABSTRACT

The leakage and mutual permeability characteristics of seawater with different concentrations at the distribution windows of a variable motor pump for reverse osmosis seawater desalination were theoretically analyzed. The influence of different swash plate inclination angles, seawater outlet pressures, and piston numbers on the leakage and permeability characteristics at the distribution windows were simulated. By comparison with the theoretical analysis results, the correctness of the simulation model and results were verified. Research results showed that the leakage and permeability characteristics at the distribution windows on both sides weakened slightly with increasing swash plate angle and showed a more strongly decreasing trend with increasing piston number. The leakage characteristics of the seawater at the inner distribution windows were hardly affected by the seawater outlet pressure change, but they were enhanced as the seawater outlet pressure increased at the outer distribution windows. As the seawater outlet pressure increased, the permeability characteristics at the inner distribution windows gradually increased, while they gradually decreased at the outer distribution windows. The research results provide a reference for the integrated design of reverse osmosis seawater desalination systems and the study of the leakage and permeability characteristics at the distribution windows.

Keywords: Reverse osmosis; Seawater desalination; Variable motor pump; Axial piston pump; Leakage characteristics; Mutual permeability characteristics

1. Introduction

Seawater desalination has become an important way to solve the global freshwater crisis. Reverse osmosis seawater desalination technology has the advantages of a stable system structure, ease of operation and control, and high efficiency of water purification. It has gradually become an important direction and focus of research in the field of seawater desalination in various countries [1–4]. Reverse osmosis seawater desalination systems produce a large amount of high-pressure concentrated seawater and the pressure energy contained therein is wasted; this greatly reduces the energy utilization rate of the systems and leads to higher energy consumption and operating costs. Therefore, an energy recovery device has been proposed to recover the pressure energy by using high-pressure

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concentrated seawater to pressurize low-pressure seawater [5–7]. However, if leaks develop, then the mixing of seawater at two concentrations reduces the working efficiency of the reverse osmosis seawater desalination system. Moreover, the relatively large number of components in the system and multiple energy conversions and transfers during the working process severely limit the improvement of the theoretical limit efficiency of the system. The plunger structure in the swash plate axial plunger pump can be replaced with a piston structure; the chambers for seawater and concentrated seawater chamber can be constructed in the cylinder; and two pairs of distribution windows can be constructed to distribute two concentrations of seawater. That is, the integration of the reverse osmosis seawater desalination system and the recovery of the pressure energy from the high-pressure concentrated seawater be realized by changing only the structure of the swash plate plunger pump, that is, without adding other complicated structures or components. Therefore, the proposal of a new type of highly efficient and highly integrated reverse osmosis seawater desalination component based on a swash plate axial plunger pump, and the analysis of the leakage and mutual permeability characteristics of seawater with different concentrations inside it, are of great significance to research and engineering.

In general, a reverse osmosis seawater desalination system is composed of a motor, a high-pressure plunger pump, a booster pump, an energy recovery device and a reverse osmosis membrane assembly. Experts and scholars have focused their attention on research to improve the integration of the reverse osmosis seawater desalination system and reduce the leakage characteristics and mutual permeability characteristics of seawater with different concentrations in the energy recovery device. Liu et al. [8] designed a full-rotary valve-type energy recovery device that uses a motor to rotate the crankshaft and achieve pressurization and pressure relief to complete the energy recovery process. Martin and Stover [9] optimized the rotor channel structure of a rotary energy recovery device and proved through experiments that the improved structure is conducive to slowing the mutual permeability of concentrated seawater and raw seawater in the channel. Yang et al. [10] analyzed the effects of the rotation speed and fluid velocity in the rotary energy recovery device on the mixing degree and energy recovery efficiency of seawater with different concentrations; they obtained the working conditions that result in the liquid mixing degree ≤4% and energy recovery rate ≥98%. Xu et al. [11] studied the influence of rotor speed on the liquid mixing degree in the device and the relationship between volumetric efficiency and mixing degree through simulation and experimental methods. An empirical formula for predicting the liquid mixing degree is obtained, and the validity of the formula is verified through experiments. Xiao [12] researched a device that integrated a reverse osmosis seawater desalination and an energy recovery device by fusing a plunger booster pump and a pressure exchanger; he analyzed the mutual permeability characteristics and distribution characteristics of the liquid in the device. Cao et al. [13] analyzed the mixing degree and flow characteristics of the fluid in a reverse osmosis seawater desalination device by numerical simulation. The results showed that the mixing degree of the fluid was minimum when the oscillating Reynolds number was 178 under different operating conditions. Sun and Gao [14] analyzed the leakage and mixing characteristics of a dual-media dual-displacement axial piston pump. Zhou et al. [15] and Liu et al. [16] found that the mixing degree of different concentrations of seawaters in the device increased with decreasing rotational speed of the device and increasing processing capacity. Shumway [17] proposed reducing the leakage of liquid by establishing a fluid circuit between the end face and the channel and pressurizing the fluid to provide a sealing force. Macharg [18] improved the structure of the rotary energy recovery device, fused the pressure lift pump and the rotary energy recovery device, and used the same motor to operate the rotary pressure energy exchanger and the pressure lift pump. Jiang et al. [19] studied the formation process of the liquid column piston in the device by deriving a two-dimensional rotating model and obtained an empirical formula for the volumetric efficiency of the device. Wang et al. [20] used finite element simulations to analyze the influence of five energy recovery device structures on the mixing degree of different concentrations of seawater in the system. Harby et al. [21] increased the overall water recovery and energy efficiency by proposing a novel combined reverse osmosis and hybrid absorption desalination-cooling system. Méndez and Bicer [22] found that additional electricity can be generated by recovering brine energy to further improve the efficiency of desalination in an integrated reverse osmosis seawater desalination system based on solar chimneys and wind energy. Alrehaili et al. [23] increased the net water recovery of reverse osmosis by using natural thermal differentials between brine and co-located water sources. Godart [24] proposed a high-performance and robust ad hoc seawater desalination method through heat-driven direct reverse osmosis. Al-Hotmani et al. [25] proposed a hybrid system using multi-effect distillation hot vapor compression and reverse osmosis technology. The new design has the characteristics of a high recovery rate, low brine flow rate, high-quality water with salinity, and lower energy consumption. Alanezi et al. [26] studied the effect of an energy recovery device and feed flow rate on energy efficiency in the reverse osmosis process. Therefore, it is necessary to study the integration of the reverse osmosis desalination system and the leakage and mutual permeability characteristics of different concentrations of seawater in the reverse osmosis desalination system. The study of the leakage and mutual permeability characteristics of different concentrations of seawater in the system can effectively improve the volumetric efficiency of the pump and the efficiency of seawater desalination. Improving the integration of the reverse osmosis seawater desalination system is conducive to further improving the working efficiency of the system, which helps to reduce the consumption of electrical energy, thereby reducing the operating cost. At the same time, the integrated reverse osmosis desalination system can continuously and efficiently recover the pressure energy of the high-pressure concentrated seawater produced after desalination. The above research helps reverse osmosis desalination become an effective choice to meet the global demand for freshwater.

To improve the integration and work efficiency and reduce the energy consumption, operating costs, and installation space of the reverse osmosis desalination system, this paper proposes a new variable motor pump based on the swash plate axial piston pump for reverse osmosis desalination. The leakage characteristics and mutual permeability characteristics of two concentrations of seawater at the distribution windows of the new reverse osmosis seawater desalination variable motor pump are deeply studied and analyzed through the software Pumplinx. The research results provide a reference for the integrated design of the reverse osmosis seawater desalination system and the study of the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows.

2. Reverse osmosis seawater desalination variable motor pump

The principle of a traditional reverse osmosis seawater desalination system with an energy recovery device is shown in Fig. 1; the energy recovery device is a key component for the recovery of the pressure energy from high-pressure concentrated seawater. The energy consumption by high-pressure plunger pumps, energy recovery devices, and booster pumps are among the main factors affecting the cost of reverse osmosis seawater desalination systems, especially for small- and medium-sized seawater desalination application environments such as islands, ships, and offshore platforms that lack electricity. At the same time, the above three components in the reverse osmosis seawater desalination system are independent of one other, so there is a large energy transmission loss during the working process that seriously affects the working efficiency and operating cost of the system.

To adapt to increasingly complex application environments and actual operating conditions, integration, energy savings, and high efficiency have become important directions for the development of reverse osmosis seawater desalination systems. In this paper, based on the swash plate axial plunger pump, the plunger in the cylinder is replaced with a piston, and one plunger chamber is changed to two closed piston chambers. At the same time, two pairs of flow distribution windows are constructed on the port plate to complete the distribution process by the two closed piston chambers, thereby forming a double displacement, double medium swash plate axial piston pump. The entire cylinder of the piston pump is assembled in the motor rotor to construct a reverse osmosis seawater desalination variable motor pump. The motor pump integrates the motor, high-pressure plunger pump, booster pump and energy recovery device, as shown in Fig. 2. The principle of the reverse osmosis seawater desalination system with the integrated design is shown in Fig. 3.

Fig. 4 shows a model of the swash plate axial piston pump in the system shown in Fig. 2. During the working process, high-pressure concentrated seawater enters the piston chamber through the distribution window and assists the motor to drive the piston to retract, thereby pressurizing the low-pressure seawater into high-pressure seawater so that it flows out through the distribution window into the reverse osmosis membrane assembly to complete the desalination treatment. Thus far, the pressure energy of the high-pressure concentrated seawater is recovered.

Compared with other energy recovery devices, the variable motor pump for reverse osmosis desalination directly integrates the cylinder of the swash plate axial piston pump into the rotor of the motor. Changing the structure of the pump cylinder, plunger, and valve plate is the only way to recover the pressure energy of high-pressure concentrated seawater and effectively control the leakage of seawater of different concentrations. Therefore, the integration of the components in the reverse osmosis desalination system reduces the operating cost and occupied space and further improves the work efficiency of the system.

3. Theoretical analysis of leakage and mutual permeability characteristics

Leakage at the distribution pair of the swash plate axial piston pump is one of the main contributions to the pump leakage, which is directly related to the volumetric efficiency of the pump. The distribution pair model of the swash plate axial piston pump is shown in Fig. 5. The distribution pair contains two pairs of distribution windows for the distribution of concentrated seawater and seawater; two concentrations of seawater are connected by a layer of liquid film at this position. Fig. 5 shows that the distribution windows for high-pressure seawater and high-pressure concentrated seawater are on the same side of the port plate,

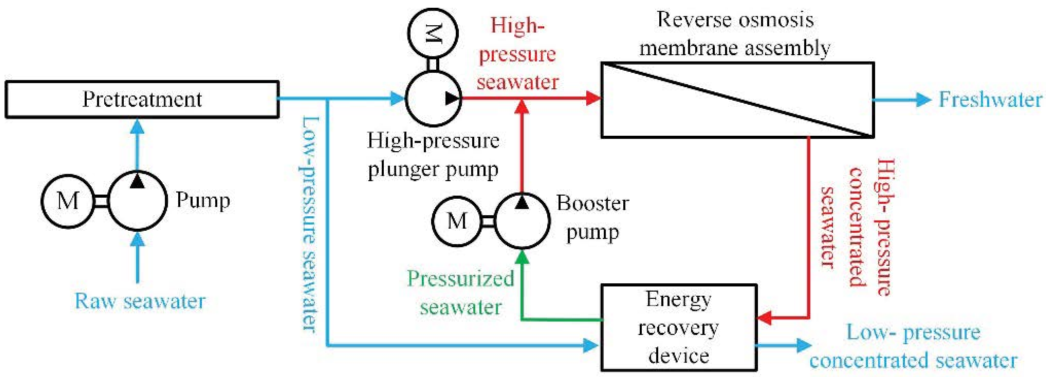

Fig. 1. Principles of a reverse osmosis seawater desalination system.

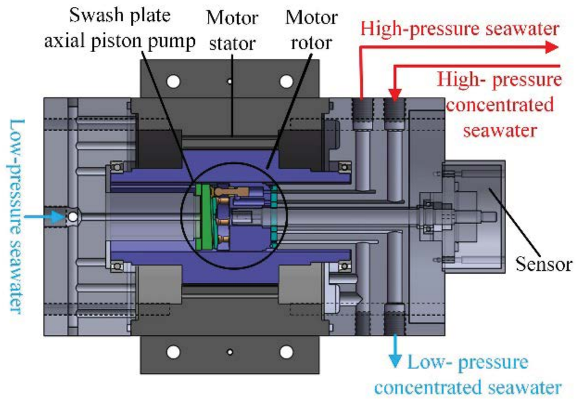

Fig. 2. Reverse osmosis seawater desalination variable motor pump.

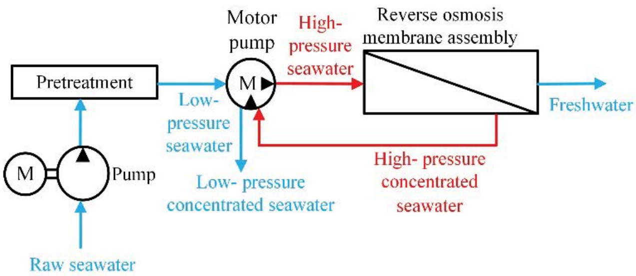

Fig. 3. Principles of the integrated system for reverse osmosis seawater desalination.

while the distribution windows for low-pressure seawater and low-pressure concentrated seawater are on the other side of the port plate. Because the angles of the distribution windows differ, the leakage characteristics and mutual permeability characteristics of seawater with different concentrations are very complicated in this design.

In this study of the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the piston pump, it is assumed that the cylinder in the pump does not tilt; that is, the liquid film thickness is uniform everywhere at the distribution pair. There is the radial flow of the liquid between two parallel circular plates at this position, and the pressure at any point is attenuated logarithmically. Based on the fluid flow theory for two parallel plates in fluid mechanics, the leakage outside the outer sealing tape shown in Fig. 5 mainly comes from the high-pressure seawater distribution window, and the amount of leakage is:

$$Q_o = \frac{\alpha_{se}\delta^3\Delta p_{se}}{12\mu_{se}\rho_{se}\ln\left(R_3/R_4\right)} \quad (1)$$

The leakage inside the inner sealing tape mainly comes from the high-pressure concentrated seawater distribution window, and the amount of leakage is:

$$Q_i = \frac{\alpha_{cs}\delta^3\Delta p_{cs}}{12\mu_{cs}\rho_{cs}\ln\left(R_2/R_1\right)} \quad (2)$$

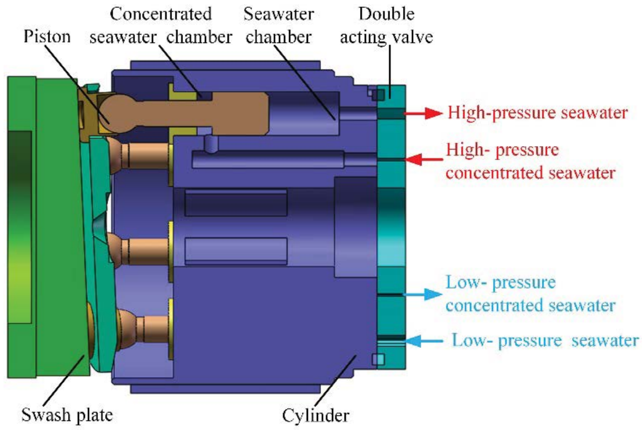

Fig. 4. Model of the swash plate axial piston pump.

where Q is the amount of leakage; α is the angle of the distribution windows; δ is the thickness of the liquid film; Δp is the pressure difference on both sides of the sealing tape; μ is the kinematic viscosity of the liquid; ρ is the liquid density; and R is the radius of the inner and outer sealing tape.

Eqs. (1) and (2) show that the amount of liquid leakage Q at the distribution pair is proportional to the pressure difference on both sides of the sealing tape Δp, the cube of the liquid film thickness δ, and the angle of the distribution windows α and is inversely proportional to the liquid kinematic viscosity μ and liquid density ρ. It is also related to the ratio of the inner and outer diameters of the sealing tape.

The concentration of seawater with different concentrations at the distribution windows shown in Fig. 5 after mutual permeability is:

$$C = \frac{V_{se}C_{se} + V_{cs}C_{cs}}{V_{se} + V_{cs}} \quad (3)$$

where C is the liquid mass concentration and V is the liquid volume.

Eq. (3) shows that the concentration of two different concentrations of seawater after mutual permeability is determined by the volume and concentration of each concentration of seawater before mixing.

4. Simulation of leakage and mutual permeability characteristics

Fig. 4 shows that there are two concentrations of seawater at the distribution pair of the swash plate axial piston pump. When the two concentrations of seawater leak at this position, they must be accompanied by different degrees of mutual permeability, which has a certain impact on the working efficiency and energy consumption of the seawater desalination system. Therefore, it is necessary to study and analyze the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the swash plate axial piston pump.

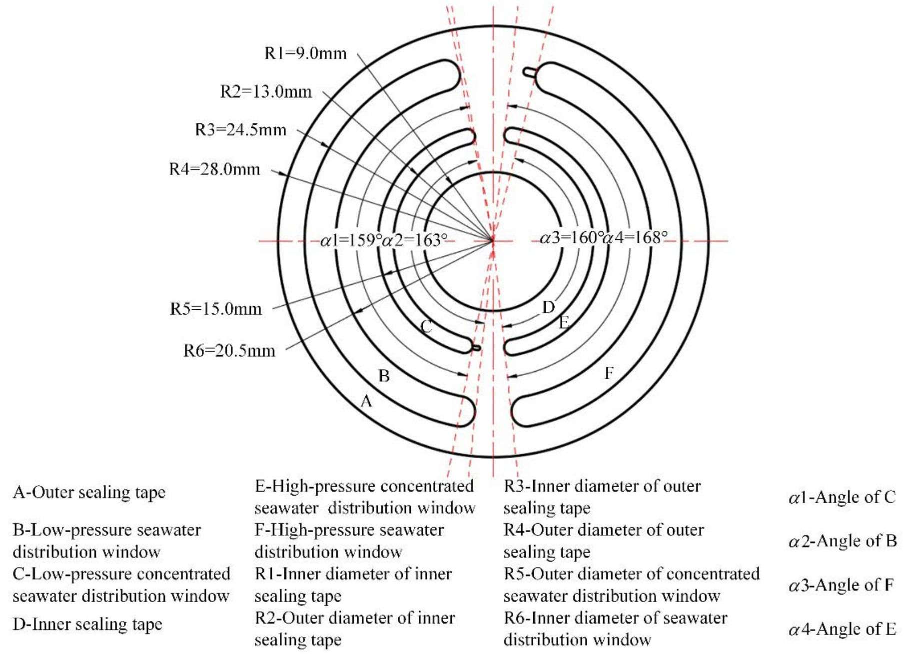

Fig. 5. Swash plate axial piston pump distribution pair model.

4.1. Geometric model

A flow field model constructed based on the above three-dimensional model of the swash plate axial piston pump is shown in Fig. 6. The red, blue, and green parts in the model represent the flow field models of concentrated seawater, seawater, and liquid film, respectively. According to the above analysis, when the structure of the port plate and the working medium of the motor pump are determined, then the pressure difference on both sides of the sealing tape and the thickness of the liquid film are the main factors that affect the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows.

Table 1 shows some initial structural parameters and operating parameters of the swash plate axial piston pump. According to the structure and operating conditions of the pump, the finite element simulation analysis software Pumplinx was used to study the effect of the swash plate inclination angle, the pressure of the seawater outlet, and the number of pistons on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the swash plate axial piston pump.

4.2. Meshing

In the simulation of the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the swash plate axial piston pump, dynamic mesh technology was used to simulate the volume changes of the seawater chambers and the concentrated seawater chambers. During the simulation process, the mesh was continuously updated with time [27]. A combination of structured and unstructured meshes was used to mesh the fluid domain. For each piston chamber whose volume changes, a structured mesh was used for mesh division, while the remainder was divided by a combination of structured and unstructured mesh. The entire meshing process was completed in Pumplinx. The liquid film model has also meshed with a structured mesh, which was conducive to more accurately simulating the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows. The final meshing result is shown in Fig. 7.

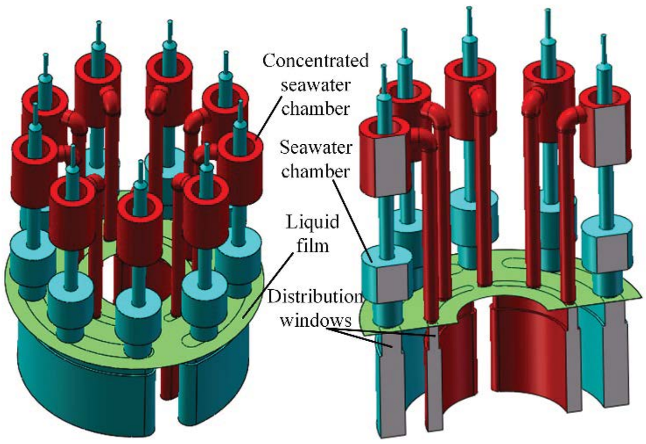

Fig. 6. Fluid domain model of swash plate axial piston pump.

4.3. Boundary conditions

The liquid film was connected to each piston chamber and the distribution windows through an interface,

Table 1
Initial structural parameters and operating parameters of the swash plate axial piston pump

Parameter type	Parameter name	Value
Structural parameters	Swash plate inclination angle (°)	15
	Number of pistons	9
	Liquid film thickness (μm)	6
Operating parameters	Cylinder rotation speed (r/min)	1,500
	Seawater concentration (g/mL)	0.2×10^{-2}
	Seawater chamber outlet pressure (MPa)	7.0
	Concentrated seawater concentration (g/mL)	0.6×10^{-2}
	Concentrated seawater inlet pressure (MPa)	6.7

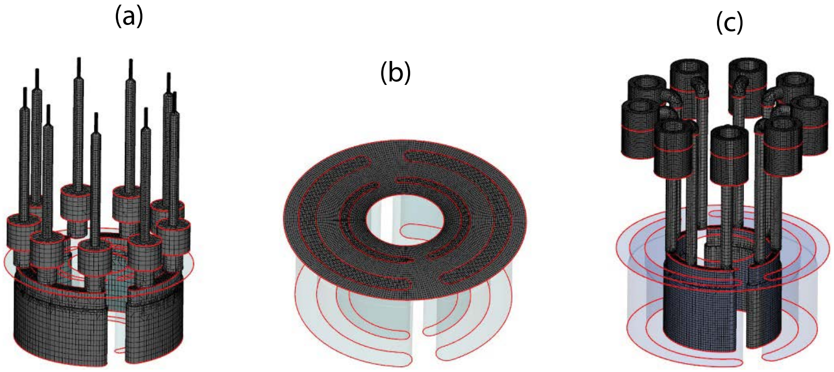

Fig. 7. Meshing results for the flow field: (a) seawater flow field, (b) liquid film flow field, and (c) concentrated seawater flow field.

and the boundary of each piston chamber was set to the boundary condition given by Pumplinx to complete the extension and retraction movements while rotating with the cylinder body. The inclination angle of the swash plate was determined by setting its normal vector. The boundary conditions of the seawater inlet and the concentrated seawater inlet were set as pressure inlets, and the pressures were 0 and 6.7 MPa, respectively. That is, the pressure of the seawater entering the motor pump was 0 MPa, and the pressure of the concentrated seawater generated from the reverse osmosis membrane assembly was 6.7 MPa. The boundary conditions of the seawater outlet and the concentrated seawater outlet were set as pressure outlets, and the pressures were 7.0 and 0 MPa, respectively. That is, the pressure of the concentrated seawater flowing out of the motor pump was 0 MPa, and the pressure of the seawater entering the reverse osmosis membrane assembly was 7.0 MPa. The pressure on the inner and outer sides of the liquid film formed at the valve plate was 0 MPa. Therefore, the inside and outside of the liquid film were set as pressure outlets, and the pressures were 7.0, 0, 0, and 0 MPa, respectively. The boundary conditions of the remaining surfaces were set as the wall. The leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the pump distribution windows were simulated after the models for turbulence, cavitation, and concentration were selected and the parameters, such as the concentration of different concentrations of seawater, cylinder rotation speed, and direction were set.

5. Results and analysis

To quantitatively analyze the influence of different parameters on the leakage characteristics and mutual permeability characteristics of different concentrations of seawater at the distribution windows, the leakage of different concentrations of seawater on the inside and outside of the liquid film during one revolution of the cylinder and the average concentration of fluid at each of the 32 points at the bottom of the distribution windows shown in Fig. 8 were monitored.

5.1. Swash plate inclination angle

The variable motor pump for reverse osmosis desalination was formed by organically fusing the principles of motor drives, axial piston pumps, energy recovery devices, and controls. The motor pump can adjust the flow by changing the motor speed (cylinder speed) or the swash plate inclination angle. The change in the swash plate inclination angle has a very complicated influence on the pressure and flow characteristics of the pump, which has a certain impact on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the pump. Therefore, it was necessary to conduct an in-depth study on the influence of different swash plate inclination angles on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations

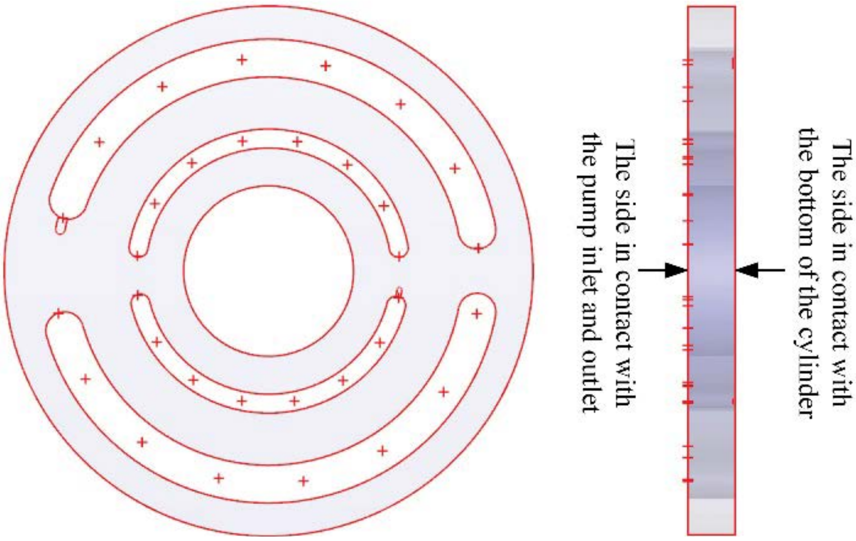

Fig. 8. Concentration monitoring points diagram.

at the distribution windows. Based on the initial parameters of the swash plate axial piston pump shown in Table 1, the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows at swash plate inclination angles of 13°, 14°, 15°, and 16° were studied. Figs. 9 and 10 show the characteristic curves for leakage and mutual permeability; they were obtained through Pumplinx simulation analysis.

Instantaneous leakage refers to the leakage of seawater with different concentrations on the inside and outside of the liquid film at a specific moment. Fig. 9 shows that during one revolution of the cylinder, there were nine periodic changes in the instantaneous leakage of seawater inside the inner sealing tape and outside the outer sealing tape because the swash plate axial piston pump contained nine pistons, and there were nine periodic pressure fluctuations during one revolution of the cylinder. The changing trend in the leakage characteristic curve in Fig. 9 can be explained by the above theoretical analysis, that is, the leakage of the liquid at the distribution windows of the pump is proportional to the pressure difference on both sides of the sealing tape. At the same time, the partially enlarged view in Fig. 9 shows a slight downward trend in the instantaneous leakage of seawater with different concentrations at the distribution windows with increasing inclination angle of the swash plate. As the inclination angle of the swash plate increases, the volume of each piston chamber increases, which increases the volume of seawater with different concentrations flowing into the chamber under the same working conditions and thereby reduces the pressure fluctuation range of seawater with different concentrations in each chamber.

The average leakage is the average value of the leakage of different concentrations of seawater on the inside and outside of the liquid film during one revolution of the cylinder. Fig. 9 shows that the average leakage of seawater with different concentrations at the distribution windows decreases as the inclination angle of the swash plate increases. The reason for this behavior is that as the inclination angle of the swash plate increases, the instantaneous leakage of seawater with different concentrations inside and outside the liquid film decreases overall.

Mutual permeability characteristics correspond to the concentration changes that occur after the interpenetration of different concentrations of seawater at the distribution windows. The initial working medium of the variable motor pump for reverse osmosis desalination is seawater. Therefore, the analysis of the mutual permeability characteristics of seawater of different concentrations at the distribution windows assumed that there was only seawater at the liquid film in the initial state. For stable pump operation, the mutual permeability characteristics of seawater with different concentrations at the distribution windows on both sides under different swash plate inclination angles are shown in Fig. 10 where the positive direction of the Z-axis is the side of the low-pressure distribution window, and the negative direction of the Z-axis is the side of the high-pressure distribution window. The rotation direction of the cylinder is shown in the figure.

The mutual permeability characteristics of seawater with different concentrations at the outer distribution windows are shown in Fig. 10a. Since the distribution window on the low-pressure side was the inlet side of the low-pressure seawater, the seawater flowed through the liquid film through the distribution window; the seawater concentration on this side was basically unchanged. Fig. 8 shows that the angle of the high-pressure concentrated seawater distribution window was greater than that of the high-pressure seawater distribution window. Therefore, part of the concentrated seawater leaked to the high-pressure seawater distribution window near the end of the low-pressure and high-pressure conversion, which made the seawater concentration increase sharply here and the seawater concentration of the entire high-pressure seawater distribution window increase.

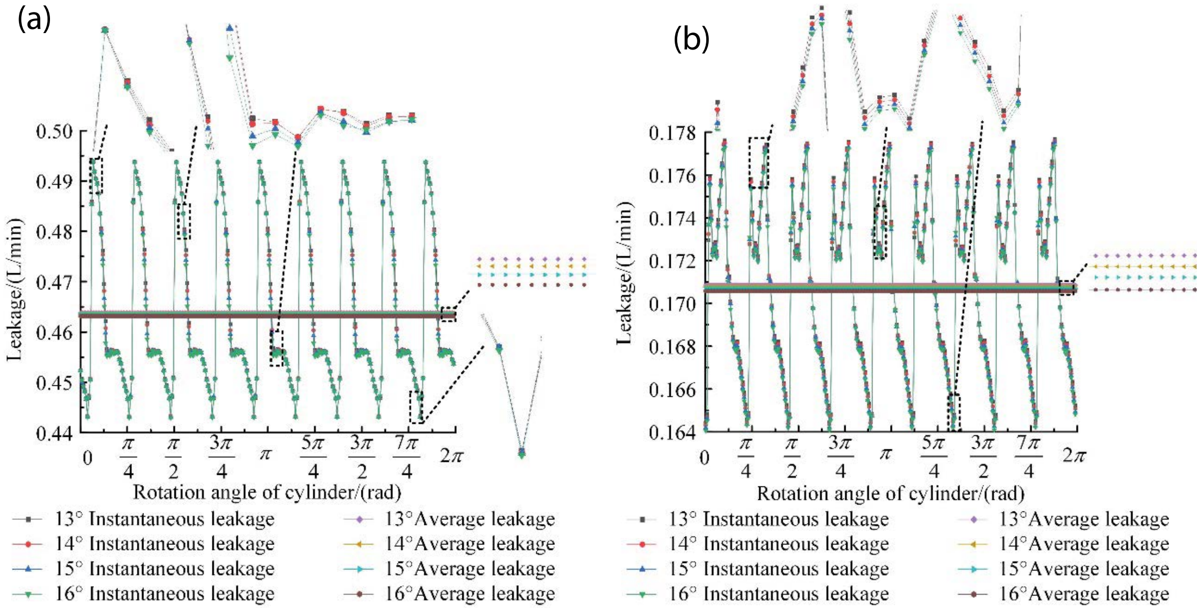

Fig. 9. (a and b) Leakage inside the inner sealing tape and outside the outer sealing tape at different swash plate inclination angles.

The mutual permeability characteristics of seawater with different concentrations at the inner distribution windows are shown in Fig. 10b. Since the distribution window on the high-pressure side was the inlet side of the high-pressure concentrated seawater and the concentrated seawater flowed through the liquid film through the distribution window, the concentration of the concentrated seawater on this side was basically unchanged. The low-pressure side distribution window was the outlet side of the concentrated seawater, and the concentrated seawater flowed through the distribution window and mixed with the seawater at the liquid film, resulting in a decrease in the seawater concentration at the low-pressure concentrated seawater distribution window shown in Fig. 10b.

Fig. 10 shows that as the inclination angle of the swash plate increased, the change in seawater concentration at both sides of the distribution windows of the pump showed a gradually decreasing trend. This is because as the inclination angle of the swash plate increased, the pressure fluctuations of the seawater with different concentrations at the distribution windows decreased, resulting in a decrease in the leakage of seawater with different concentrations inside and outside the liquid film. The liquid flow in the liquid film gradually slowed, and the volume of seawater flowing in the liquid film decreased as a result. According to the above theoretical analysis, the mutual permeability of the liquid at the distribution windows was determined by the volume and concentration of each seawater before mutual mixing occurred. Therefore, the decrease in the

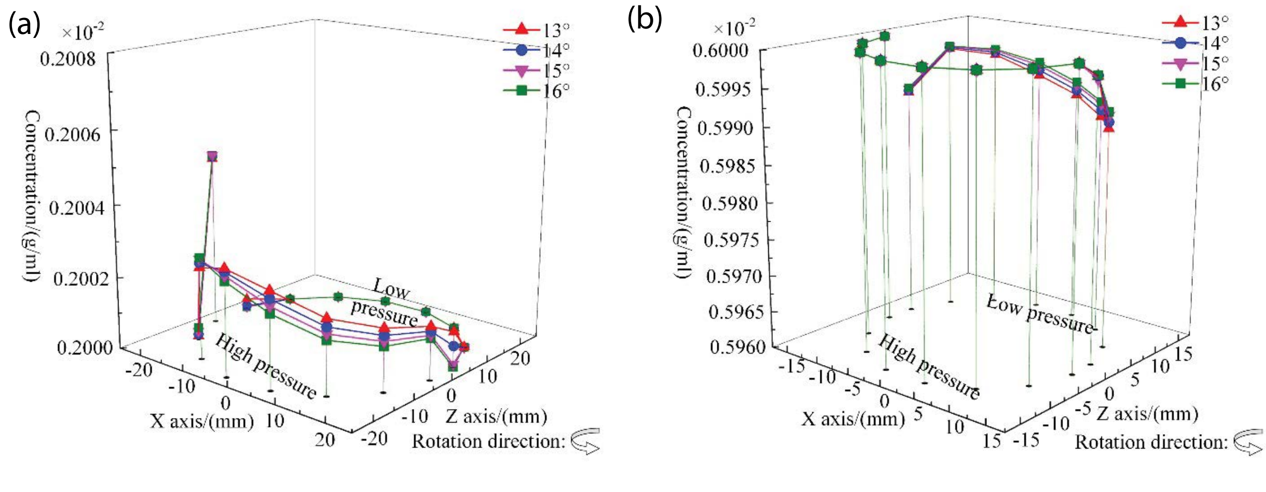

Fig. 10. Permeability characteristics of seawater with different concentrations at the distribution windows on both sides under different swash plate inclination angles: (a) outer and (b) inner distribution window.

volume of the liquid flowing in the liquid film leads to a decrease in the change in seawater concentration, which leads to a decrease in the mutual permeability of seawater with different concentrations at the distribution windows as the swash plate inclination angle increases. The decrease in permeability characteristics means that the mutual penetration between the seawater and the concentrated seawater is lessened, which helps to increase the pressure energy recovery efficiency of the high-pressure concentrated seawater, thereby improving the working efficiency of the reverse osmosis seawater motor pump and reducing its energy consumption.

5.2. Seawater outlet pressure

The variable motor pump for reverse osmosis seawater desalination transports high-pressure seawater to the reverse osmosis membrane assembly for desalination treatment. Part of the seawater passes through the reverse osmosis membrane assembly to become fresh water, while the rest is retained to form concentrated seawater. The seawater reverse osmosis rate of the membrane module gradually decreases during the working process, which causes the pressure on the seawater outlet of the pump to increase. Therefore, it is meaningful to study the influence of different seawater outlet pressures on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows. Based on the initial parameters of the swash plate axial piston pump shown in Table 1, the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows were studied at seawater outlet pressures of 6.9, 7.0, 7.1, and 7.2 MPa.

The leakage characteristic curves for different concentrations of seawater at the distribution windows obtained by Pumplinx analysis are shown in Fig. 11. Fig. 11 shows that the leakage characteristics inside the inner sealing tape and outside the outer sealing tape under the same seawater outlet pressure change with the same trend as those under the same swash plate inclination angle shown in Fig. 9. Fig. 11 shows that the change in seawater outlet pressure of the swash plate axial piston pump has almost no effect on the leakage inside the inner sealing tape. This is because the leakage of seawater inside the inner sealing tape was mainly determined by the pressure of concentrated seawater, and the pressure of seawater had almost no effect. However, the leakage of seawater outside the outer sealing tape increased significantly with increasing seawater outlet pressure, which was consistent with findings about the changing trend of seawater leakage at the liquid film reported in references [12] and [28].

The above research results are basically consistent with the results from the theoretical analysis of the liquid leakage at the distribution windows in section Theoretical analysis of leakage and mutual permeability characteristics. To make a further quantitative comparison with the results of the above theoretical analysis, the leakage characteristic curve shown in Fig. 11a was quantified to obtain the relationship between the average leakage of seawater outside the outer sealing tape and the seawater outlet pressure shown in Table 2.

Table 2 shows that the ratio of the average leakage of seawater outside the outer sealing tape to the corresponding seawater outlet pressure can be approximated by a fixed value, which is consistent with the relationship between the liquid leakage at the distribution pair and the pressure difference on both sides of the sealing tape in the theoretical analysis results of section Theoretical analysis of leakage and mutual permeability characteristics. This proves the correctness of the above analysis model and the results obtained.

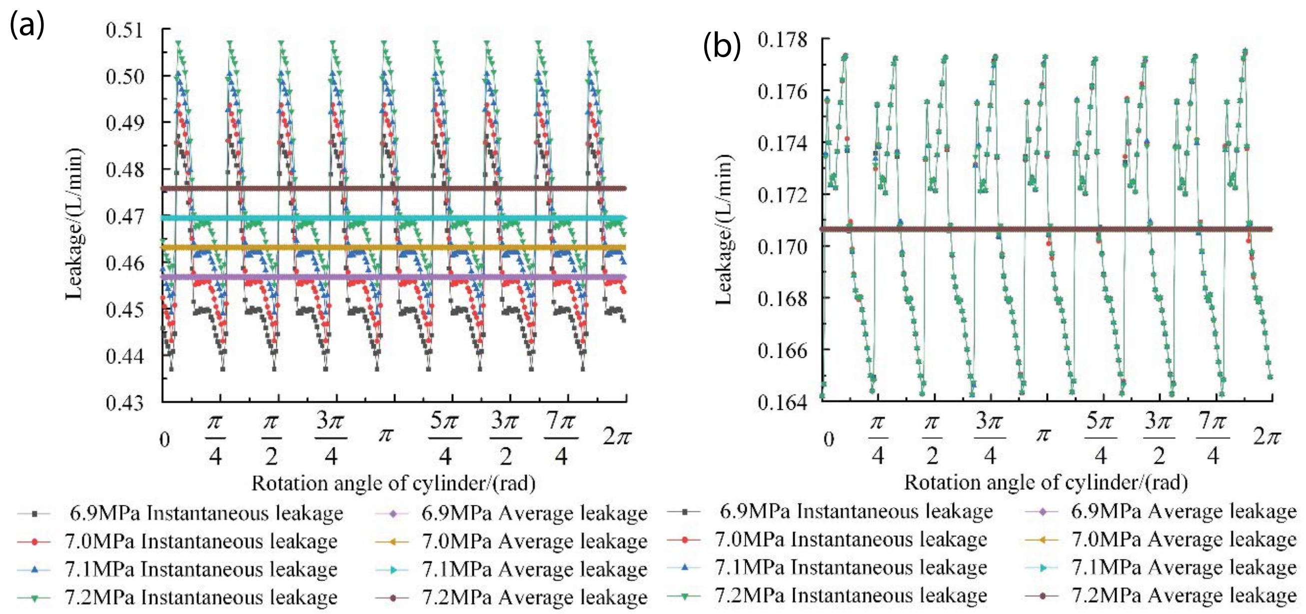

Fig. 11. (a and b) Leakage inside the inner sealing tape and outside the outer sealing tape at different seawater outlet pressures.

The characteristic curves of the mutual permeability of seawater with different concentrations at the distribution windows obtained through analysis are shown in Fig. 12. Fig. 12 shows that the mutual permeability characteristics of seawater with different concentrations at the distribution windows on both sides under the same seawater outlet pressure condition change with the same trends as those under the same swash plate inclination angle shown in Fig. 10. Fig. 12a shows that as the seawater outlet pressure increases, the mutual permeability characteristics of seawater with different concentrations in the outer distribution windows show a slight downward trend. This is because the increase in seawater outlet pressure reduces the leakage of concentrated seawater to the outer distribution windows, thereby reducing the volume of the concentrated seawater flowing to the outer distribution windows so that the change in seawater concentration at this location decreases. At the same time, Fig. 12b shows that as the seawater outlet pressure increases, the mutual permeability characteristics of seawater with different concentrations in the inner distribution windows are significantly enhanced. This is because with the increase in seawater outlet pressure, the pressure difference between the inner and outer distribution windows gradually increases, thereby enhancing the flow of liquid from the outer distribution windows to the inner distribution windows. The volume of seawater flowing to the inner distribution windows increases obviously, enhancing the mutual mixing of seawater and concentrated seawater at the inner distribution windows. Therefore, the mutual permeability characteristics of seawater with different concentrations at the inner distribution windows are enhanced.

5.3. Number of pistons

According to the traditional design theory of the swash plate axial piston pump, the influence of the number of plungers on the pressure fluctuations of the liquid at the distribution windows of the pump is complicated. Moreover, an odd number of plungers can effectively reduce the pressure and flow fluctuations of the pump, thereby ensuring the dynamic characteristics of the pump. To reveal the influence of the number of pistons on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the swash plate axial piston pump, the leakage characteristics, and mutual permeability characteristics of seawater with different concentrations at the distribution windows for 5, 7, and 9 pistons were studied on the basis of the initial parameters of the swash plate axial piston pump shown in Table 1. The characteristic curves of the leakage and mutual permeability obtained through Pumplinx analysis are shown in Figs. 13 and 14.

Table 2
Relationship between the average leakage and the seawater outlet pressure

Seawater chamber outlet pressure p (MPa)	Leakage outside the outer sealing tape Q_e (L/min)	Ratio Q_e/p
6.9	0.4568	0.066
7.0	0.4631	0.066
7.1	0.4695	0.066
7.2	0.4758	0.066

Fig. 13 shows that the leakage characteristics inside the inner sealing tape and outside the outer sealing tape under the same number of pistons change with the same trend as those under the same swash plate inclination angle shown in Fig. 9. Fig. 13 shows that during the process of one revolution of the cylinder, the number of fluctuation cycles of the instantaneous leakage of seawater with different concentrations inside the inner sealing tape and outside the outer sealing tape for different numbers of pistons is the same as the number of pistons, which is consistent with the number of fluctuation cycles of the instantaneous leakage at the distribution windows in the actual pump operation. Fig. 13a shows that for the swash plate axial piston pump, as the number of pistons increased, the peak value of the instantaneous leakage of seawater outside the outer sealing tape

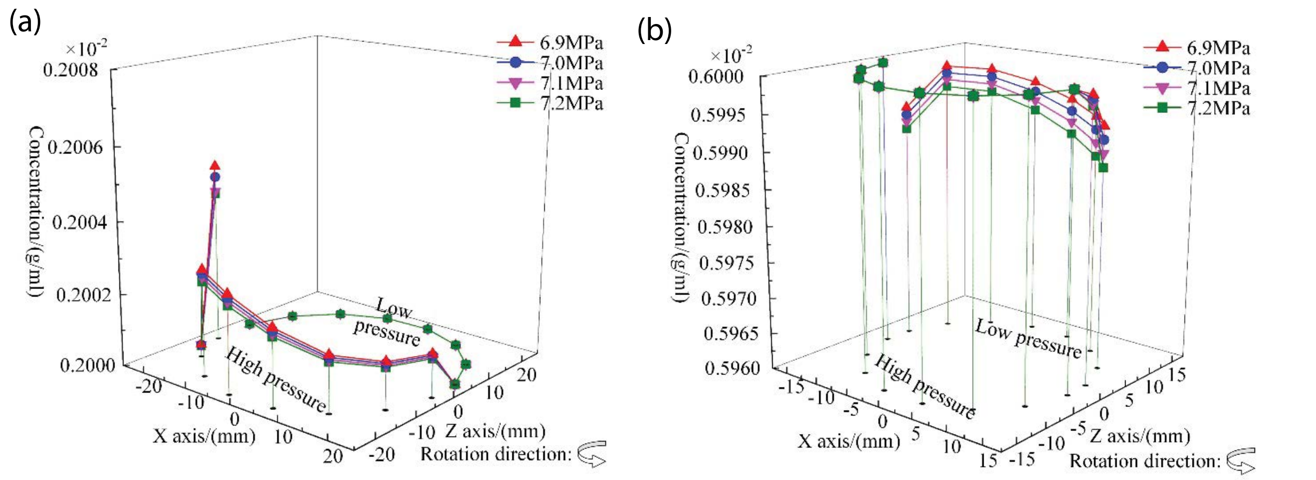

Fig. 12. Permeability characteristics of seawater with different concentrations at the distribution windows on both sides under different seawater outlet pressures: (a) outer and (b) inner distribution window.

first decreased and then increased, while the valley value showed a gradually decreasing trend. Additionally, the average leakage of seawater outside the outer sealing tape significantly declined as the number of pistons increased. At the same time, Fig. 13b shows that for the swash plate axial piston pump, the instantaneous leakage and the average leakage of seawater inside the inner sealing tape significantly decreased as the number of pistons increased.

The mutual permeability characteristic curves of different concentrations of seawater at the distribution windows on both sides under different numbers of pistons are shown in Fig. 14. Fig. 14 shows that the mutual permeability characteristics of seawater with different concentrations at the distribution windows on both sides for the same piston number followed the same trend as those under the same swash plate inclination angle shown in Fig. 10. Moreover, Fig. 14 shows that as the number of pistons increased, the mutual permeability characteristics of different concentrations of seawater at the distribution windows on both sides showed a significant downward trend. This is because as the number of pistons increased, the amount of seawater leakage inside the inner sealing tape and outside the outer sealing tape was significantly reduced, and the radial flow of seawater inside obviously slowed. The flow volume of seawater of different concentrations significantly reduced, which lessened the mutual mixing of seawater with different concentrations, that is, the mutual permeability characteristics of seawater with different concentrations became weaker.

6. Conclusions

This paper researched the swash plate axial piston pump in a new reverse osmosis seawater desalination variable motor pump. This paper analyzed the influence of different swash plate inclination angles, seawater outlet pressures, and the number of pistons on the leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows. Through this analysis, a relatively satisfactory research result was obtained, and the following conclusions were obtained:

- The leakage characteristics and mutual permeability characteristics of seawater with different concentrations at the distribution windows of the swash plate axial piston pump follow the same trends for change for the selected swash plate inclination angles, seawater side pressures, and number of pistons.
- With the increase in the swash plate inclination angle, the leakage of seawater with different concentrations at the distribution windows shows a downward trend, but the overall decrease range is smaller. As the swash plate inclination angle increases, the mutual permeability characteristics of seawater with different concentrations at the distribution windows on both sides gradually weaken.
- The change in seawater outlet pressure has almost no effect on the leakage of seawater inside the inner sealing tape, while the leakage of seawater outside the outer sealing tape increases significantly with increasing seawater outlet pressure. With the increase in seawater outlet pressure, the mutual permeability characteristics of seawater with different concentrations at the outer distribution windows show a slight weakening trend, and with the increase in seawater outlet pressure, the mutual permeability characteristics of seawater with different concentrations at the inner distribution windows are obviously enhanced.
- As the number of pistons increases, the average leakage of seawater with different concentrations at the distribution windows shows a downward trend. At the same time, as the number of pistons increases, the mutual permeability characteristics of seawater with different concentrations at the distribution windows on both sides gradually decrease.

To conduct a more comprehensive study on the leakage characteristics and mutual penetration characteristics

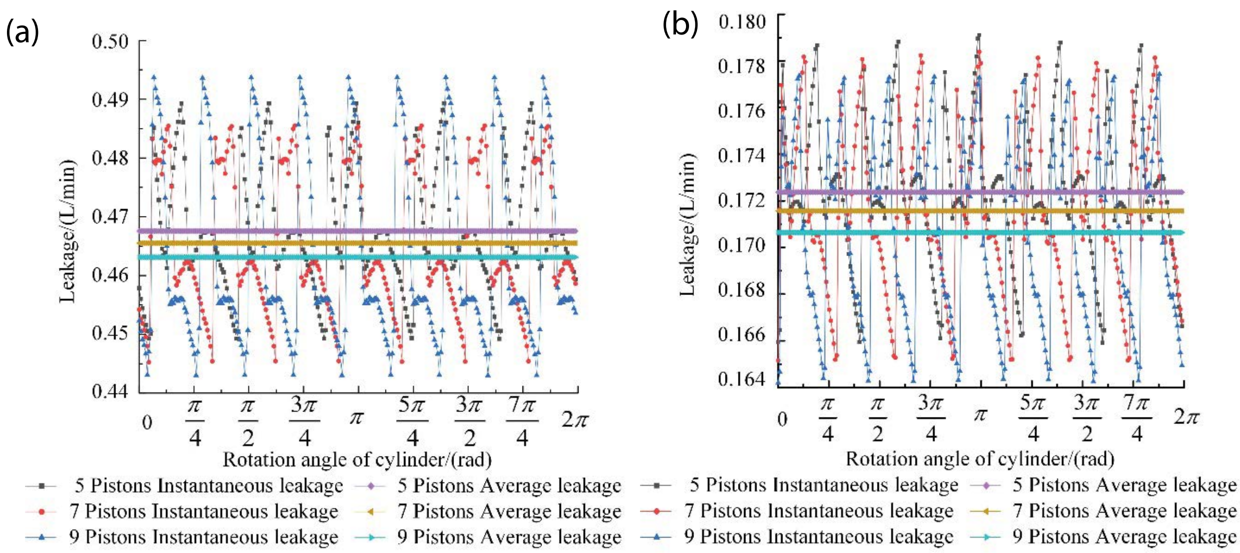

Fig. 13. (a and b) Leakage inside the inner sealing tape and outside the outer sealing tape at different pistons.

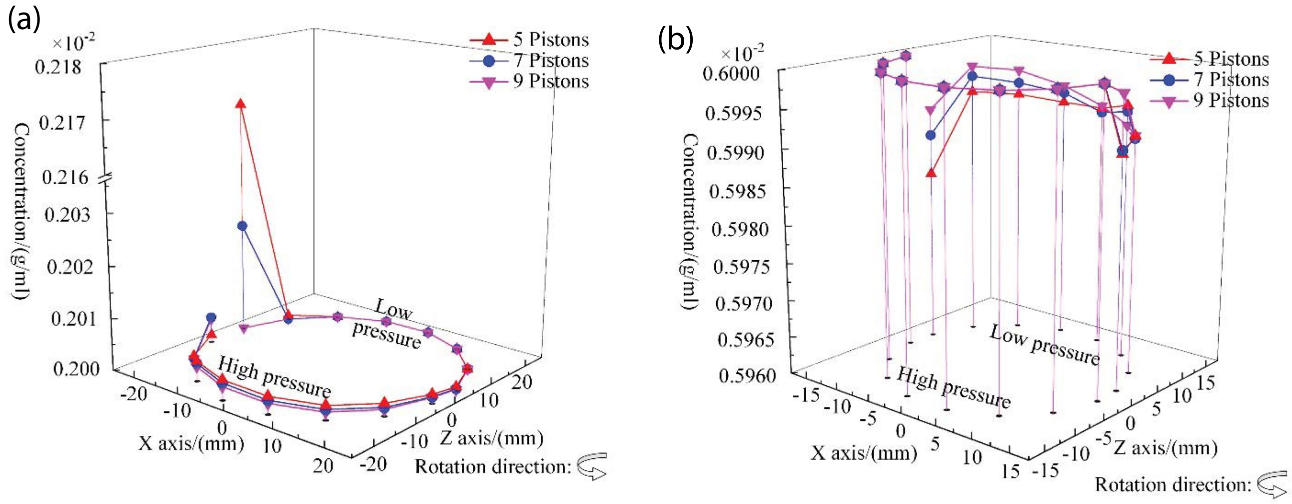

Fig. 14. Permeability characteristics of seawater with different concentrations at the distribution windows on both sides under different piston numbers: (a) outer and (b) inner distribution window.

of different concentrations of seawater at the distribution window, future work will further study the influence of other key parameters of reverse osmosis seawater desalination variable motor pumps on the leakage characteristics and mutual permeability characteristics of different concentrations of seawater at the distribution window.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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