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Exergetic analysis on the two-stage reverse osmosis seawater desalination system

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ABSTRACT

Cardona et al. proposed a two-stage RO system. As reported, this two-stage RO system presents about 20% energy saving compared with conventional single-stage RO system when pressure exchanger is excluded from consideration. Since two mixing steps occur in this two-stage RO system, will it still show advantages from the point of the second law of thermodynamics? This paper makes an exergetic discussion on this two-stage RO system and a conventional single-stage RO system. It is found that input pressure exergy accounts for a large proportion of total input exergy in RO systems. Two-stage RO system presents about 42% of rise in input pressure exergy and 33% of rise in total exergy destruction compared with single-stage system. The blending exergy destruction is much smaller than the total exergy loss. Therefore, the key points that improve the exergetic efficiency of this two-stage RO system lie in other ways. Increasing the product flow by heating feed is an effective method. Because of the higher investment, solar collector is not appropriate for application. Solar pond can also provide heat for feed water. Because the salt for the solar pond can be supplied by the brine exiting the first stage in this two-stage RO system, the main investment comes only from the construction of the solar pond. It is possible that within the life range of the solar pond, the increased investment can be offset by the increased product.

Keywords: Reverse osmosis (RO); Seawater desalination; Exergy; Solar energy

1. Introduction

Energy saving is one of the main reasons that accelerates the development of reverse osmosis (RO) desalination. With the improvement on the performance of membrane material, the operation pressure of reverse osmosis process has reduced from original over 10 MPa to present below 8 MPa [1,2]. In order to reduce the energy consumption further, more and more investigations had been done. One of the important achievements is energy recovery from the brine before disposal [3]. Attention has also been put to the hybrid process integrating distillation desalination and RO desalination. In this hybrid process the disposed brine from distillation unit is used as feedstock to the RO unit [4]. It is also reported that the product of RO unit is mixed with product of distillation unit in hybrid process [5]. Renewable energy has also been considered as the input energy of reverse osmosis desalination [6–9]. In usual cases, wind or solar energy is used to generate

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power to drive RO system. In conclusion, the applications of new modules have made reverse osmosis desalination more and more promising.

Multistage RO system means higher capital cost. In industry, multistage RO systems are usually employed in limited circumstances such as the case in which boron is required to be rejected to below acceptable limits [10]. A two-pass and two-stage RO system is introduced by AL-Enezi [11]. In this two-stage RO system, two blending processes are adopted, namely blending feed water with the brine exiting stage II and blending permeate from stage I with permeate from stage II. The first blending can reduce slightly the salinity of the feed and the required input pressure since brine exiting stage II is already pre-treated water. Higher recovery ratio can be achieved by blending permeates from stage I and stage II. This higher recovery ratio is realized at lower energy consumption for osmotic pressure and input pressure since the salt rejection for the first stage need not be quite high and the permeate from stage I typically is 1000–1200 ppm TDS. Cardona et al. investigate the energetic results of this two-pass and two-stage RO system and a single-stage system [12]. As reported from their work, the two-stage RO system shows excellent energy saving, membrane efficiency, and duration benefits when compared with single-stage system.

Although blending does not bring about energy loss, it does involve unavoidable exergy destruction from the point of the view of the second law of thermodynamics. As a result, will the choice of blending in the two-stage RO system still present advantage? Based on the work of Cardona et al. this paper makes a exergetic analysis on the two-pass RO system.

The performance of RO system varies with the temperature of feed water. Since the membrane cannot endure high temperature, solar energy can be used to heat the feed water. In this paper, the influence of the feed water temperature on the exergetic performance of the two-pass and two-stage RO system is also studied.

2. RO model for the two-stage reverse osmosis system

Fig. 1 draws the schematic diagrams of a two-stage system and a single-stage system.

In the two-pass and two-stage RO system, permeate exiting stage I achieves 1000–1200 ppm TDS. Some permeate exiting stage I is used as feed to stage II and others will then be blended with the permeate exiting stage II. I_{by-p} is by-pass index defined as the ratio of the permeate used to blend permeate exiting stage II to total permeate exiting stage I. Therefore, the ratio of permeate fed to stage II to the total permeate exiting stage I is $(1 - I_{by-p})$. The pressure gain is from pressure exchangers with the brine exiting stage I. The brine exiting stage II is blended with the feed seawater fed to the stage I in order to reduce the salinity of the feed. Operation data proposed by Cardona et al. for the two-stage reverse osmosis system are presented in Table 1.

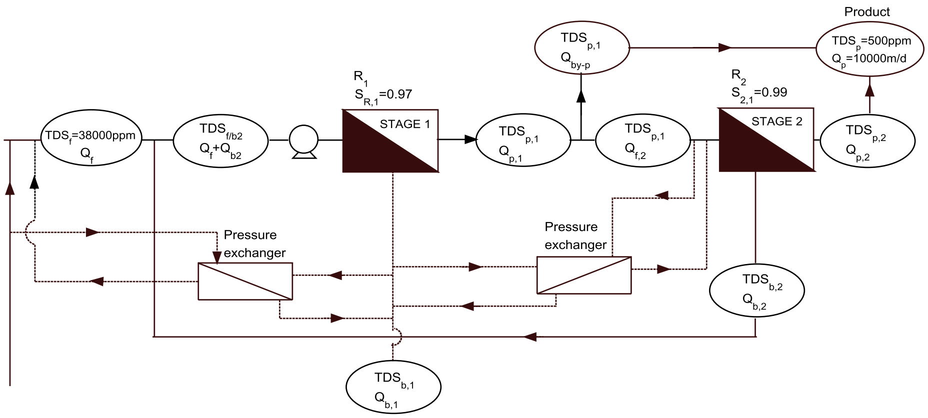
In the single-stage reverse osmosis system, the flow rate of the feed seawater is higher if the produced fresh water is required to possess the same desired salinity level. Operation data proposed by Cardona et al. for the single-stage reverse osmosis system are presented in Table 2.

As reported by Cardona et al., the two-pass and two-stage RO system shows about 20% energy saving over the conventional single-stage system.

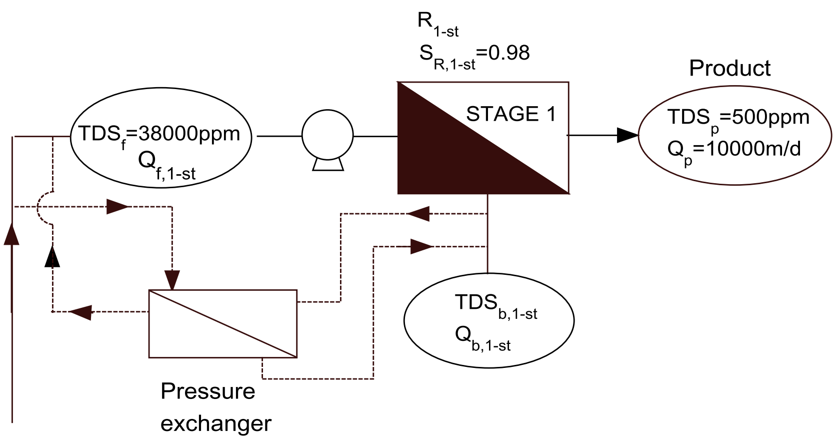
3. Exergetic analysis on the performances of the two-stage RO system and the single-stage RO system

Dincer demonstrates the linkages between energy and exergy [13]. The importance of the exergy on addressing the impact of energy resource utilization on the environment is highlighted. Exergetic analysis plays a great role on revealing whether or not it is possible to design more efficient energy systems. Exergetic analysis has also been proven to be a powerful tool in evaluating quantitatively the disadvantages of a process.

Although the two-stage and two-pass system shows energy saving compared with the conventional single-stage system as what Cardona et al. presented, blending process is adopted in the system. It is well known that blending does not bring any energy losses; it does involve unavoidable exergy destruction from the point of the view of the second law of thermodynamics. Will the two-stage and two-pass system still show advantages in term of exergetic efficiency? Furthermore, pressure exchanger is not taken into consideration in the investigation made by Cardona et al. because they consider that the values of recovery ratio are similar in single-stage systems and in the first stage of two-stage system. Therefore, they conclude that the energy recovery potential slightly changes between these two configurations. But we should note that part of the recovered energy is designed to drive the second stage in the two-stage system. As a result the net recovered pressure energy must be obviously different between these two configurations. Will the two-stage and two-pass system still present energy saving advantage over single-stage RO system when pressure energy recovery is taken into



(a) two-stage reverse osmosis system.



(b) single-stage reverse osmosis system.

Fig. 1. The schematic diagrams of the two-stage and the single-stage reverse osmosis systems.

consideration? Therefore, this work includes pressure exchanger into consideration. As shown in Fig. 1(a), some brine of the first stage flows into a pressure exchanger to recover the pressure energy for driving the second stage while the rest of the brine flows into another pressure exchanger for increasing the pressure of the feed.

3.1. Exergy modeling

The system configuration and the suggested design parameters are chosen to be the same as what Cardona et al. proposed. That is to say the operation parameters listed in Tables 1 and 2 are followed. Capacity is 10,000 m^3 per day. Salinity of the feed seawater is 38,000 ppm TDS. Operation temperature is 25℃.

Following equations are used to express the operation condition [12,14]:

$$\mathrm{TDS}_p = (1 - S_R) \cdot \mathrm{TDS}_f \tag{1}$$

$$Q_p = Q_f \cdot R \tag{2}$$

Table 1
Operation data of the two-stage reverse osmosis system

Recovery ratio R_1	$I_{by\text{-}p}$	Feed pressure (bar)	Equivalent recovery ratio, R_{eq1-2}	Energy consumption (KW h/m^3)	Overall energy consumption (KW h/ m^3)	Salt rejection, S_{R1}	Salt rejection, S_{R2}
0.47	0.38	66.52	41.2%	4.66	4.87	0.97	0.99

Table 2
Operation data of the single-stage reverse osmosis system

Recovery ratio, $R_{1\text{-}st}$	Feed pressure (bar)	Power requirement RO process (KW)	Equivalent recovery ratio, R_{eq1-2} (%)	Specific energy consumption (KW h/m^3)	Salt rejection, $S_{R,1\text{-}st}$
0.35	67.46	2260	35.0	5.67	0.98

$$Q_f = Q_P + Q_b \tag{3}$$

$$\text{TDS}_p = \frac{\text{TDS}_{P,1} \cdot Q_{by-p} + \text{TDS}_{P,2} \cdot Q_{p,2}}{Q_{by-p} + Q_{p,2}} \tag{4}$$

$$E_x = \int_{T_0}^{T} C_p \left(1 - \frac{T_0}{T}\right) dT + \int_{P_0}^{P} V dp \tag{5}$$

$$E_{xch} = \sum_{i=1}^{m} n_i \left[(e_{xch})_i + RT_0 \ln \frac{N_i}{N_{i0}} \right] \tag{6}$$

Eq. (1) gives the technical feasibility of single-stage system. Concentration of the water product is set according to the terminal application. Here the recommended value is 500 ppm TDS. When calculating the hydraulic pressure, the concentration polarization is ignored although it can increase the input pressure a little. Eqs. (2) and (3) are used to calculate the quantities of brine and feed when the recovery ratio R is known. Eq. (4) represents the relation of salt balance. Eq. (5) is used to calculate the physical exergy, namely heat exergy plus pressure exergy. Eq. (6) is used to calculate the chemical exergy. Here $(e_{xch})_i$ is the chemical exergy per molar ith ion in the base material. N_{io} and N_i are the concentration of the ith ion in the base material and the solution, respectively. Feed seawater is chosen to be the base material, namely dead state. The concentration and the corresponding chemical exergy of the ith ion in the base material can be found in reference [14] and are listed in Table 3. To be strict, seawater cannot be considered as absolute ideal solution. Therefore, N_{io} and N_i should be the activities of base material and the solution. But since all the related concentrations are not high, concentration is used to calculate E_{xch} instead of activity in this paper.

3.2. Results and discussion

In Table 4, the results of the exergetic analysis are presented.

Blending exergy destruction #1: Exergy destruction owing to blending feed water with brine exiting stage II.

Blending exergy destruction #2: Exergy destruction owing to blending part of product exiting stage I with product exiting stage II.

From Table 4, it can be see that the calculated results of input chemical exergy are smaller than the sum of output chemical exergy and rejected chemical exergy. Therefore positive work is needed to reduce the TDS of feed sea water. Smaller feed flow rate accounts for smaller input chemical exergy of the two-stage system.

Although flow rate of rejected brine of two-stage system is smaller than that of single-stage system, rejected brine of two-stage system shows higher TDS. As a result, the rejected chemical exergy is about 6% larger too.

Recoverable energy is a significant fraction of total energy consumption. Energy recovery potential mainly depends on brine flow rate and on its pressure. Brine flow rate decreases with the recovery ratio whereas brine pressure increases with it. Energy recovery potential is neglected in the report made by Cardona et al. because they consider that the values of recovery ratio are similar in single-stage systems and in the first stage of two-stage system. Therefore, they conclude that the energy recovery potential slightly changes between these two configurations and they obtain the conclusion of 20% energy saving for

Table 3
Concentration and the corresponding exergy of the ith ion in the base material

Ion	Ca^{2+}	Cl^-	Na^+	HPO_4^{-2}	SO_4^{-2}
Concentration	4×10^{-4}	1.9×10^{-2}	1.056×10^{-2}	5×10^{-8}	8.84×10^{-4}
Exergy (kJ/kmol)	717.4	117.52	343.83	859.6	598.85

Table 4
Exergetic analysis on the two-stage and two-pass system and the single-stage system unit: KW h/m^3

	Input pressure exergy	Input chemical exergy	Output chemical exergy	Rejected chemical exergy	Blending exergy destruction #1	Blending exergy destruction #2	Total exergy loss
Two-stage	31.3918	0.6463	−0.0472	2.00361	0.0686	0.0894	28.2864
Single stage	22.0141	0.8076	−0.0521	1.88405	–	–	21.1613

the two-stage system. But we should also note that nearly 40% of the recovered energy is used to drive the second stage in the two-stage system. As a result, the net recovered pressure energy should be different between these two configurations. In this paper, pressure exchanger is included into the investigation of exergetic performance between the two-stage system and the single-stage system. Here, a 0.96 Pb/Pf ratio for two-stage RO system and a 0.90 Pb/Pf ratio for single-stage RO system are proposed.

In the two-stage RO system, although a higher equivalent recovery ratio and smaller input pressure are presented, the pressure recovery factor will still bring significant impact on the analysis results. From Table 4, it can also be found that input pressure exergy accounts for a large proportion of total input exergy. At fixed capacity, 10,000 m^3 per day, although two-stage system needs smaller feed flow rate and operation pressure, it shows about 42% of increase in input pressure exergy. It can also be seen from Table 4, when pressure exchanger is considered, the two-stage system presents about 33% of increase in total exergy destruction compared with the single-stage system. These are because about 40% of recovered pressure energy is used to drive the second stage and only 60% recovered pressure energy is used to increase the pressure of the feed in the two-stage RO system.

Blending process occurs twice in the two-stage system, namely blending the feed water with the brine exiting stage II and blending part of the product exiting stage I with the product exiting stage II. As for the first blending, the TDS value of the brine exiting stage II is much lower than that of the feed seawater and the flow rate of the brine is much smaller than that of the feed seawater, so the blending exergy destruction is small. As for the last blending, flow rate of the product exiting stage I is larger than that of the product exiting stage II and the values of TDS are quite approaching, so the associated blending exergy destruction is also small. In total, blending exergy destruction is several orders smaller than the total exergy loss. So it can be concluded that although blending occurs twice in two-stage system, the corresponding exergy destruction is not dominant in the total exergy loss. Blending will not impose great influence on the exergetic efficiency of this two-stage RO system. The key potential of performance improvement of this two-stage system lies in other factors.

4. Exergetic improvement potential

In general, industry plants of water desalination, solar energy, or other renewable energy is consumed in the way of power generation [6–9]. But because of reasons of cell material cost and energy transfer efficiency, it is expensive to transfer solar energy to power.

Given salinity of feed water and salt rejection of the membrane elements, the product of RO system varies with the temperature of the feed water by the following expression [12].

$$Q = Q_0 \cdot 1.03^{T_f - 25} \tag{7}$$

Here, Q and Q_0 represent the product flow rates at T_f (℃) and ambient temperature, 25℃, respectively. Therefore raising the temperature of feed water can enhance recovery ratio effectively. But the temperature of feed water cannot be quite high because membrane used for RO system cannot sustain quite high working temperature. Usually, the favorable temperature range is from 20℃ to 35℃.

Under the same operation data listed in Table 1 and at fixed product flow rate (10,000 m^3/d), the trend between working temperature and total exergy destruction is diagramed in Fig. 2. As shown in Fig. 2, total exergy destruction will fall with working temperature. The main reason is the resulted reduction in quantities of the feed flow rate. When working temperature comes to 35℃, the total exergy destruction can be reduced by about 13.8%.

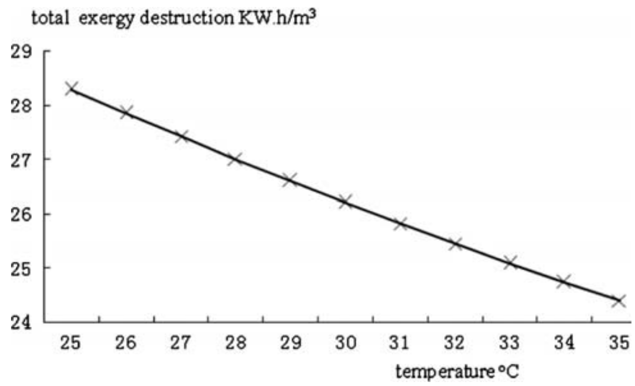


Fig. 2. The trend between working temperature and total exergy destruction.

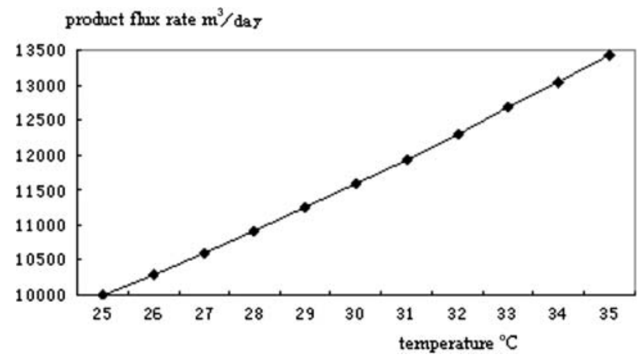


Fig. 3. The product flux rate vs. the working temperature.

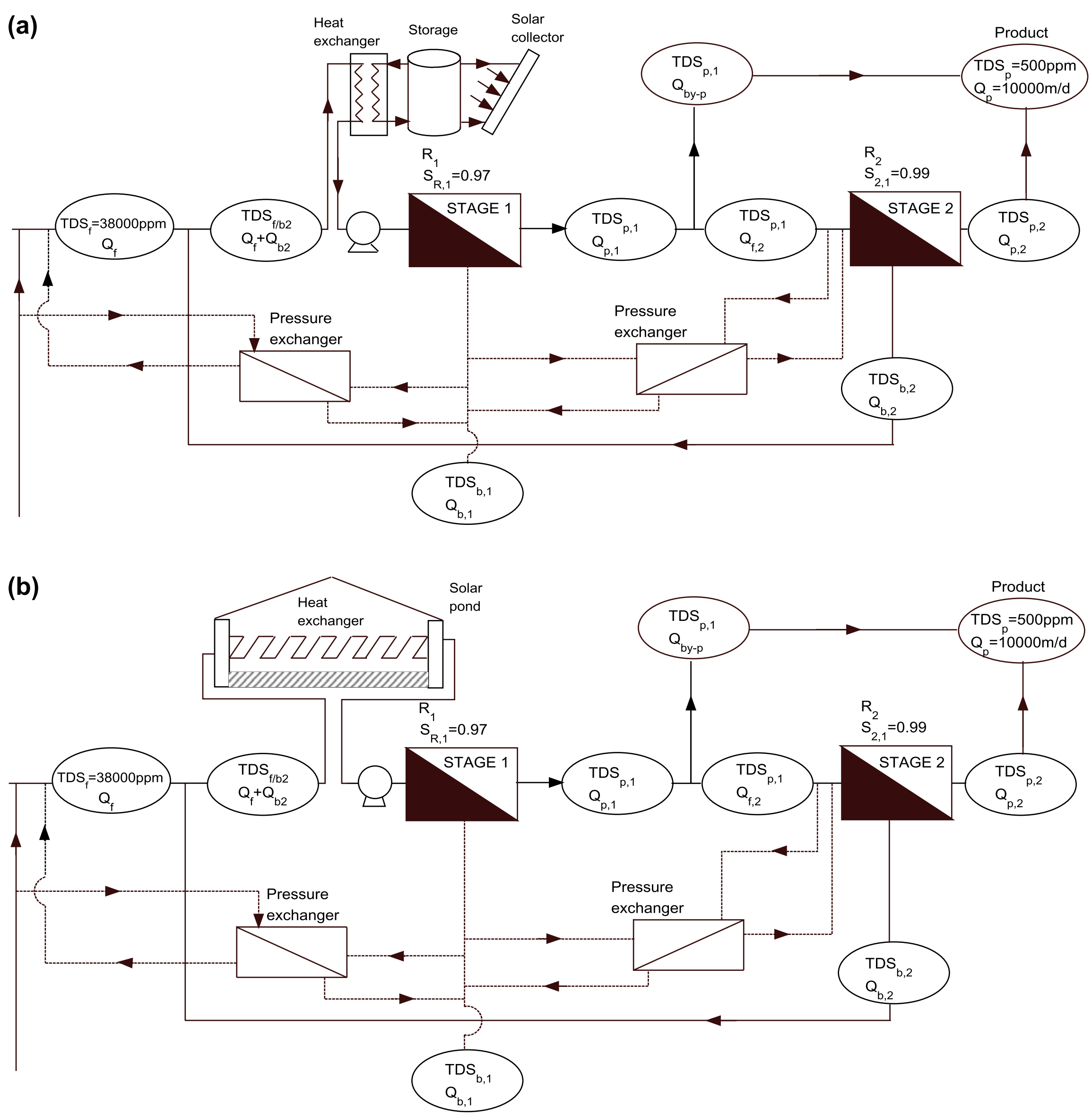


Fig. 4. Two-stage RO system preheated by solar energy.

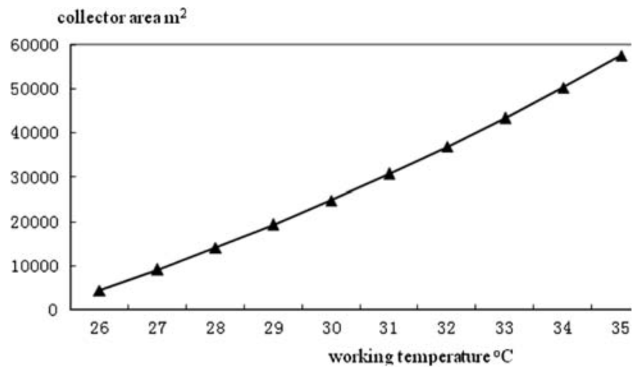


Fig. 5. The needed collector area vs. working temperature.

In Fig. 3, the product flow rate is plotted vs. the working temperature on the basis of the same operation data as listed in Table 1 and at fixed feed water flow rate (24271.8 m^3/d). As shown in Fig. 3, product flux rate will increase with working temperature. When working temperature comes to 35℃, the product flow rate can be increased by about 34%.

Because the working temperature can only be between the range from 20℃ to 35℃, it is not worthwhile to burn fossil fuel to heat the feed water because fossil fuel belongs to energy with high chemical exergy. Furthermore, fossil fuel is exhaustible. If not, the high input chemical exergy of fossil fuel will reduce exergetic efficiency of the system obviously. Feed water can be heated by heat exchange with industry waste heat. But where industry waste heat is not available, solar energy will be an appropriate choice [15]. Although radiation energy is still energy with high value of exergy, the advantage resulted from solar energy is that we need not pay for it at present. Solar collector or solar pond can be used to provide low temperature heat for RO system. Fig. 4 is the diagram of a two-stage RO system in which feed water is heated by solar energy.

As shown in Fig. 4(a), solar radiation energy will heat the liquid running through the solar collector. Liquid exiting solar collector will then heat the feed water. Storage barrel acts as heat storage unit in order to prolong work hours in cloudy or rainy days. Auxiliary fuel equipment is used to deal with emergency. Eq. (8) is the basic equation for calculating the heat absorption of the solar collector [16].

$$Q_u = A_c F_R [S - U_L (T_{f,i} - T_a)] \quad (8)$$

Here, Q_u is the valid heat absorbed by the solar collector. F_R is the heat removal factor of the solar collector. A_C is the area of the collector. U_L represents the overall heat loss coefficient. $T_{f,i}$ and T_a indicate the liquid inlet temperature and the ambient temperature, respectively.

The feed flow ($Q_f + Q_{b2}$) of two-stage system usually has lower TDS than that of single-stage RO system. If the working temperature of the two-stage system is increased, the TDS of feed flow ($Q_f + Q_{b2}$) can be decreased further as a result of the increased Q_{b2}.

According to Eqs. (1)–(8), Fig. 5 plots the needed collector area vs. working temperature on the basis of the operation data listed in Table 5 and at fix feed water flow, 24271.8 m^3/d. Investment in solar collector is proportional to the collector area. The investment in solar collector is about 1800 Yuan RMB/m^2 and the selling price of the fresh product water is about 6 Yuan RMB /m^3. On the basis of the operation situation listed in Table 1 and at fixed seawater flow, 24271.8 m^3/d, Fig. 6 let us observe the difference between the additional benefit coming from increased product output and the additional investment in the solar collector. As shown in Fig. 6, in the life range of the solar collector, the increased benefit cannot offset the increased investment. Therefore solar collector is not favorable for application.

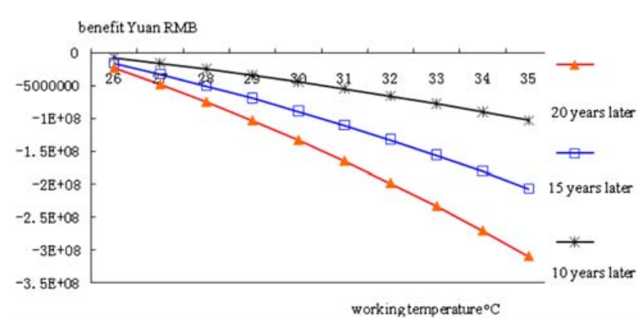


Fig. 6. The difference between the additional benefit coming from increased product output and the additional investment in the solar collector.

Table 5
Operation data of the solar collector

Heat removal factor, F_R	Overall heat loss coefficient, U_L (W/m^2 ℃)	Liquid inlet temperature, $T_{f,i}$ (℃)	Ambient temperature, T_a (℃)	Efficiency of the heat exchanger
0.78	3.03	20	18	0.8

The feed water can be heated by solar pond also. Heat exchanger is put at the bottom of the solar pond. As shown in Fig. 4(b), the feed flow ($Q_f + Q_{b2}$) of two-stage system is pumped through the heat exchanger before entering the high pressure pump. At fix feed water flow, 24271.8 m^3/d, a solar pond with area of 40,000 m^2 and depth of 3 m can heat the feed water up to 35℃. The salt for the solar pond can be supplied by the brine exiting the first stage after it is condensed. Therefore, the main investment of the solar pond comes from the constructing investment. When the constructing investment of the solar pond is less than 250 RMB/m^2 and the life of the solar pond is more than 16 years, it is enough for the increased product to offset the increased investment.

5. Conclusion

Cardona et al. proposed the two-stage and two-pass RO system. As reported, this RO system presents about 20% energy saving compared with single-stage RO system. But blending processes, which mean unavoidable exergy destruction, occur in this two-stage and two-pass RO system. Furthermore, pressure exchanger is not included into consideration.

Input pressure exergy accounts for a large proportion of total input exergy for both the two-stage system and the single-stage system. But two-stage system produces about 42% of rise in input pressure exergy.

The two-stage system presents about 33% of rise in the total exergy destruction compared with the single-stage system when pressure exchanger is considered. The blending exergy destruction is several orders smaller than the total exergy loss.

Solar energy can be used to heat the feed water to improve the performance. Because of the higher investment, the solar collector is not appropriate for application. Because the salt for the solar pond can be supplied by the brine exiting the first stage, the main investment comes from the construction of the solar pond. It is possible that within the life range of the solar pond, the increased investment can be offset by the increased product.

Nomenclature

Symbols

A	—	area
C_p	—	specific heat (J/(kg ℃))
E_x	—	exergy (J)
E_{xch}	—	chemical exergy (J)
F_R	—	heat removal factor of the solar collector
$I_{by\text{-}p}$	—	by-pass index
n_i	—	mole concentration
N_i	—	concentration of *i*th constituent in the solution
P	—	pressure (bar, Pa)
Q	—	flux rate (m3/d, namely cubic meter per day)
Q_u	—	valid heat absorbed by the solar collector (J)
R	—	recovery ratio
S_R	—	salt rejection
T	—	temperature (℃, K)
TDS	—	total Dissolved Salt (g/l, ppm)
U_L	—	overall heat loss coefficient (J/m^2 K)

Subscripts

a	—	ambient
b	—	brine
by-p	—	by-pass
C	—	collector
eq 1–2	—	equivalent
f	—	feed
p	—	permeate

Acknowledgments

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