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Exergy analysis of a solar-assisted MED desalination experimental unit

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ABSTRACT

A five-effect distillation desalination experimental unit thermally assisted by a flat plate solar collector is thermo-economically investigated. The exergy-based methology is used to identify the specific contributions of any sub-process to the overall exergy destruction under a series of different operating conditions. The integration of the solar heat collectors using the heating carrier medium of hot water with multi-effect distillation (MED) is an effective combination for solar desalination. The calculation results reveal that the exergy efficiency in individual MED effects is as high as the design of MED contributes to reducing the exergy destruction in pre-heaters. Reasonably reducing heat transfer temperature difference would serve as a priority for an efficient design. Appropriately increasing heating steam temperature, which will extend the total evaporation range, would be a possible way to improve the systematic efficiency due to lowering the dominant exergy destruction of evaporation process in evaporators.

Keywords: Multi-effect distillation; Exergy efficiency; Exergy destruction; Desalination

1. Introduction

Seawater desalination has proven to play an important role in solving fresh water scarcity situations in northern coastal China. However, the most important factors related with high water costs in desalination industry are the high energetic costs and capital costs. Thus, the application of renewable energy replacing conventional fossil fuel and minimization of energy consumption may be the promising ways to effectively reduce water costs. Solar energy as a kind of renewable energy to power desalination facilities is receiving increased interest as the conventional fossil fuel is depleting and its price is growing expensive.

It may be one of the most promising that solar energy powers the desalination processes by providing thermal energy. There are a variety of desalination methods among which low-temperature multi-effect distillation (LT-MED), multi-stage flash (MSF) and reverse osmosis (RO) dominate the desalination market. Solar energy can be converted to thermal energy via solar collectors or electricity through Photovoltaic cells as well as concentrated solar power plants. The analyse of the combination of concentrated solar power plants for electric generation with RO desalination plants shows that their water costs are higher than those of desalination methods powered by conventional fossil

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fuel [1–4]. The possible reason may attribute to the low energy density of solar and the high capital costs of the solar electricity generation which account for the foremost water cost. Since electricity is a kind of high-grade energy compared with low temperature steam or hot water generated by solar radiation, a solar-assisted thermal desalination method may pave the way to more accessible fresh water. Solar energy density is low and varies with time and geography. MSF demands precise pressure control and constant pressure difference between stages and requires relatively high temperature heating source, while LT-MED adapts to partial loading operating situations and works at low temperature conditions. Therefore, the combination of LT-MED and solar thermal energy may be an economic way in the small-scale desalination plants especially in remote locations.

Much significant research has been done to utilize solar thermal energy for distillation desalination processes. The distillation process in solar still, which is the most popular, has been investigated in great details and many installations have been built up based on the single basin solar still [5–7]. However, the most advantaged system of solar still under the most favourable solar radiation conditions is characterized as low efficiency systems, which does not exceed 40–50% [8]. The following possible reasons may respond for its low efficiency. To begin with, the latent heat of condensation is not recycled. Even if the multi-effect basin solar stiller is introduced, there seems to be little improvement in its water production efficiency. Next, the low heat transfer coefficient of natural convection limits the efficiency of distillation. Finally, the high thermal capacity of seawater in the solar distiller lowers the driving force of the evaporation process. Due to the advantages of MED in low temperature evaporating, thin liquid film on the outer surface of horizontal tubes and high heat transfer efficiency in the process of falling film evaporation and condensation, the water production rate can approach 20 times as much as a single effect solar distillation. The recent development in the solar thermal collector has made the solar-assisted MED desalination to the point of competing technically and economically with conventional fuel desalination. Several solar-assisted MED demonstration units have obtained relatively high performance [9–13]. The solar-assisted MED units integrated with absorption vapour compression were experimentally investigated [14,15]. These researches have proved its feasibility.

The present research on solar-assisted MED desalination unit can be further developed in the following two aspects. Firstly, in the above mentioned configurations, oil is utilized as heat carrying medium in the solar collector to generate pressured steam driving MED evaporators. But the temperature of pressured steam does not match the heating steam temperature for the first effect, about 65℃, which will lower systematic energy efficiency. As the oil recycle schemes need extra energy consuming pump and heat exchanger and too complicated, they may not work on the solar-assisted MED units which are usually small scale in remote area. Secondly, as the solar collectors account for the foremost cost of water production, it is of importance to improve the efficiency of MED subunit. A multiple attempts have been expended on analysing the energetic efficiency of MED units based on the 1st law. However, they have only seen limited success in reducing water production cost as the 1st law analysis is not adequate enough to reveal the actual margins for efficiency improvement. Some efforts have been made to quantify energy inefficiencies by introducing the exergy-based methodology [16,17]. But their analysis is not on experimental data but on theoretical calculating ones. Thus, they may not exactly pinpoint the possible way to decrease the exergy destruction.

In order to generate an in-depth insight towards its behaviour and its improvement, an exergy analysis was investigated on a solar-assisted MED experimental unit. A five-effect distillation experimental unit thermally assisted by a flat plate solar collector with heat carrying medium of water was presented and a series of experiments were performed on the five-effect distillation experimental unit. Based on the experimental data, the paper indentified the specific contributions of any sub-process to the overall exergy destruction under a series of different operating conditions and obtained the detailed information of exergy destruction in individual evaporator and the MED.

2. Experimental facility

A schematic flow diagram of the experimental facility is shown in Fig. 1. The desalination system consists of two sub-units: a solar thermal subunit and a MED subunit. The solar thermal subunit includes solar heat collectors and flash evaporator connected to the top effect evaporator. Hot water, heating carrier medium, is naturally circulated through the solar collectors and heated to the desired temperature. The heated water is introduced to flash evaporator where the solar heated water is flashed under vacuum condition. The flashed vapour releases from the top and flows to heat the MED sub-unit.

The MED sub-unit mainly contains five-effect evaporators with falling film horizontal tubes

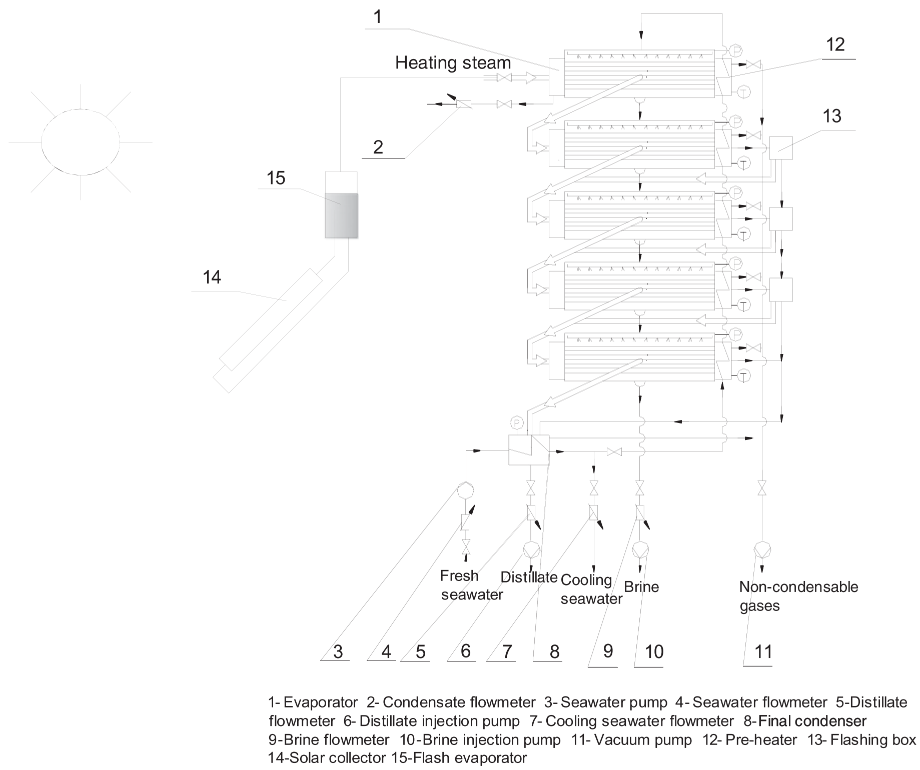

Fig. 1. Schematic diagram of the experimental setup.

vertically stacked one on top of the other. A picture of the five-effect distillation desalination setup is shown in Fig. 2. Seawater is pre-heated in the final condenser eight by condensing the vapour produced in the last

Fig. 2. Picture of the experimental five-effect distillation desalination setup.

evaporator. The pre-heated seawater passes successively through pre-heaters 12 to increase its temperature close to the saturated one in the top evaporator. On leaving the top most pre-heater, the feed seawater is sprayed in the form of thin film on the outside of the succeeding rows of tubes arranged horizontally. The flashed vapour condenses in the top effect and the condensate returns back to the solar collector. After the brine absorbs the latent heat, part of it is evaporated and the rest is introduced to the next effect. The evaporated vapour is condensed in the next evaporator. The processes of spray, evaporation and condensation are repeated in successive effects. The distilled water is collected at the flashing box 13 and the vapour produced by the flashing process together with the vapourized vapour in the evaporator works as heating source for the next effect. The vacuum pump 11 continuously works to extract non-condensable gas in the final condenser and pre-heaters which is released during the process of falling film evaporation.

Compared with other solar-assisted desalination unit, this process has the following advantages:

(1) The cost of solar thermal sub-unit is greatly reduced. Hot water as a kind of low-grade energy is implemented as the heating source for the MED

sub-unit, thus the low cost plate solar collectors rather than expensive parabolic collectors are required. This is of great significance to effectively reduce the water cost by reducing the investment of the solar thermal sub-unit.

(2) The thermal solar unit does not need to pump a large amount of water through solar collectors because the heat carrying medium of hot water is naturally circulated.

(3) The MED sub-unit saves pump work for pumping brine between evaporators as brine cascades downwards by gravity in the stacked arrangement.

Due to the limitation of laboratory condition, the in-door tests of the MED sub-unit were carried out to evaluate the thermodynamic performance of the elements and system in the MED.

3. Exergy models

The exergy-based methodology is applied to calculate the exergy budgets for each element. The exact allocation of losses due to irreversibility was identified. The specific exergy of seawater or brine consists of three contributions: thermal exergy related to temperature, mechanical exergy related to pressure and chemical exergy involved salt concentration variation .

$$e = e^{\mathrm{CH}} + e^{\mathrm{T}} + e^{\mathrm{P}} \tag{1}$$

Where the specific thermal exergy is expressed as:

$$e^{\mathrm{T}} = C_p \times \left(T - T_0 - T_0 \ln \frac{T}{T_0}\right) \tag{2}$$

The specific mechanical exergy is calculated by using (3)

$$e^{\mathrm{P}} \approx \frac{p - p_0}{\rho_1} \tag{3}$$

The specific chemical exergy is obtained as [18] follows:

$$e^{\mathrm{CH}} = RT_0 \sum \ln \frac{X_i}{X_{i,0}} \tag{4}$$

The exergy destruction in the MED sub-unit shown in Fig. 1 takes place in four sub-processes as follows:

- The overheated brine flashes and produces a very low amount of vapour at the outlet of a brine distributor in an evaporator. The exergy destruction due to brine flash in No i effect evaporator is given by

$$I_i^{\mathrm{bf}} = E_{\mathrm{b}_{i-1}} - E_{\mathrm{b}_{i-1}-\mathrm{d1}_i} - E_{\mathrm{d1}_i,\mathrm{vap}} \tag{5}$$

- Phase changes take place on both sides of a horizontal tube which includes internal vapour condensing and external falling film evaporation of brine as shown in Fig. 3. The exergy destruction due to evaporation in No i effect evaporator is calculated as

$$I_i^{\mathrm{eva}} = D_i \times r_i \times \left(\frac{1}{t_{b_i}} - \frac{1}{t_{e_{i-1}}}\right) \times t_0 \tag{6}$$

- Part of the accumulated condensate flashes in a flash box due to the condensate saturated pressure higher than in the flashing box as shown in Fig. 4. The exergy dustruction due to condensate flash in No. i flash box is given by

$$I_i^{\mathrm{cf}} = E^{\mathrm{T}}_{\mathrm{e}_{i-1,\mathrm{cond}}} - E^{\mathrm{T}}_{\mathrm{e}_{i-1,\mathrm{cond}}-d2_i} - E^{\mathrm{T}}_{\mathrm{d2}_i,\mathrm{vap}} \tag{7}$$

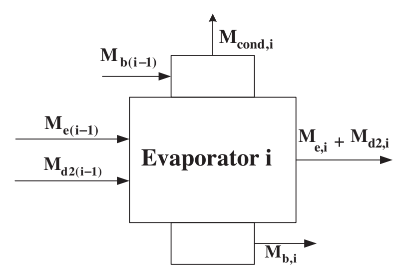

Fig. 3. Schematic representation of No. i effect evaporator.

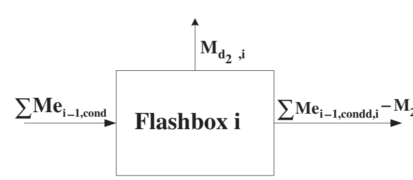

Fig. 4. Schematic representation of No. i flash box.

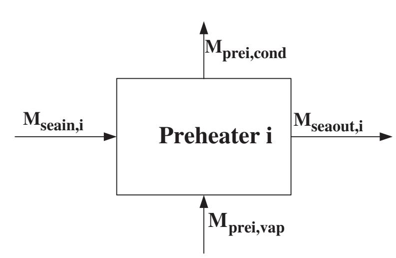

Fig. 5. Schematic representation of No. i pre-heater.

- The feed seawater is pre-heated in the pre-heater by a finite quantity of vapour. The exergy destruction in No. i pre-heater is given as

$$I_i^{\mathrm{pre}} = E_{\mathrm{seain}_i}^{T} - E_{\mathrm{seaout}_i}^{T} + E_{\mathrm{pre}_i,\mathrm{vap}}^{T} - E_{\mathrm{pre}_i,\mathrm{cond}}^{T} \tag{8}$$

The exergy efficiency of MED is expressed as

$$\eta_{\mathrm{es}} = \frac{E_{\mathrm{last,vap}}^{T} + E_{\mathrm{last,b}} - E_{\mathrm{seain,b}}}{E_{\mathrm{e0}}^{\mathrm{T}}} \tag{9}$$

4. Results and discussion

The designing parameters of the experimental unit are as follows: the heating steam temperature is 70℃, the evaporating temperature in the last effect is 54℃, the temperature of fresh seawater is 20℃, the salinity of fresh seawater has the value of 3.4%, the concentration of brine is 2, the rated capacity of produced water is 300 kg/h and the environment state is 20℃, 101.3 kPa.

The results of the exergy destruction and the percentage share of the overall exergy destruction for the designing condition are presented in Table 1. Table 1 shows that the exergy destructions in pre-heaters are much smaller than those in evaporators, which proves the design of the MED sub-unit to be efficient. The seawater pre-heater, shown in Fig. 6, is selected as coil heat exchanger, thus its terminal temperature difference can be designed as low as possible. As the pre-heater consumes the most un-condensable vapour at the outlet of a horizontal tube to increase the feed seawater temperature, the vapour extracted with non-condensable gas is obviously reduced. Therefore, the negative effect of non-condensable gas on the heat transfer process is limited in the pre-heater rather than the evaporator. As a result, the systematic heat transfer efficiency can be further increased.

It can also be observed that the exergy destructions due to heat exchange in evaporators are the dominant.

Table 1
Results of the exergy destructions in all effects

	No.1 evaporator		No.2 evaporator		No.3 evaporator		No.4 evaporator		No.5 evaporator	
	I (kW)	(%)	I (kW)	(%)	I (kW)	(%)	I (kW)	(%)	I (kW)	(%)
Brine flash	0.000	0.0	0.010	1.9	0.006	1.1	0.006	0.9	0.006	0.9
Evaporator	0.456	92.5	0.481	91.1	0.505	91.6	0.554	81.5	0.639	99.1
Flash box	0.000	0.0	0.004	0.8	0.012	2.2	0.098	14.4	0.000	0.0
Pre-heater	0.037	7.5	0.033	6.2	0.028	5.1	0.022	3.2	0.000	0.0
Exergy efficiency (%)	58.9									

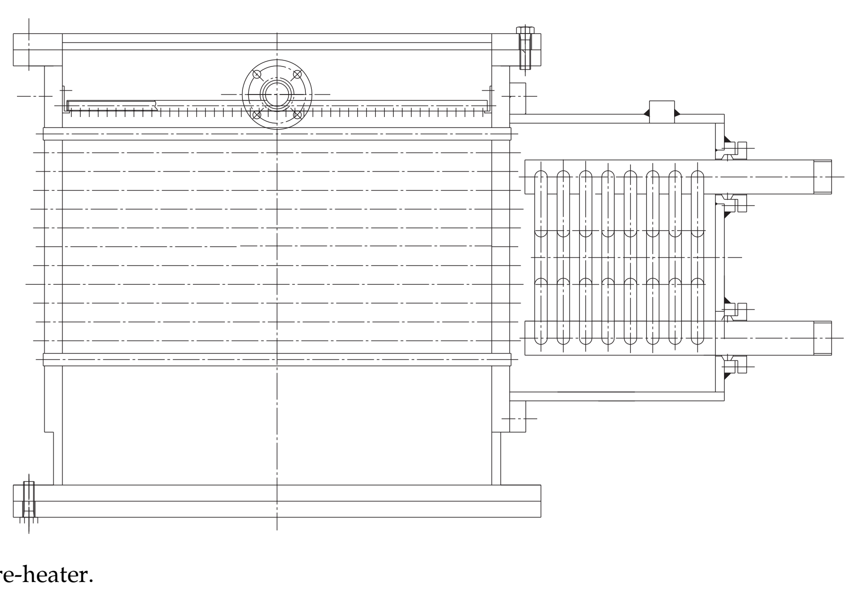

Fig. 6. Structure of pre-heater.

Table 2
Results of the exergy destructions for different heating steam temperatures

	70℃		80℃		90℃	
	I (kW)	(%)	*I* (kW)	(%)	*I* (kW)	(%)
Brine flashe	0.028	1.0	0.032	1.4	0.029	1.6
Evaporator	2.636	91.0	1.876	81.0	1.410	76.9
Flash boxes	0.115	4.0	0.147	6.3	0.184	10.0
Pre-heater	0.120	4.1	0.262	11.3	0.210	11.5

The reason is that the falling film evaporation is the irreversible process with the highest entropy generation. Due to its sensitive to the heat transfer temperature difference in evaporator, ΔT, reducing ΔT contributes to improve the exergy efficiency. However, excessively reducing ΔT will cause heat transfer area to sharply increase ΔT, about 2.6℃. In this experiment, it has been proved to be an optimal one in a large-scale MED desalination plant in China [19]. This small heat transfer temperature difference is lower than the values in other experimental and simulation research.

Table 2 presents the exergy destructions for different heating steam temperatures when the capacity of produced water keeps the rated one. It is evident that exergy destructions in evaporators decrease obviously with an increase in heating steam temperature while the other sources increase. The exergy destructions in evaporators are mainly caused by a decrease in latent heat with an increase in heating steam temperature. This tendency tells that high temperature heating steam would contribute to increasing the exergy efficiency of MED sub-unit. For higher heating steam temperature more evaporators can be arranged, which is of great significance for the solar-assisted MED desalination system to reduce water cost. Thus, increasing heating steam temperature may be a possible way to reduce the water cost for the solar-assisted MED desalination plant. However, the heating steam temperature is usually controlled below 70℃ due to the scaling and corrosion problem.

5. Conclusions

A flow diagram of a solar-assited MED desalination unit is presented and a five-effect distillation desalination experimental unit was built and tested. The integration of the solar heat collectors using the heating carrier medium of hot water with MED is an effective combination for solar desalination. An exergy-based methology is used to identify the specific component of any sub-process to the overall exergy destruction under a series of different operating conditions. The exergy analysis highlighted that the individual effect evaporator has high exergy efficiency as the design of MED contributes to reducing the exergy destruction in pre-heaters. Reasonably, reducing heat transfer temperature difference would serve as a priority for an efficient design. Appropriately increasing heating steam temperature, which will extend the total evaporation range, would be a possible way to improve the systematic efficiency due to lowering the dominant exergy destruction of evaporation process in evaporators.

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Nomenclature

C_p	—	specific heat (kJ/kg·K)
D	—	evaporating vapour flow rate (kg/s)
E	—	exergy (kW)
e	—	specific exergy, kJ/kg
I_i^{bf}	—	exergy destruction due to brine flash in No. *i* effect evaporator (kW)
I_i^{eva}	—	exergy destruction due to evaporation in No. *i* effect evaporator (kW)
I_i^{cf}	—	exergy destruction due to condensate flash in No. *i* flash box (kW)
I_i^{pre}	—	exergy destruction in No. *i* pre-heater (kW)
P	—	pressure (kPa)
r	—	latent heat (kJ/kg·K)
R	—	Universal constant of gases
T	—	temperature (K)
T	—	temperature (℃)
X	—	concentration
ρ	—	density (kg/m^3)
η_{es}	—	exergy efficiency of MED

Superscripts

CH	—	chemical
T	—	thermal
P	—	mechanical
bf	—	brine flash
eva	—	evaporation
cf	—	condensate flash
pre	—	pre-heater

Subscripts

b	—	brine
Con	—	condensate
d1	—	brine flash at the outlet of distributor
d2	—	condensate flash in flash box
e	—	evaporator
l	—	liquid
pre	—	pre-heater
seain	—	sea at inlet
seaout	—	sea at outlet
vap	—	vapour
0	—	environment state

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