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Test method of seawater desalination plant based on information fusion

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ABSTRACT

In order to reduce the energy consumption of seawater desalination, this paper proposes an operation test method of seawater desalination device based on information fusion. Based on the theoretical analysis and calculation of energy consumption of seawater desalination system, the influences of feed water salinity, recovery rate, energy recovery device, high-pressure water pump and other factors on energy consumption and water quality of seawater desalination system are analyzed. An energy-saving integrated desalination process with differential pressure exchange energy recovery device is proposed, and a differential pressure exchange energy source matching with a small desalination system is independently developed. The results show that the produced water quality of the desalination device basically meets the design requirements, and the energy consumption of the motor and pump is only 2.0 kWh/m^3 without considering the loss of the motor and pump, which can greatly reduce the water production energy consumption of the system, and has a certain application value.

Keywords: Information fusion; Desalination plant; Running test method

1. Introduction

Seawater desalination is an important part of strategic emerging industries. It can not only provide fresh water for industry and life, but also transform coastal saline land, concentrate salt in seawater, extract a variety of heavy metal ions and other industrial raw materials, and improve marine biological support system, From the perspective of practicality, economy and social application, seawater desalination is also the most effective way to alleviate and solve the global water shortage [1].

Seawater desalination device is an important equipment to desalinate seawater. In order to improve the operation performance of seawater desalination device, many scholars have carried out experimental research. In view of the defects of metal organic frameworks (MOFs), which play an important role in the development of MOFs as a promising reverse osmosis (RO) membrane for seawater desalination, Lyu et al. [2] studied a desalination reverse osmosis membrane potential analysis method based on the defect UiO-66 desalination equipment, and discussed the influence of experimental defects in UiO-66 on its desalination performance, so as to improve the desalination performance operation performance of chemical plant. Nagaraj et al. [3] proposed fuel cells as an effective energy source for desalination reverse osmosis desalination devices powered by photovoltaic systems, including photovoltaic and self-rechargeable fuel cells, specifically designed to ensure the injection of brackish water and reverse osmosis desalination of seawater needed for operation for irrigation in remote areas. The optimal configuration is determined on the basis of the minimum energy cost and the minimum total

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net present value cost, and is compared with stand-alone diesel power generation and grid expansion. Homer software is used to model, simulate and evaluate different systems including photovoltaic system [4].

Although the above methods have made some progress, the desalination also needs energy supply, which brings forward new problems for the energy crisis area. In order to reduce the water production energy consumption of the system, this paper proposes a desalination test method based on information fusion [5–7]. Based on the theoretical analysis and calculation of the energy consumption of desalination system, the influence of salt content, recovery rate, energy recovery device and high pressure water pump on the energy consumption and water quality of desalination system is analyzed [8]. A new energy-saving integrated desalination process with differential pressure exchange energy recovery device is proposed. The differential pressure exchange energy matching with small desalination system is developed independently to reduce the investment and water production cost of desalination equipment, to provide fresh water for small island, coastal villages, tourist resorts, offshore drilling platforms, ocean going ships, and stationed forces, or through vehicles, ships and other vehicles provide fresh water for the dynamic development of geological, oil, mineral and field forces with large dispersive mobility [9,10]

2. Reverse osmosis desalination system based on information fusion

2.1. Basic principles of reverse osmosis based on information fusion

The essence of information fusion is the overall coordination and optimization of the system. It can combine different levels of information organically, so as to obtain consistent explanation and comprehensive description of the problems evaluated, so as to make the performance of RO desalination system better than its components or its simple sum [11–13]. Reverse osmosis is the process of forcing water molecules to diffuse from one side of the concentrated solution to the diluted solution when sufficient pressure is applied on one side of the concentrated solution [14]. As shown in Fig. 1. The separation of solute macromolecules and solvent molecules can be realized by using the selective permeability of semi permeable membrane.

2.2. Basic equation of reverse osmosis process

Only when the external pressure is greater than the osmotic pressure of seawater, the water molecules in seawater can pass through the reverse osmosis membrane, so as to realize the separation of salt and water. Moreover, the greater the pressure and osmotic pressure difference, the better the membrane separation effect. Therefore, in order to improve the separation capacity of reverse osmosis membrane, high pressure is usually applied to seawater by booster pump. For 5.5–6.0 MPa, reverse osmosis technology shows a simple process in Fig. 2.

As shown in Fig. 2, seawater is pressurized by a booster pump (5.5° 6.0 MPa), which enters the pressurized feedwater into the RO membrane device, where fresh water is obtained at the outlet, and salt-rich concentrated seawater is injected into the sea or used as raw materials for the production of products such as refined salt.

- Osmotic pressure

The osmotic pressure (λ) of the solution is related to the type and concentration of solute in the solution and the solution temperature [15]. The osmotic pressure of dilute solution can be calculated according to the formula.

$$\lambda = R \times T \times D_j \tag{1}$$

where R is a constant, taking 0.008039 MPa L/(mol K); T is the thermodynamic temperature, unit is K; D_j is the sum of ion concentration, unit: mol/L.

It can be calculated from Eq. (1) that the osmotic pressure of 3.5% NaCl is about 2.8 MPa. Therefore, the selection of operating pressure in the design of reverse osmosis system needs to be greater than this pressure.

- The relationship between water flux and driving pressure (external pressure and osmotic pressure difference) of reverse osmosis membrane can be calculated by the following formula:

$$J_w = A\left(\Delta P - \Delta\lambda\right) \tag{2}$$

$$Q_P = J_w \times S_i + A \times \left(\frac{P_p + P_b}{2} - P_p - \frac{\lambda_p + \lambda_b}{2} + \lambda_p \right) \tag{3}$$

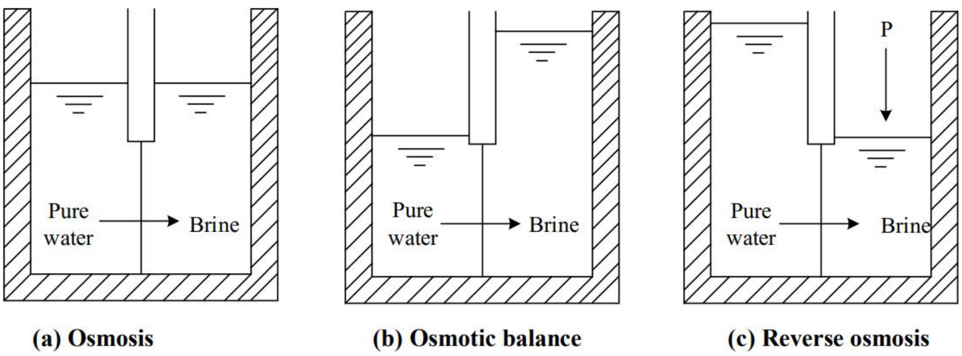

Fig. 1. Information fusion based reverse osmosis principle.

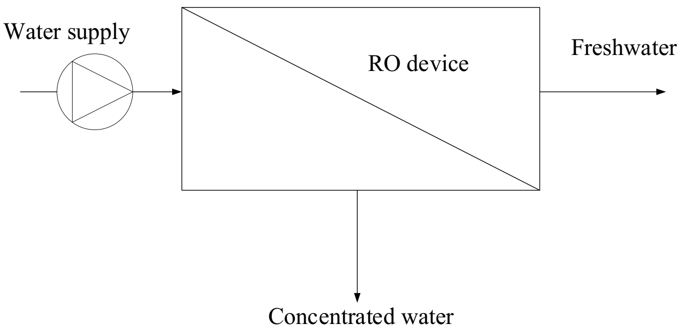

Fig. 2. Reverse osmosis simple flowchart.

where J_w is the water flux through the membrane, in L/(m^2·h); Q_P is the water permeability in L/h; A is the water permeability factor of the membrane, in L/(m^2·h·Pa); S_i is the membrane area, in m^2; P_p is the water pressure at the water producing side of the membrane, in Pa; P_b is the water pressure at the concentrated water side of the membrane, in Pa; λ_p is the osmotic pressure of the permeate, in Pa; and λ_b is the osmotic pressure of the feed liquid, in Pa.

- The relationship between the salt flux of reverse osmosis membrane and the salt concentration difference on both sides of the membrane can be calculated by the following formula:

$$J_s = B_b \times \Delta C_i \tag{4}$$

$$Q_S = J_S \times S_i + B \times \left(\frac{C_p + C_b}{2} - C_p \right) \tag{5}$$

where J_S is the salt flux through the membrane, in mg/(m^2 h)); Q_S is the salt permeability, in mg/h; B is the salt transmission factor of the membrane, in L/(m^2 h); S_i is the membrane area, in m^2; C_p is the salt concentration in the water producing side of the membrane, in mg/L; C_b is the salt concentration in the concentrated water side of the membrane, in mg/L.

- The salt content in the effluent of reverse osmosis membrane can be calculated by the ratio of salt to water passing through the membrane.

$$C_P = \frac{Q_S}{Q_P} \tag{6}$$

- Desalination rate:

$$R_1 = \left(1 - \frac{C_P}{C_{FC}} \right) \times 100\% \tag{7}$$

$$C_{FC} = \frac{C_F + C_C}{2} \tag{8}$$

The calculation formula of desalination rate is as follows:

$$R_V = \left(1 - \frac{C_P}{C_F} \right) \tag{9}$$

where R_1 is the average desalination rate (%); C_P is the salt content of the produced water, in mg/L; C_C is the salt content of the concentrated water, in mg/L); C_{FC} is the average concentration of the influent and turbidity, in mg/L; C_F is the salt content of the influent, in mg/L; R_V is the desalination rate (%).

- Recovery R_h and flow balance:

$$R_h = \frac{Q_P}{Q_F} \times 100\% \tag{10}$$

$$Q_F = Q_P + Q_B \tag{11}$$

where Q_P is the water flow rate of the product, and the unit is mg/L; Q_B is the salt concentration at the concentrated water side of the film, in mg/L; Q_F is the salt concentration on the inlet side of the membrane, in mg/L.

- Concentration factor C_{FP}:

$$C_{FP} = \frac{1}{1 - R_h} \tag{12}$$

- Concentration polarization in the separation process, after the water passes through the reverse osmosis membrane, the salt content in the feed liquid near the membrane surface increases and forms a concentration difference with the feed liquid body. The ratio of the two is C_{PF}, which is seriously changed in the membrane elements at the end of the membrane stack. In order to maintain the separation efficiency of the membrane, C_{PF} should be less than 1.2, which can be expressed by the following formula:

$$C_{PF} = \frac{C_m}{C_f} \tag{13}$$

where C_m is the salt concentration on the membrane surface, in mg/L; C_f is the salt concentration on the inlet side of the membrane, in mg/L.

2.3. Composition of reverse osmosis desalination system

Reverse osmosis desalination systems typically consist of three components: a seawater pretreatment system, a reverse osmosis system and a reprocessing system [16], as follows:

2.3.1. Pretreatment system

Seawater usually contains solid suspended solids, bacteria, proteins, colloids and other pollutants, which are easy to deposit on the membrane surface in the process of reverse osmosis separation, thereby increasing the membrane resistance and weakening the membrane production capacity (the flux is obviously reduced), requiring frequent cleaning, which not only reduces the production efficiency but also reduces the service life of the membrane. Therefore, necessary pretreatment of seawater is required to reduce membrane pollution [17].

The purposes of pretreatment are usually: (1) to remove suspended solids and reduce turbidity; (2) to inhibit and control the precipitation of slightly soluble salts; (3) to regulate and control the temperature and pH of influent water; (4) to kill and inhibit the growth of microorganisms; (5) to prevent heavy metal ions and silicate from forming precipitations on the surface of the membrane [18].

Membrane fouling can be effectively prevented by effectively removing pollutants from seawater [19]. Therefore, qualified pretreatment can make the reverse osmosis system yield, desalination rate, recovery rate, operation cost to achieve the best. The effect of pretreatment can be judged from the contents in Table 1.

The silt density index (SDI) is an important indicator of the quality of incoming water from the reverse osmosis system. It refers to a certain amount of water at a certain pressure and standard time through the pore diameter of 0.45 μm of the blocking rate of microporous membrane. Mainly used to indicate the amount of solid suspended matter in a body of water [20]. The relationship between SDI and contamination level is shown in Table 2.

Hollow fiber reverse osmosis device has higher requirement for inlet water, and the SDI of inlet water is less than 3, while the quality of inlet water is lower in coil reverse osmosis device, if the SDI of inlet water is less than 4.

Therefore, the international community is committed to the development of a new pretreatment process, in the hope of improving the treated water quality. For example, in the pretreatment process, the SDI of water treated by continuous microfiltration can be less than 2, and the particle size is less than 0.2 μm. Ultrafiltration separation technology as a pretreatment system can treat highly polluted seawater, can ensure the reverse osmosis system for long-term operation.

2.3.2. Reverse osmosis system s

Reverse osmosis system s, also known as core separation systems, include membrane assemblies, high-pressure pumps, and energy recovery devices [21].

2.3.2.1. Membrane modules

Membrane assemblies are made up of reverse osmosis diaphragms, inlet water separation nets and central pipes according to specific requirements. The core of the modules is reverse osmosis diaphragms, which can be classified into different types from different angles [22].

- According to membrane materials, reverse osmosis membrane can be divided into cellulose acetate membrane (CA) and aromatic polyamide membrane (PA).
- According to the type of membrane, the membrane can be divided into roll type, plate type, tube type, hollow fiber type membrane module.
- The reverse osmosis membrane can be divided into low-pressure membrane (brackish water desalination membrane), ultra-low-pressure membrane, seawater desalination membrane, etc.
- According to the pressure level can be divided into 150, 250, 300, 400, 600, 1,000 and 1,200 psi, etc. Reverse osmosis membranes with a pressure range of 150–600 psi are generally used for desalination of brackish water, while pressure vessels with a pressure range of 1,000–1,200 psi are used for desalination.

2.3.2.2. High-pressure pump

The reverse osmosis relies on the external pressure to realize the brine separation, the external high pressure needs to realize by the high pressure pump to the seawater. High-pressure pump operation is the main part of the reverse osmosis system, its power consumption cost of the entire system operating cost of about 40% [23]. Therefore, the performance of high-pressure pump affects the cost and benefit of reverse osmosis system. High pressure pump commonly used there are two main types: reciprocating pump and centrifugal pump, reverse osmosis system using high pressure pump performance parameters as shown in Table 3.

2.3.2.3. Energy recovery devices

The pressure of desalination by reverse osmosis is usually 4.0–6.0 MPa, while the pressure of concentrated

Table 2
Relationship between SDI value and pollution degree

SDI value	Degree of pollution
<3	Low
3–5	General
>5	High

Table 1
Pretreatment effect judgment method

Membrane cleaning frequency	Is pretreatment reasonable or appropriate
3 months or longer	Moderate
1–3 months	Pretreatment may need to be enhanced
More than 1 time in 1 month	There is a real need for enhanced preprocessing

Table 3
High-pressure pump performance parameters for reverse osmosis systems

Category	Flow m^3/h	Efficiency	Merit
Reciprocating pump	1–10	70%–80%	High efficiency
Reciprocating pump	10–80	>85%	High efficiency
Centrifugal pump (high speed)	10–70	50%–75%	Small number of stages, small impeller diameter, light weight
Centrifugal pump (sectional)	80–200	70%–80%	Small size, light weight, low price
Centrifugal pump (medium open)	>200	75%–85%	No axial thrust, easy to maintain and repair

seawater discharged from membrane modules is still up to 3.8–5.8 MPa. At present, the water production rate of seawater desalination in our country is 35%–45%. Both 55%–65% of high pressure seawater is discharged directly through the pressure reducing valve. Therefore, in order to reduce energy consumption and save costs, it is necessary to install energy recovery device in high-pressure concentrated brine discharge pipeline.

According to its working principle, the energy recovery device can be divided into two types: hydraulic turbine type and functional exchange type. Among them, in the hydraulic turbine energy recovery system, the energy recovery process through the "pressure energy – mechanical energy – pressure energy" conversion, the energy recovery efficiency of the device can reach 50%~75%. The energy recovery rate of the energy recovery system of functional exchange type is up to 94.0%, so it has become the focus of scholars at home and abroad.

In order to reduce the energy consumption, the energy recovery device is used in series with the high pressure pump, and the recovered energy can be used for the high pressure pump to pressurize the seawater feed to achieve the required operating pressure. Compared with the reverse osmosis system without the energy recovery device, not only the requirement for the outlet pressure of the high pressure pump reduced, but also the operating cost is saved [24]. Fig. 3 shows a typical process for reverse osmosis and hydraulic turbine type energy recovery plants.

In this system, the residual pressure energy of high concentration brine in the outlet can be pressurized directly through the conversion system, reducing the amount of sea water that needs to be pressurized through the high-pressure pump, and reducing the cost. However, there is a loss of energy in the pressure exchange process, and the loss of pressure can be compensated by increasing the pressure lift pump. Fig. 4 shows a typical process for reverse osmosis and functional exchange energy recovery.

The product water reprocessing system can improve the water quality. Generally speaking, the produced water after only one reverse osmosis separation needs to be further treated.

2.3.3. Product water reprocessing system

Different reprocessing methods will be adopted according to different uses of produced water. For example, the reverse osmosis effluent for potable water needs to meet the following requirements:

- Accord with national drinking water standard;
- TDS ≤ 500 mg/L;
- The pH of produced water ranged from 6.5 to 8.5, and the hardness ($CaCO_3$) ranged from 29 to 75 mg/L;
- Chlorination sterilization.

3. Operation test experiment of seawater desalination device

Reverse osmosis is one of the most energy-saving and efficient seawater desalination technologies. Its principle is: under pressure drive, the solvent (water) enters the low-pressure (water-producing) side through the reverse osmosis membrane, and other components (salts) in the solution are blocked at the high-pressure (concentrated

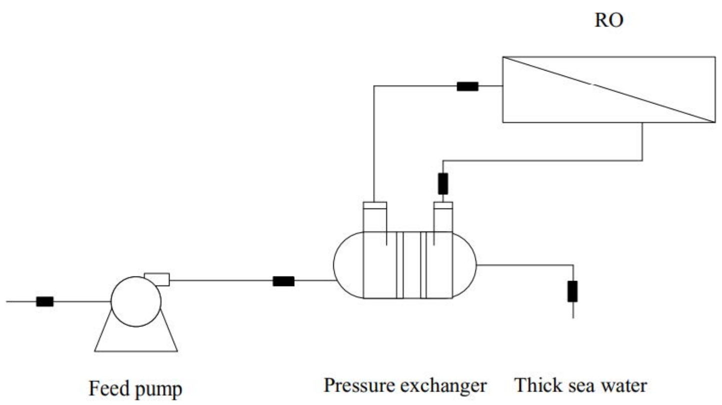

Fig. 3. Typical reverse osmosis and hydraulic turbine energy recovery process in series.

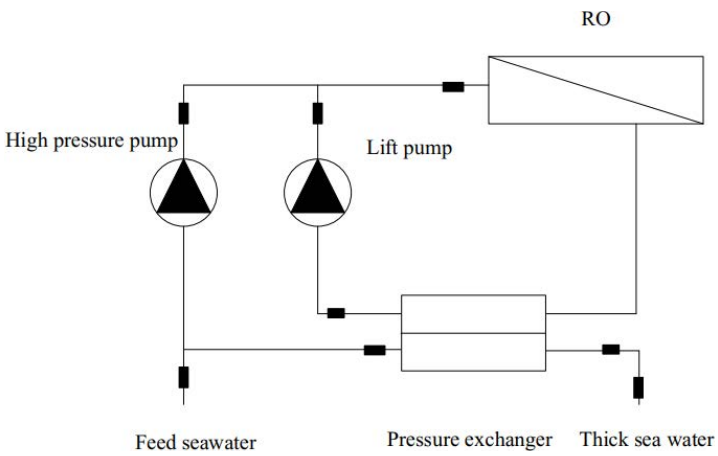

Fig. 4. Typical parallel reverse osmosis and functional exchange energy recovery process.

water) side of the membrane, and are discharged along with the concentrated seawater to achieve an effective separation process. The energy consumption of reverse osmosis process is analyzed, and the effects of salt content, recovery rate, energy recovery efficiency and high pressure pump efficiency on the membrane system are investigated.

3.1. Experimental preparation

From the thermodynamic point of view, the separation of salt from water is a kind of anti-spontaneous process, and the theoretical energy consumption of these processes is equal. After years of ocean research, it is found that although the salinity of seawater varies from place to place, the composition of seawater is basically the same. There are 12 elements more than 1 mg/kg in seawater, which are Cl, Na, Mg, S, Ca, K, Br, C, Si, B, Sr and F. Add H, O, the total elements of seawater 99.9%. For the convenience of further study, the concept of standard seawater was put forward. The composition of standard seawater is shown in Table 4.

3.2. Transient performance analysis of seawater desalination plant

In the seawater desalination plant test, there are many parameters. In order to better test and study the performance of the plant, each test changes only on variable parameters, other parameters unchanged. Transient performance is one of the evaluations of the instantaneous performance of the device in the running state, so it is necessary to analyze the transient performance of the device in the experiment.

According to the per capita daily water 250 L/d calculation, an island with a population of about 100 people, the need for a daily production of fresh water desalination device 25 m^3/d. According to this case: the system yields 25 m^3/d, with the yield concentration ≤300 mg/L, the standard seawater concentration 35,000 mg/L, and pH = 7.

The design parameters are shown in Table 5.

Among them 2/1 means to choose 2 pressure vessels, each pressure vessel is equipped with 1 membrane element, and adopt one stage and two stage process.

In Fig. 5, the intracavity pressure of the effective cavities has been on an upward trend since the beginning of the operation of the system, indicating a continuous increase in the pressure within the system. In theory, after the system works, the increase of steam makes the pressure increase. After the steam condenses into liquid fresh water, the pressure drops back. Therefore, the pressure should be

Table 4
Composition of standard seawater (S = 35) (g/kg)

Anion	g/kg	g/mol	mmol/l
Cl^-	19.3	35.5	545.1
SO_4^{2-}	2.7	96.0	28.2
Br^-	0.0673	79.904	0.8423
F^-	0.0013	18.998	0.0684
HCO_3^-	0.142	61	2.3279
B	0.0035	10.811	0.3237
Na^+	10.77	22.9898	468.4686
Mg^{2+}	1.29	24.305	53.0755
Ca^{2+}	0.4121	40.08	10.2819
K^+	0.399	39.098	10.2051
Sr^{2+}	0.0079	87.62	0.0902

Table 5
Design selection conditions

Project	Design parameters
Membrane module	SW30HRLE-400,2
Membrane arrangement	2/1
High pressure pump efficiency	85%
Motor efficiency	95%
Year of operation	0,1,2
Water flux	14.02 L/(m^2 h)
Energy recovery	None
Annual decay rate of water yield	7%
Annual growth rate of salt permeability	10%
Recovery rate	35%

kept at a constant state during the operation of the system. The rise of the pressure curve indicates that there is air leakage in the system. There should be an obvious pressure difference between the pressures in each chamber, because the effective pressure comes from the previous one. The steam pressure of each effect is strictly sealed. After the hot steam enters into each effect, there are more evaporation and condensation processes, accompanied by a small amount of heat loss, which makes the steam pressure lower than that of the previous one. Therefore, there is an obvious pressure difference between the first effect, the second effect and the third effect after the system starts working. The theory is more consistent, which also shows that the sealing performance between the three effects is good, but the pressure difference between the third effect and the fourth effect (also known as condenser) is fuzzy. It can be distinguished that the pressure of the third effect is higher than that of the fourth effect, indicating that the sealing between the two effects is poor. The steam in the third effect chamber can enter the condenser directly, but the third effect evaporative condenser can not only condense heat. At the same time, the steam can be evaporated again by using the latent heat released during steam condensation, and the condenser only condenses the steam, so the pressure of the condenser is lower than that of the third effect chamber. After that, we can see that the four effect pressure has the phenomenon of fusion. This is because at this time, the evaporator stops heating, the condenser stops condensing, and the hot steam between the four effect chambers begins to gradually reach the balance, so the pressure in the four effect chamber gradually moves towards the same pressure.

3.3. Test method for operation of desalination plant experimental results

3.3.1. Changes in system conductivity

The electrical conductivity of the test system for seawater desalination operation is shown in Fig. 6:

As shown in Fig. 6, the conductivity of water is an important index to measure the desalination degree of

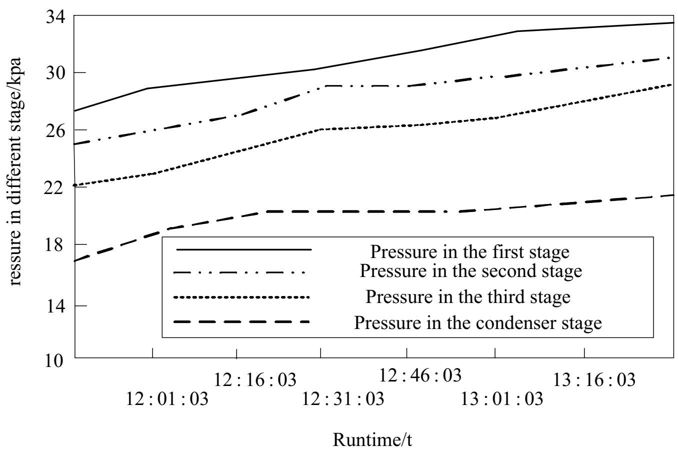

Fig. 5. Pressure transient performance of seawater desalination plant.

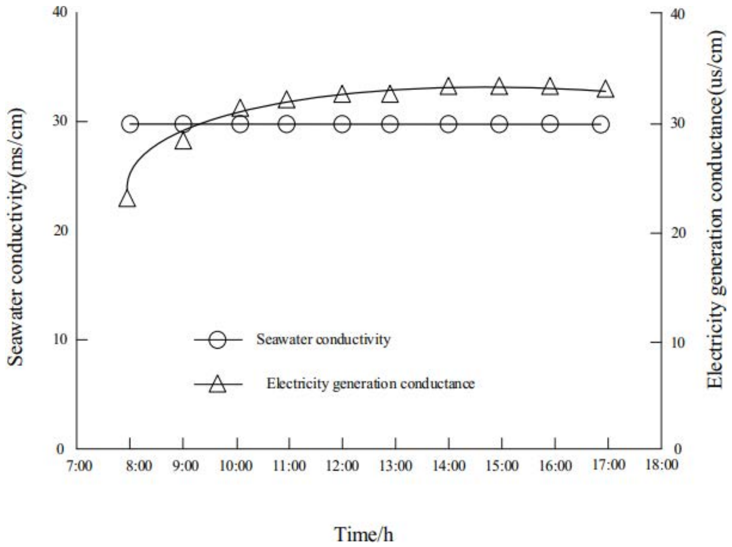

Fig. 6. Diagram of system conductivity change.

membrane. The conductivity of natural water is 50–500 μS/cm. Seawater desalination device operation of the use of self-prepared seawater, seawater conductivity of about 30,000 μS/cm^{-1}, the conductivity of water production constant between 200 and 400 μS/cm^{-1}. The desalination rate of reverse osmosis is above 98.5%, and the quality of produced water basically meets the design requirements.

3.3.2. Changes in system flow

The flow change of the test system for seawater desalination plant operation is shown in Fig. 7:

As can be seen from Fig. 7, the flow rate of the SWRO plant is stable from 25 to 28 L/h, and the flow rate of concentrated water is stable from 300 to 350 L/h, which is consistent with the designed water recovery efficiency of 7.5%. SWRO unit daily water flow rate is about 275 L/d. The energy consumption accounts for more than 40% of the operation cost of seawater desalination plant, and the main energy consumption is high pressure pump. Because the new desalination device adopts highly efficient differential pressure exchange energy recovery device, does not need high-pressure pump with high lift, and does not consume extra electric energy, so it can greatly reduce the energy consumption of water production. The pressure output of seawater booster pump is increased by energy saving integrated seawater desalination device, which is about 2 times of that of traditional seawater booster pump. The results show that the energy consumption of the new desalination system is only 1/5 of that of the traditional desalination system under the same conditions. In addition, there is no need to configure high-pressure pump with high head, so that the system operating noise significantly reduced, with better environmental benefits. The energy consumption is only 2.0 kWh/m^3 when the loss of motor and pump is not considered, which shows that improving the efficiency of motor and pump can greatly reduce the energy consumption of water production.

4. Conclusion and prospects

4.1. Conclusion

In order to solve the problems of high energy consumption, unchanged transportation, expensive imported components and complicated operation in seawater desalination plants, this paper presents a test method for seawater desalination plant based on information fusion. In view of the characteristics of the seawater desalination device under information fusion, independently develop a differential pressure exchange type energy recovery device, cooperate with the use of domestic multi-stage centrifugal pumps, take into full consideration the compactness and mobility of the device in the design and selection of materials, highly integrate all equipment in the system, adopt modular and integrated design ideas, give full play to the advantages of advanced technologies, and trial-produce a prototype of energy-saving integrated seawater desalination device, and carry out experiments and research on water consumption, water quality, operation noise and other aspects of the prototype. The experimental analysis shows that the produced water quality of the desalination device basically meets the design requirements, and the energy consumption of the motor and pump is only 2.0 kWh/m^3 without considering the loss of the motor and pump, which can greatly reduce the water production energy consumption of the system, and has a certain application value.

4.2. Prospects

Wind energy and solar energy are renewable energy. They are rich in resources. They can be used free of charge and do not need transportation. They do not cause any pollution to the environment. Using wind energy and solar energy for desalination can save conventional energy and reduce carbon emissions. It is a forward-looking and strategic reserve research. Therefore, seawater desalination based on renewable energy resources in coastal areas can alleviate the two problems of freshwater resources and energy shortage, improve the quality of life of residents, and promote the development of marine emerging industries, which has broad market prospects.

It is suggested that the reverse osmosis seawater desalination device powered by new energy shall be developed in the next step, which can be independently operated by utilizing new energy such as wind energy and solar energy, with no pollution, low energy consumption, safe, stable and reliable operation, no consumption of conventional energy such as petroleum, natural gas and coal,

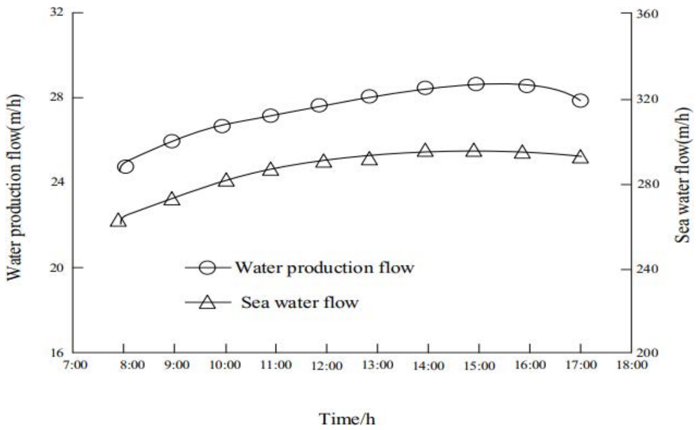

Fig. 7. System flow change diagram.

etc., and shall have great application value for the regions that are short of energy and have high requirements for environmental protection. Secondly, the production scale may be organically combined, with good adaptability, relatively less investment and low cost of water production. New water resources can be added to coastal and island areas, especially isolated islands off the grid of the mainland, to improve the situation of water shortage in these areas, break the bottleneck of water resources that restricts the economic and social development of islands and coastal areas, promote the development of marine industry and improve the economic development level of these areas.

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