

The salinity gradient power generating system integrated into the seawater desalination system

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Abstract. Seawater desalination is an important way to solve the problem of fresh water shortage. Low energy efficiency and high cost are disadvantages existing in seawater desalination. With huge reserve and the highest energy density among different types of marine energy, salinity gradient energy has a bright application prospect. The promotion of traditional salinity gradient power generating systems is hindered by its low efficiency and specific requirements on site selection. This paper proposes a salinity gradient power generating system integrated into the seawater desalination system which combines the salinity gradient power generating system and the seawater desalination system aiming to remedy the aforementioned deficiency and could serve as references for future seawater desalination and salinity gradient energy exploitation. The paper elaborates on the operating principles of the system, analyzes the detailed working process, and estimates the energy output and consumption of the system. It is proved that with appropriate design, the energy output of the salinity gradient power generating system can satisfy the demand of the seawater desalination system.

1. Introduction

Energy consumption is increasing rapidly along with technology development across the world, therefore exploitation of new energy resources and reductions of energy loss have become a task of top priority. On the other hand, fresh water shortage has become an indisputable fact among the world. Huge marine energy and potential to be desalinated to fresh water makes ocean a research hotspot. Marine researches follow two major routes including marine energy generation and seawater desalination. Seawater desalination is one of the major approaches to solve the problem of fresh water shortage. According to [1], current frequently applied methods of seawater desalination in the world include multi-stage flash evaporation (MSF), low temperature multi-effect distillation and reverse osmosis. Statistics at the end of year 2003 by International Desalination Association shows that market share of MSF accounts for 66.3% of the aforementioned three major methods of seawater desalination. However, the essence of seawater desalination is to exchange electricity for fresh water. Roughly, one third of cost in seawater desalination is energy consumption. It has always been the goal of researchers and one of the major repetition and development during the past several decades to cut the energy consumption during seawater desalination in order to lower the cost of seawater desalination. Consequently, reducing the energy consumption of seawater desalination is topic of great importance faced by researchers.

Salinity gradient energy is one of many ocean energy sources. It is estimated by experts that the energy capacity of salinity gradient energy is approximately 10 GkW [2]. Furthermore, salinity gradient energy has the largest energy density in comparison with other types of marine energy

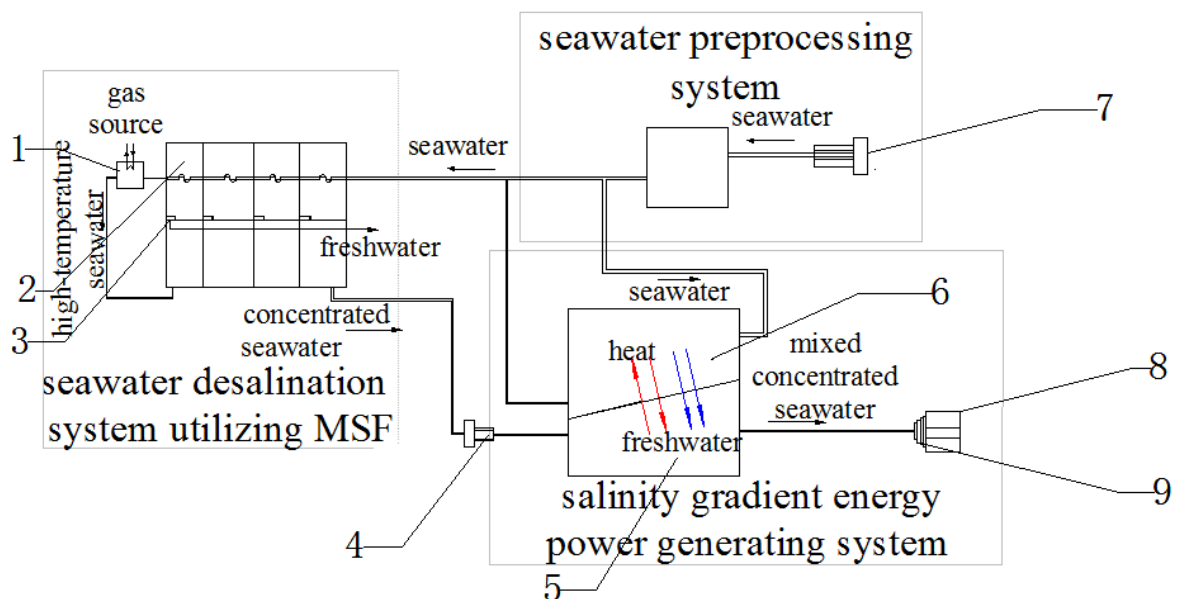


sources, which is of great value in real projects. Salinity gradient energy which is also called concentration gradient energy is a kind of electrochemical potential energy generated by the gradient difference between seawater and fresh water or seawater of different salinity gradient. According to [3], major salinity gradient energy exploitation method includes pressure retarded osmotic; reverse electrodialysis; vapour pressure differences. At present, the application of salinity gradient energy is limited to estuaries. The efficiency of salinity gradient energy is relatively low because of the limited concentration gradient between seawater and fresh water, therefore applications of salinity gradient energy don't apply to areas that are short of fresh water. Rivers in China are severely polluted, which makes a relatively high pre-processing cost, therefore traditional power-generating method based on salinity gradient energy does not meet conditions for large-scale applications. Salinity gradient energy power generating system broadens integrated in seawater desalination system takes seawater of high concentration outputted by seawater desalination as draw solution and seawater as raw material solution, which broadens application range of salinity gradient energy, adds to osmotic pressure which will boost power density, reduces energy cost of seawater desalination system, and adds to economic value.

Based on principles of osmotic pressure energy method, this paper proposes a salinity gradient energy power generating system integrated in seawater desalination system which combines salinity gradient energy power generating system and seawater desalination system, which will reduce the energy cost during the process of seawater desalination, and boost the economic value of the system.

2. Scheme Design and Principle Explanation

2.1. System Structure and Working Principle



1. seawater heater 2. MSF room 3. gas-water separator 4. pump 1 5. tank for draw solution 6. tank for raw material solution 7. pump 1 8. generator 9. water turbine.

Figure 1. Structure chart of the seawater desalination system combined with the salinity gradient power generation system.

As shown in Figure 1, the system consists of seawater preprocessing system, seawater desalination system utilizing MSF and salinity gradient energy power generating system. Water pump 1 draws ordinary seawater into seawater preprocessing system where regular preprocessing including sterilization, sediment and deoxidize is conducted; then, seawater after preprocessing is fed into

cooling water pipe at the upper section of the last stage of MSF. The seawater flowing into the MSF during operation of the device is preheated, and serves as cooling water at the same time. The preheated seawater is discharged from upper section of the first stage of MSF, and turns into high-temperature seawater. Then, high-temperature seawater is fed into the bottom of first flashing stage of MSF. Pressure inside the flash evaporation room is lower than the pressure of saturated vapor corresponded to the high-temperature seawater, therefore as superheated vapor, high-temperature seawater is evaporated rapidly. Tiny droplet of seawater brought by evaporated vapor is eliminated by gas-water separator at the middle section of the flash evaporation room. Separated vapor ascends to the upper section of the flash evaporation room, and condensates fresh water when coming across pipes in condensation zone. Drops of fresh water drips into plates of fresh water, and is led to water tank outside the MSF room for storage after converge. Desalinated seawater discharged after desalination flows into tank of draw solution of salinity gradient energy power generating system through water pump 2, and ordinary seawater drawn by water pump 1 flows into tank of raw material solution after preprocessing. Following the principles of osmotic pressure, fresh water in ordinary seawater is drawn by desalinated seawater. The mixed desalinated seawater drives the water turbine through water pipe. Then, generator is driven by water turbine. The ordinary seawater discharged by salinity gradient energy system is fed into MSF seawater desalination system again through recycle water pipe for cyclic utilization.

2.2. Salinity Gradient Power Generation System

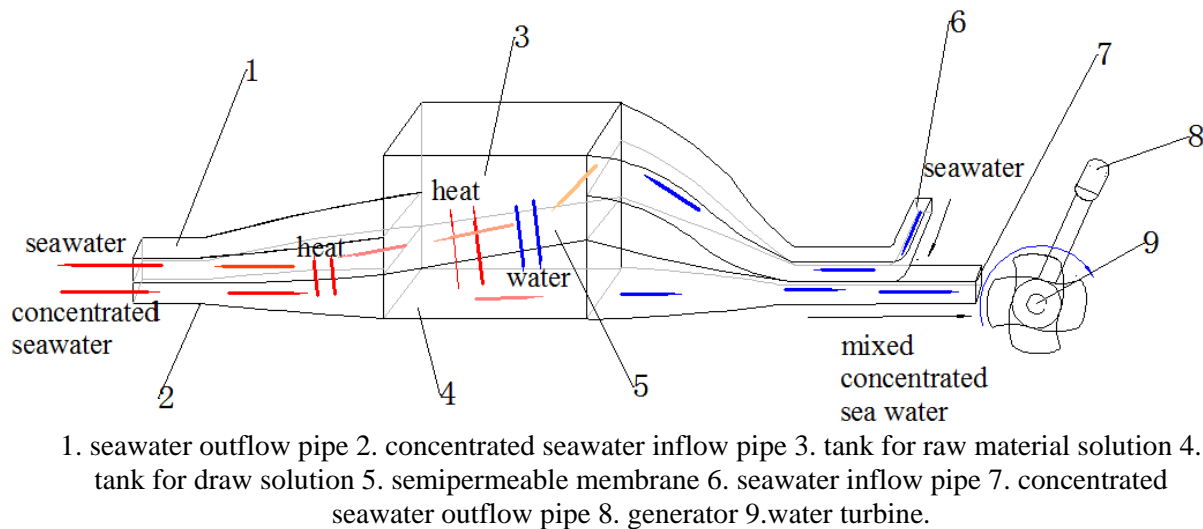


Figure 2.Structure chart of the salinity gradient power generation system.

Salinity gradient energy power generating system consists of 4 parts, as shown in Figure 2. The first part includes concentrated seawater inflow pipe, seawater outflow pipe and heat conduction layer; the second part includes tank for draw solution, tank for raw material solution and semipermeable membrane; the third part includes seawater inflow pipe, concentrated seawater outflow pipe and heat conduction layer; the fourth part includes water turbine and generator. Desalinated seawater discharged from seawater desalination system flows into tank for draw solution through desalinated seawater inflow pipe. Seawater is pumped into tank for raw material solution from upper section through seawater inflow pipe, and is discharged through seawater outflow pipe at the bottom of the tank for raw material solution. Then, seawater discharged from tank for raw material solution is fed into MSF seawater desalination system through circulating pipe for cyclic utilization. According to the principle of osmotic pressure, water of ordinary seawater in tank for raw material solution passes through osmotic membranes and flows into tank for draw solution. The mixed desalinated seawater

discharged from tank for draw solution of which the hydraulic pressure is relatively high outflows through desalinated seawater outflow pipe, and drives the water turbine. Then, the generator is driven by water turbine and electric power is generated. Circulating pipes of desalinated seawater and circulating pipes of seawater in the whole system is closely fitted, which contributes to the adequate heat exchange with desalinated seawater during the whole circulating process of the seawater, and reduces the energy cost of the whole system.

3. Capacity and Energy Consumption Analysis

Reviewed references of seawater desalination and salinity gradient energy power generation, this assumes operation mode and parameters of the system based actual situation, and analyzes energy cost, power generating efficiency of salinity gradient energy and status of auxiliary facilities.

3.1. Energy Consumption of MSF Seawater Desalination System

Assume that a MSF seawater desalination system which can produce 1t fresh water per hour is to be constructed in a location that suffers from electricity deficit and fresh water shortage. Flash evaporation rate of MSF is generally between 0.4% and 12%, and 5% is chosen as flash evaporation rate in this paper. With flash evaporation rate of 5%, seawater that should be fed into the system per hour is 20t. Energy cost of seawater desalination is calculated in [4], ratio energy cost of MSF is 17.62kWh/m³. Assume that the density of fresh water is 1000kg/m³, then energy cost of MSF seawater desalination system per hour is 17.62kW.

3.2. Energy Consumption of Seawater Pretreatment System

Preprocessing technology of seawater desalination is one of the key factors to ensure the stable, reliable and long-term operation of the seawater desalination system. State-of-the-art preprocessing methods for seawater desalination mainly includes regular preprocessing, membrane preprocessing and Actiflo high efficiency sedimentation tank [5]. Seawater desalination methods varies according to technique requirements differences. Requirement of preprocessing of seawater for MSF seawater desalination is relatively simple, and energy cost of cyclic process is low. Energy cost by seawater preprocessing can be ignored, because only regular preprocessing is needed.

According to the assumption, 20t seawater should be fed into the system. Assume that m1t seawater pumped by pump 1 into the seawater preheating system per hour, and m2t of seawater is fed into the tank for raw material solution. As is known that quality of seawater fed into the system by water pump is equal to the quality of water discharged from the system. According to the calculation of water flow of the osmotic membranes, osmotic water flow is 0.3t when 1t of fresh water is discharged. Therefore, quality mixed desalinated seawater discharged from salinity gradient energy power generating system is 19.3t. m1+m2=20.3t/h is fed into the system by pump 1. Pump 10m head is chosen for calculation in this section, and power of the pump is calculated as (1) :

$$W = \frac{Vgh}{3600\eta} \quad (1)$$

Where V is seawater flow, h is the head of the pump, η is the efficiency of the pump, and is generally chosen as 0.6.

Substitute $v=20.3t/h$ into equation (1), power cost by pump 1 is calculated as $w1=0.92kW$.

3.3. Capacity of the Salinity Gradient Power Generation System

Osmotic pressure of sweater with different concentration can be calculated according to following formulas (temperature is chosen as 25°C) [6]:

$$\pi1 = \frac{2RT}{1000} \int_0^I \frac{1}{v_1} \left\{ 1 + 2bI + 3bI^2 - \frac{S(I)^{1/2}}{2[1+1.5(I)^{1/2}]^2} \right\} dI \quad (2)$$

$$\pi2 = \frac{RTM_1}{1000V_1} \sum \phi_i v_i m_i \quad (3)$$

According to the commonly used marine table [7], salinity(S‰) and osmotic pressure of seawater (MPa) at 25°C can be found. As known that concentration of seawater is 34.448‰, osmotic pressure can be deduced by interpolation technique. As shown in table 1.

Table 1. The osmotic pressure of seawater at different concentrations at 25 °C(MPa).

concentration (ppm)	π_1 (MPa)	π_2 (MPa)	π_1 (MPa)
6000	0.424	0.428	0.420
7000	0.493	0.496	0.488
8000	0.563	0.566	0.558
9000	0.632	0.636	0.628
10000	0.697	0.707	0.698
20000	1.401	1.422	1.408
34448	2.466	2.464	2.465
40000	--	2.876	2.884
50000	3.676	3.643	--
75000	5.815	5.664	--

Ordinary seawater of 34448ppm and desalinated seawater of 50000ppm are chosen as example for analysis. As shown in table 1, osmotic pressure of seawater of 24448ppm is 2.464MPa and 2.466MPa according to equation (2) and (3). The average value 2.465MPa is chosen in this paper. Osmotic pressure of desalinated seawater of 50000ppm is 3.676MPa and 3.643MPa according to equation (2) and (3). The average value 3.65MPa is chosen in this paper. Osmotic pressure between two sides of the semipermeable membrane is $\Delta\pi = 3.65 - 2.465 = 1.185\text{MPa}$.

A preliminary overall estimation of the power of the semipermeable membrane is performed in this paper regardless of the energy lost and the operation efficiency of parts. Formula calculating the water flux of water molecules passing through the semipermeable membrane is :

$$J_w = A \times (\Delta\pi - \Delta P) \quad (4)$$

Where J_w is the water flux of semipermeable membrane, A is the permeability coefficient of semipermeable membrane, $\Delta\pi$ is the osmotic pressure of the system, ΔP is the pressure from external.

Water flux through the semipermeable membrane depends on many factors, and the most important factor is the characteristic of the semipermeable membrane. Efficiency of the salinity gradient energy devices is influenced by water flow directly. Cellulose acetate membrane produced by Hydration Technologies Inc (HTI) is the only semipermeable membrane for business use until now.

Table 2. Water flux of CTA-W forward-osmosis membrane in different conditions.

temperature (°C)	raw material solution (mol/L)	draw solution (mol/L)	active layer orientation	water flux (LMH)
20	0.05NaCl	1.5 NaCl	DS	31.78[8]
20	0.5 NaCl	1.5 NaCl	FS	5.77[8]
20±1	0.05NaCl	4.0NaCl	FS	27[9]
20±1	0.05NaCl	4.0NaCl	DS	37.8[9]
23	10m NaCl	1.0 NaCl	DS	26.8[10]
23	10m NaCl	1.0 NaCl	FS	15.8[10]
23	10m NaCl	0.5 NaCl	FS	4.4[11]
25	DIwater	0.87 NaCl	FS	12.07[12]
50	0.05 NaCl	6NH ₄ HCO ₃	FS	36.5[13]

As shown in table 2, water flux is influenced by factors such as temperature、raw material solution、draw solution、active layer orientation. When temperature is 20℃, raw material solution is 0.05 mol/L NaCl, draw solution is 1.5 mol/L NaCl, active layer orientation is DS, the water flux is 5.77 L/m² · h. When temperature is 20℃, raw material solution is 0.5 mol/L NaCl, draw solution is 1.5 mol/L NaCl, active layer orientation is DS, the water flux is 31.78L/m² · h. By comparison, we can know that when the working environment is higher than 20℃, the active layer orientation is DS, the concentration difference between the absorbing liquid and the raw material is higher than 1 mol/L, the water flux should be much higher than 5.77 L/m² · h. Operation temperature of the salinity gradient energy power generating system in this paper is higher than 25℃. 5.77 L/m² · h is chosen as water flow with the consideration for convenience of analysis of the following article. It is assumed in this paper that the area of semipermeable membrane in salinity gradient energy power generating devices is 50m², therefore volume of water passing through the semipermeable membrane every half an hour is 300L.

As known that desalinated seawater delivered by pump 2 is 19t/h. As long as desalinated seawater can flow into the tank for draw solution, and the concentration of tank for draw solution remains constant, the whole cycle can be completed. Therefore, requirements on the head of the pump is not very difficult to fulfill.

The calculation of this part chooses the pump with 8m head, the power consumption of pump 2 is $W_2 = 0.69\text{kW}$.

The hydraulic turbine power calculation formula is:

$$P = gHQ = 9.81HQ \quad (5)$$

Where H is the water head (m) , Q is the water flow (m³/s) .

According to calculation performed, osmotic pressure is $\Delta\pi = 1.185\text{MPa}$. 1Mpa is equal to water head of 100m, therefore water head $H=118.5\text{m}$. Water flow passing through osmotic membranes and flowing into the system is $Q_0 = 0.003 \times 50 = 0.15\text{m}^3$. Mixed desalinated seawater discharged per hour is 19.3t. Assume that the density of mixed desalinated seawater is $\rho = 1025\text{kg/m}^3$, water flow per hour will be $Q = 18.83\text{m}^3$. Substituting aforementioned data into (5), power capacity of semipermeable membrane per unit area can be calculated

$$P = 9.81 \times 118.5 \times 18.83 \div 3600 \div 50 = 0.122\text{kW}$$

As is known that the efficiency of the water turbine is 0.7, the power capacity of per unit area of membrane is

$$P = 0.7 \times 0.122 = 0.085\text{kW}$$

Overall power cost of the system can be concluded as table 3.

Table 3. Table of the energy consumption of the system.

energy-consuming system	Energy consumption (kW)
multi-stage flash seawater desalination system	17.62
seawater pretreatment system	0.92
salinity gradient power generation system	0.69
Total energy consumption	19.23

Therefore, area of osmotic membranes required for MSF seawater desalination system that can produce 1t fresh water per hour is:

$$S = \frac{W}{P} = \frac{19.23}{0.085} = 226.24\text{m}^2$$

Salinity gradient energy power generating system can generate electricity that can compensate the power cost by the whole system if it is equipped with osmotic membranes with area of 226.24m^2 .

4. System Characteristic Analysis

The salinity gradient energy power generating system integrated in the seawater desalination system proposed by this paper which combines salinity gradient energy power generating system and seawater desalination system is superior to either salinity gradient energy power generating system or seawater desalination system in the following aspects: electricity required by the system can be generated by the system itself; site selection limitation is broken, size of devices is reduced, flexibility is increased; differential osmotic pressure is increased, and overall power generating efficiency is increased. The proposed system will be introduced from following three aspects including energy cost reduction, site selection and electricity generation cost.

(1) From the perspective of energy cost consumption, salinity gradient energy power generating system integrated in seawater desalination system combines salinity gradient energy power generating system and seawater desalination system. Taking discharge (desalinated seawater) from seawater desalination system as draw solution and ordinary seawater as raw material solution, and applying principles of osmotic pressure, the system converted salinity gradient pressure into the electric power we need. In reasonable scope of design, while producing fresh water, the system can generate electricity utilizing salinity gradient energy power generating system which could compensate the electricity cost of the whole system. Therefore, self-balance of electricity consumption is reached, cost of seawater desalination is reduced and development of seawater desalination is promoted.

(2) From the perspective of site selection, traditional salinity gradient energy power generating system takes ordinary seawater as draw solution and fresh water as raw material solution, which requires sites of salinity gradient energy power generating system must be chosen as estuaries where both fresh water and ordinary seawater can be found. Therefore, salinity gradient energy power generation is difficult to develop in areas short of fresh water. The seawater desalination system powered by salinity gradient energy power generating system proposed by this paper increases the possibility of the construction of seawater desalination plant in areas lack of energy sources, which contributes to mitigates the problem of seawater shortage to some extent.

(3) From the perspective of economics of power generation, traditional salinity gradient energy power generation system takes ordinary seawater as draw solution and fresh water as raw material solution for electricity production. For fresh water in rivers in China is severely polluted, preprocessing cost of fresh water is relatively high. Seawater preprocessing in the proposed system needs only simple and regular treatment, which cuts the cost to a certain degree. At present, efficiency of salinity gradient energy plant is relatively low that generating capacity of semipermeable membrane is 1.3W per square meter at a latest established salinity gradient energy plant in the Netherlands. The generating capacity of semipermeable membrane of the salinity gradient energy power generating system proposed in this paper is increased to 8.5W per square meter.

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5. Conclusion

This paper proposes a salinity gradient power generating system integrated in seawater desalination system which includes a seawater preprocessing system, a seawater desalination system based on multi-stage flash desalination and a salinity gradient power generating system. Salinity gradient energy power generating system together with seawater desalination system based on MSF reduces energy consumption required during seawater desalination, which enables energy balance of the whole system during fresh water production. The proposed integrated seawater desalination system breaks the site selection limitation of salinity gradient energy power plant, increases power generation efficiency and economic value of the overall system, adds to the possibility of establishing seawater

desalination plant and salinity gradient plant in areas with few resources, and boosts the exploitation of marine energy. Based on principles of osmotic pressure and quantitative calculation of energy consumption and salinity gradient energy power generation, this paper proves that the proposed system can realize energy self-balance and produce fresh water in reasonable range. On the basis of conducted research, future study will focus on the feasibility analysis of the system in real projects, which can offer comprehensive references for development and construction of future seawater desalination system and salinity gradient energy system.

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