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A hybrid solar desalination process of the multi-effect humidification dehumidification and basin-type unit

Shaobo Hou*, Hefei Zhang

School of Aeroengine and Thermal Power Engineering, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China
Tel. +86 759 2886705; Fax +86 759 2383636; email: sbhou@163.com, sbhou@tom.com

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Abstract

This paper presents a hybrid solar desalination process of the multi-effect humidification dehumidification and the basin-type unit. The sketch of the hybrid solar desalination process is given. The solar vacuated tube collector is employed in the desalination system, multi-effect humidification dehumidification desalination (HDD) process is plotted according to pinch technology, and then the water rejected from multi-effect HDD process is reused to desalinate in a basin-type unit further. The gain output ratio (GOR) of this system will rise by 2–3 at least through reusing the rejected water. The research proves that the multi-effect HDD has much room to be improved. A hybrid solar desalination process of the multi-effect humidification dehumidification and the basin-type unit should be noticed.

Keywords: Solar desalination; Hybrid; MEH; Basin

1. Introduction

Water is available in abundant quantities in nature; however, there is a shortage of potable water in some places of many countries in the world. Desalination seems to be the most suitable solution. Solar desalination is gradually emerging as a successful renewable energy source of producing freshwater. Solar multi-effect humidification (MEH) units based on the humidification dehumidification principle are considered as the most viable among solar desalination units.

The standard desalination techniques like multi-stage flash (MSF), multi-effect (ME), vapor compression (VC) and reverse osmosis (RO) are only reliable for large capacity ranges of 100–50,000 m^3/day of freshwater production [1]. These technologies are expensive for small amounts of freshwater, and they cannot be used in locations such as islands and remote areas where there are limited maintenance facilities and energy supply. Additionally, the use of conventional energy

*Corresponding author.

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sources to drive these technologies has a negative impact on the environment. Solar energy is the most important renewable source of energy in south China. Consequently, solar desalination is a suitable solution to supply some remote islands in south China with freshwater.

Solar desalination can be either direct or indirect [2]. One of the well-known indirect solar desalination systems is the humidification dehumidification distillation (HDD) process.

Bacha et al. [3] presents the new concept of the multi-effect humidification dehumidification process (MEH), the mathematical model of components of the desalination unit, including solar collector, humidifier and dehumidifier, and some simulated and experimental results such as the impact of water temperature at the evaporation tower inlet on the condensate flow rate, the air humidity, the air temperature on the outlet of the evaporation tower and the cooling water temperature of the inlet of the hot water. The obtained results are then compared against the experimental results. The good quality of distilled water obtained by this new concept favors its use for producing water for drinking and irrigation.

Nawayseh et al. [4,5] have done much research work on the MEH. These include the method of evaluating the heat and mass transfer coefficients in the humidifier, computer simulation and so on. Their researches show that solar desalination with the humidification dehumidification process is an efficient means of utilizing solar energy for the production of freshwater from saline or seawater.

Nafey et al. [6,7] presented a numerical and experimental investigation of a HDD process using solar energy at the weather conditions of Suez City, Egypt. Both tested and numerical results showed that the productivity of the system is strongly affected by the saline water temperature at the inlet to the humidifier, dehumidifier cooling water flow rate, air flow rate and solar intensity and the wind speed and ambient temperature variation have a very small effect on the system productivity.

Farid et al. [8] gave a mathematical modeling and simulation study of solar MEH units based on the humidification dehumidification, which was focused on studying and analyzing the effects and performance of various components involved in the process along with the study of the effect of water feed flow rate on the desalination production.

Parekh et al. [9] provided a comprehensive technical review of solar desalination with a multi-effect cycle and indicated solar desalination based on the humidification dehumidification cycle presents the best method of solar desalination due to overall high-energy efficiency.

Hou et al. [10] presented a method of performance optimization of solar HDD process using pinch technology and indicated that there exits an optimum mass flow rate ratio of water to dry air if given the temperature of spraying water and cooling water and that if the minimum temperature difference at pinch points are 1°C, the energy recovery rate could reach 0.75 when the spraying water temperature is 80°C and cooling water temperature is 25°C.

Xiong et al. [11] developed a comprehensive steady-state mathematical model for the multi-effect HDD process, and it includes the heat and mass balances on both sides of the desalting column, the mass transfer rate at the humidification side and the heat transfer rate between the dehumidification side and humidification side. They also discussed the mass transfer coefficient at the humidification side and the total heat transfer coefficient between the dehumidification side and humidification side and presented the formulas to calculate them.

Al-Hallaj et al. [12] reviewed the solar desalination with humidification dehumidification cycle economically.

Hou et al. (2007) [13] gave a method of exergy analysis of solar multi-effect HDD process. From exergy analysis, the solar collector has lowest exergy efficiency, HDD process has lower exergy efficiency and the water rejected has large exergy loss. Solar multi-effect HDD process has much room to improve. Three ways to enhance freshwater output per square meter area of solar collector are suggested. The first is to enhance the energy efficiency and exergy efficiency and that is, to take measures for more amount of energy and more exergy. The second is to improve the flow of solar multi-effect HDD process in order to gain a high-energy recover rate and the gain output ratio (GOR). The last is to reuse the rejected water to get freshwater. For example, to use solar distill method to desalinate.

Tanaka and Nakatake [14] presented a theoretical analysis of a basin type still with internal and external reflectors and proposed a geometrical method to calculate the solar radiation reflected by the internal and the external reflectors and then absorbed on the basin liner. They also performed numerical analysis of heat and mass transfer in the still and found that the internal and the external reflectors can remarkably increase the distillate productivity throughout the year except for the summer season, and the increase in the daily amounts of distillate by adding the internal and the external reflectors to the single-slope basin type still for the entire year would be averaged as 48%.

In order to enhance the freshwater output per square meter area of solar collector, this paper presents a hybrid solar multi-effect HDD process according to exergy and pinch technology analysis. Solar vacuated tube collector is employed in the desalination system, multi-effect HDD process is plotted according to pinch technology, and the water rejected from multi-effect HDD process is reused to desalinate in basin distill unit to distill water further in day and night.

2. System process model

The system consists of two parts. One is a solar multi-effect HDD unit, and another is a multi-stage basin distill unit. The solar multi-effect HDD unit consists of two vertical ducts connected by the top and the bottom to form a closed loop for air circulation. The unit is operated in a forced draft mode by using a fan. A large surface condenser is fixed in one of the ducts, while wooden packing is used in the other duct for efficient humidification of the air. Firstly, the saline water at 1 is fed to the condenser to condense partially the water vapor from the air at 6. The latent heat of condensation is used to preheat the feed water to 2. The air at 5 is finally got at the bottom of the condenser. Then, the saline water at 2 is further heated in a flat plate solar collector. Last, the feed water at 3 is sprayed over the wooden packing in the humidifier. The air is continuously heated and humidified. The desalinated water is collected from the bottom of the condenser, while is rejected from the bottom of the humidifier. The warm brine rejected from 4 is reused to desalinate in a multi-stage basin distill unit to distill water further. The basin distill unit can be made by plastics and work at day and night. The basin-type desalination unit is adiabatic at the bottom and around sides. The temperature of the seawater in the basin unit is a little higher than the surroundings. The heat will transfer from the bottom to the cover by vaporization and condensation at each stage. So, the distill water can produce at each stage and collected by collectors. Although the temperature difference is small, we can keep the heat transfer for all night. A sketch of a hybrid solar desalination process of the multi-effect humidification dehumidification and the basin-type unit is shown in Fig. 1.

2.1. Energy balance equations in multi-effect HDD

The energy balance equation can be written for the entire system in the following manner, by taking input energy terms equal to output energy terms:

$$\dot{m}_{w}h_{1w} + \dot{m}_{w}h_{3w} = \dot{m}_{w}h_{2w} + \dot{m}_{w4}h_{4w} + \dot{m}_{cw}h_{cw} \tag{1}$$

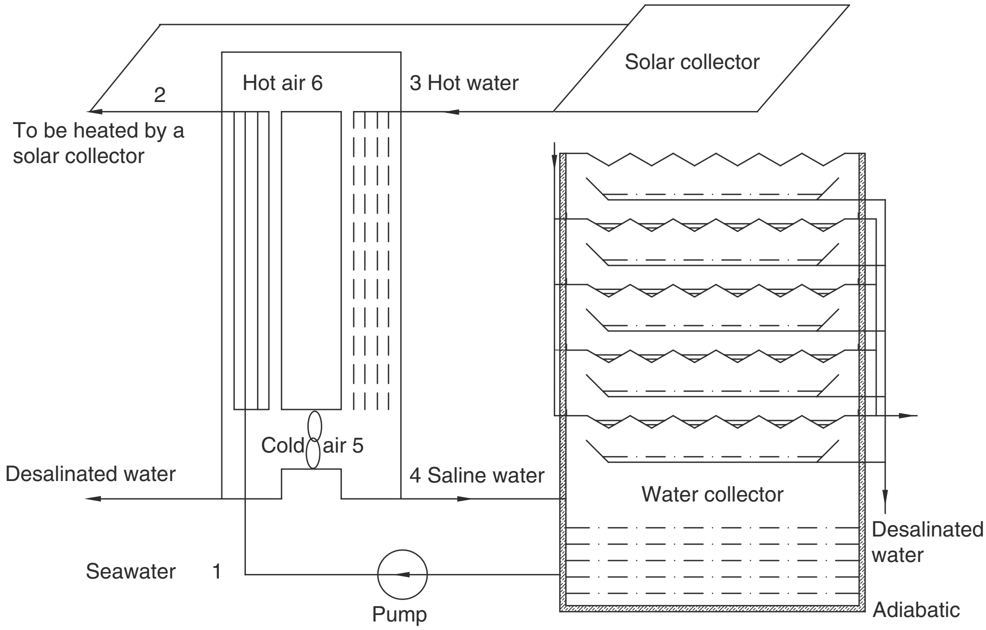

Fig. 1. Sketch of a hybrid solar desalination process of the multi-effect humidification dehumidification and basin-type unit.

where the enthalpy of water at each point n can be calculated by

$$h_{\mathrm{nw}} = (c_{\mathrm{p}})_{\mathrm{w}} t_{\mathrm{n}} \tag{2}$$

in which $n = 1, 2, 3, 4, c$

$$\dot{m}_{\mathrm{cw}} = 0.001\,(d_6 - d_5)\,\dot{m}_{\mathrm{da}} \tag{3}$$

$$\dot{m}_{\mathrm{w4}} = \dot{m}_{\mathrm{w}} - 0.001\,(d_6 - d_5)\,\dot{m}_{\mathrm{da}} \tag{4}$$

$$\begin{aligned}\mathrm{GOR}_{\mathrm{HDD}} &= \frac{0.001r(d_6 - d_5)}{m_{\mathrm{w}}(h_{3\mathrm{w}} - h_{2\mathrm{w}})} \\ &= \frac{0.001r(d_6 - d_5)}{\mathrm{ratio}\ (h_{3\mathrm{w}} - h_{2\mathrm{w}})}\end{aligned} \tag{5}$$

2.2. Energy equations in solar collector

The heat energy rate gained by water from solar collector is calculated by

$$\dot{Q}_{\mathrm{collector}} = \dot{m}_{\mathrm{w}}(h_{3\mathrm{w}} - h_{2\mathrm{w}}) \tag{6}$$

Also $\dot{Q}_{\mathrm{collector}} = S - \dot{L} = S\eta_{\mathrm{collector}}$ (7)

$$Q_{\mathrm{collector}} = \int (S - \dot{L})\,d\tau = \int S\eta_{\mathrm{collector}}\,d\tau \tag{8}$$

2.3. Energy equations in multi-stage basin-type unit

The energy balance equation in multi-stage basin-type unit can be written as the following form:

$$\begin{aligned}H_{\mathrm{in,basin}} &= Q_{\mathrm{useful}} + Q_{\mathrm{loss}} + (\mathrm{Mu})_{\mathrm{final,basin}} \\ &\quad - (\mathrm{Mu})_{\mathrm{initial,basin}}\end{aligned} \tag{9}$$

in which

$$H_{\mathrm{in,basin}} = \int \dot{m}_{4\mathrm{w}} h_{4\mathrm{w}}\,d\tau \tag{10}$$

is the total enthalpy gained from multi-effect HDD

And $Q_{\text{useful}} = rM_{\text{w,single}}$ (11)

The total water product is the plus of two parts

$$M_{\text{w,sum}} = M_{\text{w,HDD}} + M_{\text{w,basin}} \quad (12)$$

In which $M_{\text{w,basin}} = M_{\text{w,single}} N$ (13)

The GOR of multi-effect HDD is calculated by

$$\text{GOR}_{\text{HDD}} = \frac{r\,(d_6 - d_5)}{m_{\text{w}}\,(h_{3\text{w}} - h_{2\text{w}})} = \frac{r\,(d_6 - d_5)}{\text{ratio}\,(h_{3\text{w}} - h_{2\text{w}})} \quad (14)$$

The GOR of a multi-stage basin-type unit is calculated by

$$\text{GOR}_{\text{basin}} = N \quad (15)$$

The total GOR of the hybrid desalinate unit is calculated by

$$\text{GOR} = \text{GOR}_{\text{HDD}} + \text{GOR}_{\text{basin}} \quad (16)$$

3. Analysis of working process

This hybrid system is consisted by the vacuated solar collector, multi-effect HDD and a basin-type desalination unit. The solar energy is collected by the vacuated solar collector and transferred to multi-effect HDD and then transferred to a basin-type desalination unit and finally transferred to surroundings. In order to produce more freshwater, we should take the following measures.

Firstly, we should gain more thermal energy in the vacuated solar collector as possible. Also, the thermal energy should have high quality. That is to say, the water should have a higher temperature.

Secondly, we should enhance the energy recover rate of multi-effect HDD. They include using multi-stage and using circulating water. Thirdly, we should reuse the seawater rejected from multi-effect HDD through using multi-stage basin-type distillation. If it is 3 stages basin type, the GOR will increase by about 2–3.

4. Conclusions

This study gives a hybrid solar desalination process of the multi-effect humidification dehumidification and the basin-type unit. The GOR of this system will rise by 2–3 at least through reusing the rejected water.

Notation

$\dot{m}$	Mass flow rate, kg/s
h	Specific enthalpy, kJ/kg
c_p	Heat, kJ/kg K
t	Temperature, °C
d	Humidity ratio, g/kg (da)
GOR	The gain output ratio
$\dot{Q}$	Rate of heat transfer, kJ/s
Q	The amount of heat transfer, kJ
r	Latent heat of water vapor, kJ/kg
M	Mass, kg
N	Number of stages of basin-type unit
u	Specific inner energy, kJ/kg
S	Solar radiation heat rate, kJ/s
$\dot{L}$	Loss flow rate, kJ/s
H	Enthalpy, kJ
τ	Time
Ratio	Mass flows rate ratio of water to dry air
η	Efficiency

Subscripts

added	Added by thermal source (solar collector or others)
rec	Recovered by heat exchanger
rej	Rejected by the unit
da	Dry air
w	Seawater
cw	Condensed water
HDD	Multi-effect humidification dehumidification desalination

basin	Basin-type desalination unit
loss	Loss from base and besides of basin
useful	Useful for distillation
in	Flow in
initial	Initial state of basin
final	Final state of basin
collector	Solar collector
single	Single stage basin-type unit
sum	Sum of both desalination parts
1	Water inlet to condenser
2	Water outlet from condenser
3	Water inlet to humidifier
4	Water outlet from humidifier
5	Air at bottom of unit
6	Air at top of unit

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