Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.795021

51 (2013) 3735–3742
May

Taylor & Francis
Taylor & Francis Group

The research on thermal and economic performance of solar desalination system with salinity-gradient solar pond

Xiaohua Liu[a,*], Guojian Cao[a], Shengqiang Shen[a], Ming Gu[a], Chang Li[b]

[a]*Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, P.R. China*
Tel. +86 131 3040 1799; email: lxh723@dlut.edu.cn
[b]*Faculty of Chemical, Environmental and Biological Science and Technology, Dalian 116024, P.R. China*

Received 15 May 2012; Accepted 19 March 2013

ABSTRACT

Conventional seawater desalination technology could solve the problem of fresh water shortage, but consumes a large amount of fossil fuel and causes the environmental problems such as global warming, acid rain, etc. On account of this, solar desalination is one of the promising methods. Mathematical and economic models of solar desalination system with salinity-gradient solar pond (SP) which both supplies the energy and store energy in system are established. A Visual Basic and A MATLAB computer programs of solar-powered low temperature multi-effect distillation (LT-MED) processes are developed. It is researched that the effect of the temperature of stream entering into the external heat exchanger and the temperature of stream returning to SP on thermal and economic performance of solar desalination system. The conclusions are helpful to the design and operation of solar desalination plant.

Keywords: Solar desalination; Salinity-gradient solar pond; Low temperature multi-effect distillation (LT-MED); Thermal and economic performance

1. Introduction

Water is essential for life. Around 97.5% of earth's water is salt water while only 2.5% is fresh water that can be used by humans. It is the basis for social well-being of people. As populations continue to grow, scarcity of fresh water sources has driven technological advances in desalination of brackish water and seawater for meeting social and economic needs for potable water [1]. The most important technologies for desalination, include phase-change and membrane processes, including multi-effect distillation (MED), multistage flash (MSF), vapor compression (VC), freezing, humidification/dehumidification, solar still, membrane distillation (MD), reverse osmosis (RO), and electro-dialysis (ED) [2]. However, the separation of salts from seawater requires large amounts of energy which, when produced from fossil fuels, can cause harm to the environment. Therefore, there is a need to employ environmentally-friendly energy sources in order to desalinate seawater [3]. Thermal desalination by salinity-gradient SPs is one of the most promising solar desalination technologies. Compared with other solar desalination technologies, SPs provide the most

*Corresponding author.

Presented at the 2012 Qingdao International Desalination Conference June 26–29, 2012, Qingdao, China

convenient and least expensive option for heat storage for daily and seasonal cycles [4].

Solar desalination system with solar pond (SP) is studied and some independent parameters which have influence on the thermal and economic performance of system are researched in this paper. Recommendations given in this paper could be helpful in future initiatives regarding the research and development of this promising solar desalination technology.

2. The solar pond LT-MED system

The system investigated in this paper is an low temperature multi-effect distillation (LT-MED) system coupled with a salt-gradient SP for desalting seawater. The solar desalination system concludes SP subsystem, heating/cooling subsystem, external heat exchanger subsystem, parallel flow LT-MED subsystem. And Fig. 1 shows the coupling of them. Heat extraction is performed by using brine-withdrawal method exclusively. In this method hot brine is pumped from the storage zone by means of a diffuser mounted in the lower convective zone (LCZ), passed through an external heat exchanger. After exchanging heat, the cooler stream temperature decrease and returned to the bottom of the pond through another diffuser. This system is assumed to be built besides the salt filed. The discharged concentrated salt solutions from the LT-MED system would be discharged into the evaporation pond in the salt filed. After being further concentrated, one part of the brine in the evaporation pond was put in SP to maintain the salt concentration gradient of the SP; the other was used to produce the salt. There are cooling and heating systems to insure the stream temperature entering into external heat exchanger is fixed, which is an important factor helping to provide a steady thermal energy to the thermal desalination processes. This system's advantage is that it not only saves a large amount of salt and reduces the cost of the SP, but also prevents high salinity brine from discharging into the sea to protect the coastal seawater from the possible pollution.

2.1. Solar pond subsystem

A typical salinity-gradient SP generally consists of three regions namely the upper convective zone (UCZ), the middle non-convective zone (NCZ), and the LCZ. It is a shallow pond with a vertical salt-water gradient; the denser saltier water stays at the bottom of the pond and does not mix with the upper layer of fresher water. Consequently, the lower salty layer gets very hot. A SP is a thermal solar collector that includes its own storage system. It collects solar energy by absorbing direct and diffuse sunlight and produces relatively low grade, less than 100℃, thermal energy and is therefore generally considered well suited for supplying direct heat for thermal distillation processes [5].

2.2. Heating/cooling subsystem and external heat exchanger

It is assumed that the stream temperature entering into the external heat exchanger equals to T_e, when the SP supply stream temperature T_{sps} equals to T_e, the stream enters the external heat exchanger directly; when the SP supply stream temperature T_{sps} greater

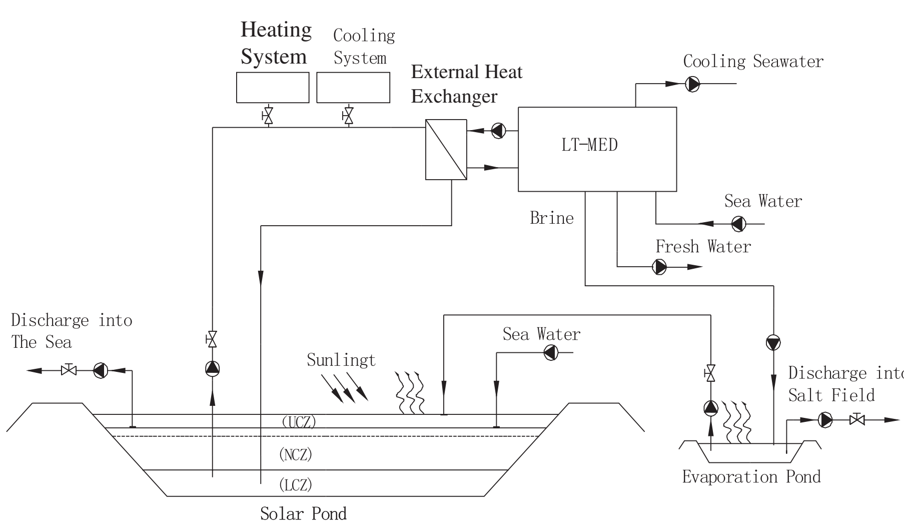

Fig. 1. Schematic of solar-pond desalination.

than T_e, the cooling system begins to run until the stream temperature equals to T_e; when the SP supply stream temperature T_{sps} is less than T_e, the electric heater begins to run until the stream temperature equals to T_e. After exchanging thermal energy, the cooler stream temperature decreases to T_{spr} and returned to the bottom of the pond through another diffuser. At the same time the external heat exchanger supplies thermal energy for LT-MED system.

2.3. Parallel flow LT-MED subsystem

LT-MED means the desalination technology that the highest temperature of the first effect heating steam can't exceed 70℃, It has some technical advantages through the possibility of utilizing low temperature waste heat sources, reducing water cost and relieving scaling and corrosion problem. And it concludes two basic flows, namely serial flow, parallel flow. Fig. 2 is the typical representative of parallel flow: in the parallel feed system, the feed water leaving the condenser is divided and distributed almost equally to each effect. Because of pressure difference between the evaporators, the brine that enters into the bottom of the next evaporator flash out some steam, and the condensed water of the former evaporator also flash out some steam at the steam entrance of the next evaporator.

3. Mathematical model

3.1. Solar pond subsystem

Some basic assumptions were made for simplifying the analysis as follows:

(1) The pond has three distinct zones, which are the LCZ, NCZ, and UCZ, and the coordinates of the zone boundaries are fixed.
(2) Heat losses through sidewalls of the pond are considered small enough, due to all the sides of the pond being well insulated, to be considered negligible.
(3) The bottom surface is blackened in order to maximize the radiation absorption. Therefore, the radiation energy reaching the LCZ is completely absorbed by the solution and the bottom of the pond.
(4) The temperature of UCZ equals ambient temperature.

3.2. Governing differential equation

A one-dimensional governing equation suitable for pond can be expressed as [6]:

$$\rho c_p \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) - I\,\frac{dh(x)}{dx} - q_{ext} \tag{1}$$

where C_p is specific heat of the solution (J/kg℃), k is thermal conductivity of the solution (W/m℃), ρ is density of solution (kg/m^3), q_{ext} is the rate of heat extraction per unit area of the SP from the heat extraction layer (W/m^2). I and $h(x)$ are the solar-radiation intensity at the SP surface (W/m^2) and non-dimensional transmission function, respectively. Using Cartesian system of coordinates, x is measured as positive downward with the origin ($x = 0$) at the surface of the pond.

This equation is adjusted accordingly depending on the location of calculation for simplicity, the effects of wind-mixing and a double-diffusion mechanism are not considered here.

3.3. Boundary and initial conditions

(1) Upper zone temperature:

$$T|_{x=0} = T_a \tag{2}$$

According to the climatic conditions of the Dalian [7]:

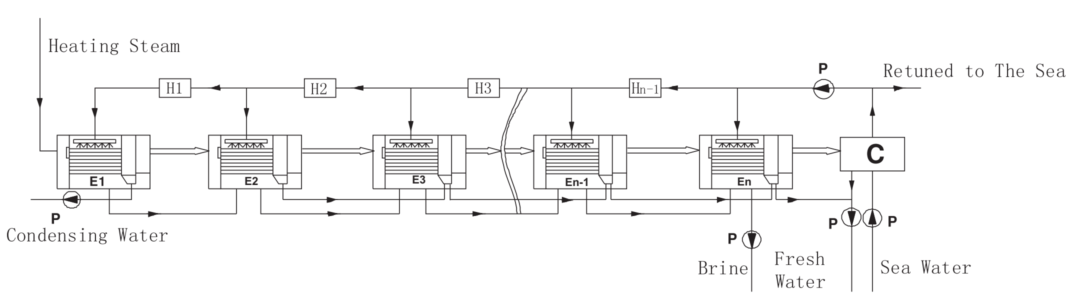

Fig. 2. Schematic of parallel flow LT-MED. (P—water pump, H_1–H_{n-1}—preheater, E_1–E_{n-1}—evaporator, C—condenser, n—number of effects).

$$T_a = 12.3 + 13.6 \sin\left(\frac{2\pi(D-27)}{365}\right) \tag{3}$$

where T_a is ambient temperature (℃).

(2) Blew boundary condition of the LCZ is given as:

$$k\frac{\partial T}{\partial x}|_{x=H} = 0 \tag{4}$$

where H is the total depth of the SP.

(3) The temperature of the various layer of the SP to be equal to 20℃ at time, $t = 0$.

3.4. Heating/cooling subsystem

(1) $T_{sps} \geqslant T_e$, the energy supplied by cooling system can be expressed as:

$$Q_c = \sum_{j=1}^{l} c_p \times 24 \times 3,600 \times m_{sp} \times A_{sp} \times (T_{sps} - T_e) \tag{5}$$

where Q_c is the thermal energy cooled by the cooler (J), l is the number of cooled day (d). m_{sp} is the feed flow rate (kg/m^2/s).

(2) $T_{sps} \leqslant T_e$, the energy supplied by heater system can be expressed as:

$$Q_H = \sum_{j=1}^{l} c_p \times 24 \times 3,600 \times m_{sp} \times A_{sp} \times (T_e - T_{sps}) \tag{6}$$

where Q_h is the energy supplied by heater system (J).

3.5. External heat exchanger subsystem

The energy supplied by external heat exchanger Q_e:

$$Q_e = 3.6 \times c_p \times m_{sp} \times A_{sp} \times (T_e - T_{spr}) \tag{7}$$

Published Ref. [8] provides mathematical model of parallel flow LT-MED system.

4. Economic model

The cost of this system contents two parts: capital cost and operational cost. The capital cost includes cost of SP lining system, electric heater and cooler, land, condenser and preheater in the LT-MED system, the external heat exchanger and evaporator in the LT-MED system; pump investment and civil installation and auxiliary equipments; the operational cost includes the operating cost of pump, manpower, pre-treatment, electricity using by heater.

4.1. The cost of solar pond lining system

The bottom of the SP is insulated with 100 mm [9] thick expanded polystyrene (EPS) insulation to reduce the average heat loss. Then the high-density polyethylene is installed on the surface of the SP.

The economic model of SP lining system can be expressed as:

$$J_{a1} = F_c \times \left[\phi \times \left(A_{sp} + 4H^2 - 4H\sqrt{A_{sp}} + 4H\sqrt{2A_{sp}} - 4\sqrt{2}H^2\right) + \varphi \times \left(A_{sp} + 4H^2 - 4H\sqrt{A_{sp}}\right)\right] \tag{8}$$

where J_{a1} is the cost of SP lining system (￥/y), F_c is the depreciation and maintenance rate, 0.1. A_{sp} is the area of the SP (m^2), ϕ is the price of high-density polyethylene and is estimated to be 30, (￥/m^2), φ is the price of EPS and is estimated to be 35, (￥/m^2).

4.2. The cost of electric heater and cooler

The economic model of electric heater and cooler can be expressed as:

$$J_{a2} = F_c \times a \times P_{ele} \tag{9}$$

$$J_{a3} = F_c \times \delta \times A_{coo} \tag{10}$$

where J_{a2} is the cost of electric heater (￥/y), and J_{a3} is the cost of cooler (￥/y), F_c is the depreciation and maintenance rate, 0.05. P_{ele} is the power of double-pipe electric heater (kW), a is the price of per electric heater power and is estimated to be 300 (￥/kW), A_{coo} is the heat transfer area of cooler (m^2), δ is the price of per cooler area and is estimated to be 1,600 (￥/m^2).

4.3. The cost of land

The economic model of land can be expressed as:

$$J_{a4} = 0.02 \times 1.1 \times A_{sp} \times C_{land} \tag{11}$$

where J_{a4} is land cost (￥), C_{land} is the land cost per unit area and is estimated to be 200 (￥/m^2).

4.4. The cost of condenser and preheater

The economic model of condenser and preheater can be expressed as:

$$J_{a5} = F_c \times A_{con} \times \alpha \quad (12)$$

$$J_{a6} = F_c \times A_{pre} \times \alpha \quad (13)$$

where J_{a5} is the cost of condenser and J_{a6} is the cost of preheater, F_c is the depreciation and maintenance rate, 0.05. A_{con} is heat transfer area of condenser (m^2) and A_{pre} is heat transfer area of preheater (m^2), α is the price of per area of condenser and preheater and is estimated to be 3,500 (￥/m^2).

4.5. The operating cost of pump

The economic model of pump can be expressed as:

$$J_{b1} = \frac{60 \times 60 \times 24 \times 365 \times \sum N_i}{3,600,000} \times \psi \quad (14)$$

where J_{b1} is the operating cost of pump (￥), N is the power of pump, ψ is the price of per electricity (￥/kWh).

The cost of the external heat exchanger and evaporator in the LT-MED system, pumps investment, civil installation and auxiliary equipments, manpower, pretreatment and electricity using by heater can be found in [10].

4.6. The cost of fresh water

The economic model of fresh water can be expressed as:

$$J = 1,000 \times \frac{\sum J_{ai} + \sum J_{bj}}{DD \times 365 \times 24} \quad (15)$$

where J is fresh water cost (￥/t), $\sum J_{ai}$ and $\sum J_{bj}$ are capital cost and operating cost, respectively (￥/y), DD is fresh water yield (kg/h).

5. The thermal and economic performance of solar desalination system

The key design and operating parameters controlling the performance of the system—the temperature of stream entering into the external heat exchanger, the temperature of stream returning to SP—were studied.

5.1. The temperature of stream entering into the external heat exchanger

When the SP area is 5,000 m^2; the feed flow rate is 0.003 kg/m^2/s; the temperature of stream returning to SP is 70℃; the heating steam temperature of the first effect is 65℃; the evaporation temperature in the last effect is 40℃ and the number of effects of LT-MED system is 10. When the temperature of stream entering into the external heat exchanger changes, the variations of the performance of system are shown in Figs. 3–5.

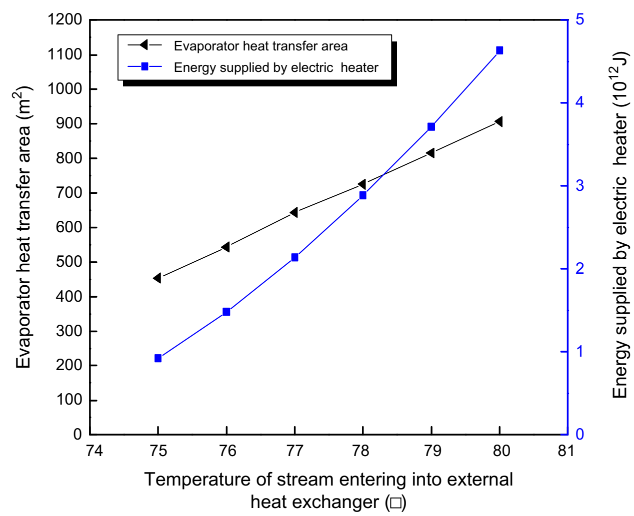

Fig. 3. Effect of the temperature of stream entering into the external heat exchanger on evaporator heat transfer area and the energy supplied by electric heater.

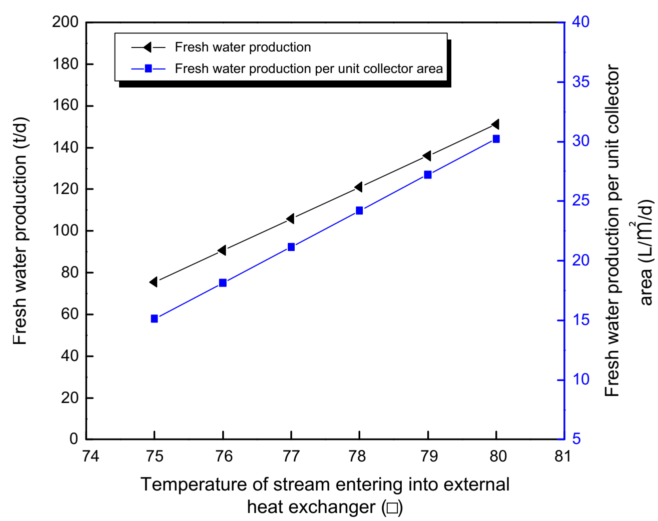

Fig. 4. Effect of the temperature of stream entering into the external heat exchanger on fresh water production and fresh water production per unit collector area.

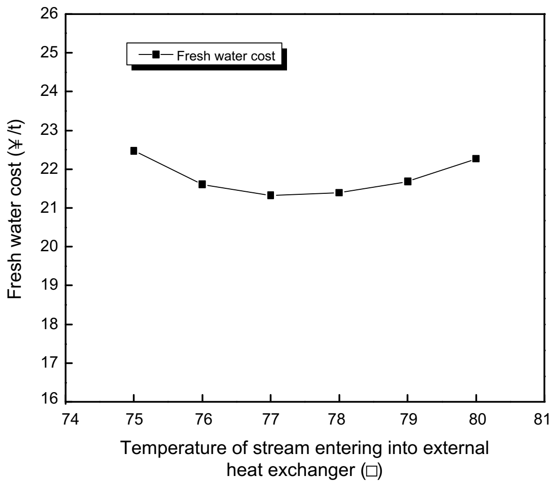

Fig. 5. Effect of the temperature of stream entering into the external heat exchanger on fresh water cost.

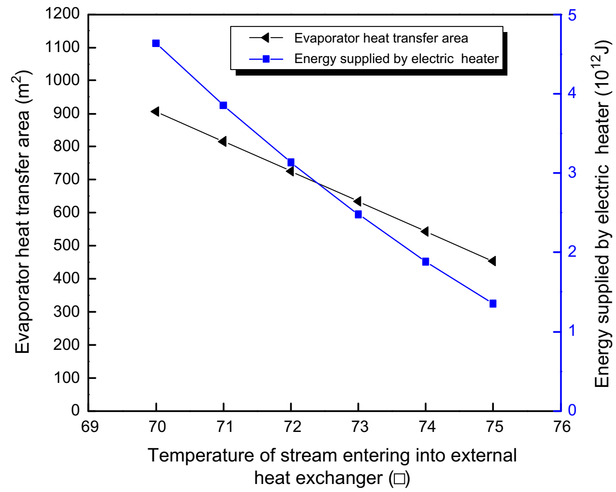

Fig. 6. Effect of the temperature of stream returning to solar pond on evaporator heat transfer area and the energy supplied by electric heater.

With the increasing of the temperature of stream entering into the external heat exchanger, the energy supplied by electric heater, evaporator heat transfer area, fresh water production and fresh water production per unit collector area increase greatly; and fresh water cost decreases firstly and then increases. The temperature of stream returning to SP and feed flow rate are constant, thus the SP supply stream temperature is constant. In order to increase the temperature of stream entering into the external heat exchanger, the electric heater must supply much more energy. At the same time, the thermal energy supplied by the SP system to the LT-MED system increase, so the evaporator heat transfer area, fresh water production and fresh water production per unit collector area increase. Under the calculation condition of this paper, when the temperature of stream entering into the external heat exchanger is 77℃, the fresh water cost reduces to the lowest price.

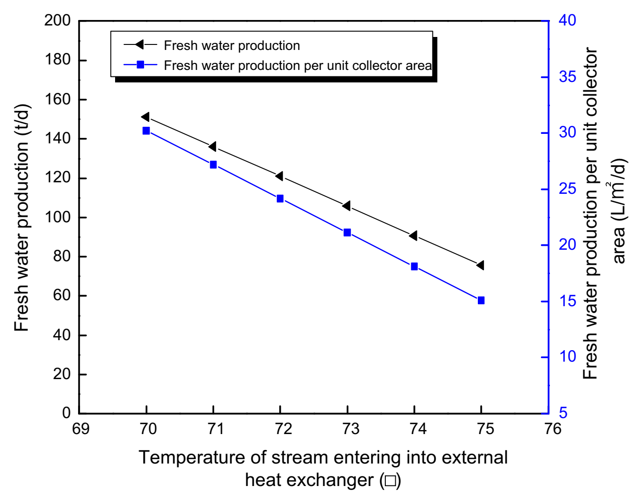

Fig. 7. Effect of the temperature of stream returning to solar pond on fresh water production and fresh water production per unit collector area.

5.2. The temperature of stream returning to solar pond

When the SP area is 5,000 m^2; the feed flow rate is 0.003 $kg/m^2/s$; the temperature of stream entering into external heat exchanger is 80℃; the heating steam temperature of the first effect is 65℃ and he evaporation temperature in the last effect is 40℃; the number of effects of LT-MED system is 10. When the temperature of stream returning to SP changes, the variations of the performance of system are shown in Figs. 6–8.

With the increasing of the temperature of stream returning to SP, the energy supplied by electric heater, evaporator heat transfer area, fresh water production and fresh water production per unit collector decrease greatly; and fresh water cost decreases firstly and then increases.

The temperature of stream entering into the external heat exchanger and feed flow rate are constant, and temperature of stream returning to SP increases, so the SP supply stream temperature increases and the electric heater supply less energy. At the same time, the temperature difference of stream through the external heat exchanger decreases, so the thermal energy supplied by the SP system to the LT-MED system decreases, thus the evaporator heat transfer area, fresh water production and fresh water production per unit collector area decrease. Under the calculation condition

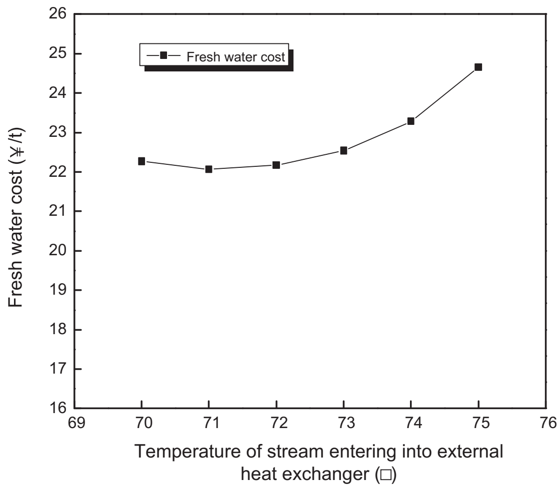

Fig. 8. Effect of the temperature of stream returning to solar pond on fresh water cost.

of this paper, when the temperature of stream returning to the external heat exchanger is 71℃, the fresh water cost reduces to the lowest price.

6. Conclusion

The thermal and economic performance on solar desalination system with SP and LT-MED is presented in this paper. Taking the actual project into account, the temperature of stream entering into the external heat exchanger, the temperature of stream returning to SP impacting on the system performance are analyzed, Under the calculation conditions of this paper, the following conclusions can be drawn:

With the increasing of the temperature of stream entering into the external heat exchanger, the energy supplied by electric heater, evaporator heat transfer area, fresh water production and fresh water production per unit collector area increase greatly; and fresh water cost decreases firstly and then increases.

With the increasing of the temperature of stream returning to SP, the energy supplied by electric heater, evaporator heat transfer area, fresh water production and fresh water production per unit collector decrease greatly; and fresh water cost decreases firstly and then increases.

Acknowledgements

This work is supported by the Fundamental Research Funds for the Central University (DUT10ZD109, the Technology Fund of Dalian Construction Commission, the Foundation of Key Laboratory of Liaoning Province for Desalination and the Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education.

Nomenclature

T_e	—	the stream temperature entering into the external heat exchanger, ℃
T_{sps}	—	the SP supply stream temperature, ℃
T_{spr}	—	the temperature of stream returning to SP,℃
C_p	—	specific heat of the solution, J/kg℃
K	—	thermal conductivity of the solution, W/m℃
Ρ	—	density of solution, kg/m^3
q_{ext}	—	the rate of heat extraction per unit area of the SP from the heat extraction layer, W/m^2
I	—	the solar-radiation intensity at the SP surface, W/m^2
X	—	positive downward with the origin (x = 0) at the surface of the pond, m
T_a	—	ambient temperature, ℃
H	—	the total depth of the SP, m
Q_L	—	the thermal energy cooled by the cooler, J
L	—	the number of cooled day, d
m_{sp}	—	the feed flow rate, kg/m^2/s
Q_e	—	the energy supplied by external heat exchanger, J
J_{a1}	—	the cost of SP lining system, ￥/y
F_c	—	the depreciation and maintenance rate
A_{sp}	—	the area of the SP, m^2
ϕ	—	the price of high-density polyethylene, ￥/m^2
φ	—	the price of EPS, ￥/m^2
J_{a2}	—	the cost of electric heater, ￥/y
J_{a3}	—	the cost of cooler, ￥/y
P_{ele}	—	the power of double-pipe electric heater, kW
A	—	the price of per electric heater power, ￥/kW
A_{coo}	—	the heat transfer area of cooler, m^2
δ	—	the price of per cooler area, ￥/m^2
J_{a9}	—	the land cost, ￥/y
C_{land}	—	the land cost per unit area, ￥/m^2
J_{a5}	—	the cost of condenser, ￥/y
J_{a6}	—	the cost of preheater, ￥/y
A_{con}	—	heat transfer area, m^2
A_{pre}	—	heat transfer area, m^2
α	—	the price of per area of condenser and preheater, ￥/m^2
J_{b1}	—	the operating cost of pump, ￥/y
Ψ	—	the price of per electricity,￥/kWh
J	—	fresh water cost, ￥/t
$\sum J_{ai}$	—	capital cost, ￥/y
$\sum J_{bj}$	—	operating cost, ￥/y
DD	—	fresh water yield, kg/h

References

[1] M.T. Ali, H.E.S. Fath, P.R. Amstrong, Comprehensive techno-economical review of indirect solar desalination, Renew. Sustain. Energy Rev. 15 (2011) 4187–4199.

[2] Tsung-Ching Chen, Chii-Dong Ho, Immediate assisted solar direct contact membrane distillation in saline water desalination, J. Membr. Sci. 358 (2010) 122–130.

[3] S.A. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci. 31 (2005) 242–281.

[4] A. Saleh, J.A. Qudeiri, M.A. Al-Nimr, Performance investigation of a salt gradient solar pond coupled with desalination facility near the Dead Sea, Energy 36 (2011) 922–931.

[5] Hazim Mohameed Qiblawey, Fawzi Banat, Solar thermal desalination technologies, Desalination 220 (2008) 633–644.

[6] Changzhi Liu, Wence Sun, Applied research on double heat source solar pond heat pump technology, J. Thermal Sci. Technol. 8 (2009) 80–84.

[7] Hongkun Pan, Experimental Study of Radiation Transmission and the Turbidity on the Solar Pond, Master Degree Thesis of Dalian University of Technology, 2005.

[8] Luopeng Yang, Thermodynamic Study on Low Temperature Multi-Effect Distillation in Dual-Purpose Power Plant Configuration, Master Degree Thesis of Dalian University of Technology, 2007.

[9] Jimmy Leblanc, Aliakbar Akbarzadeh, John Andrews, Lu. Huanmin, Peter Golding, Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency, Solar Energy 85 (2010) 3103–3142.

[10] Wenbo Chen, The Research on Solar Desalination System with Evacuated Tube Collectors, Master degree thesis of Dalian University of Technology, 2011.