

Two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis

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Abstract

This paper presents a two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis. The sketch of two-stage solar multi-effect humidification dehumidification desalination process is given. The solar vacuated tube collector is employed in the desalination system, multi-effect humidification dehumidification desalination (HDD) process are plotted two different temperature range according to pinch technology. The higher temperature range is from 60 to 80°C, and the lower is from 30 to 60°C. The mass flow rates of dry air in the two stage desalination units are different. The pinch analysis chart is given. According to the pinch chart, the energy recover rate could get higher according to working temperature range. The research proves that the multi-effect HDD has much room to be improved.

Keywords: Solar desalination; HDD; MEH; Pinch technology

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 fresh water. 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 m³/day of fresh water production [1]. These technologies are expensive for small amounts of fresh water, and they cannot be used in locations such as islands and remote

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areas where there are limited maintenance facilities and energy supply. Additionally, the use of conventional energy 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 fresh water.

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] presented 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 multi-effect humidification–dehumidification process (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 fresh water from saline or seawater.

Nafey et al. [6,7] presented a numerical and experimental investigation of a humidification–dehumidification desalination (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 multi-effect humidification (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 humidification–dehumidification desalination (HDD) process using Pinch technology, and indicated that there exists 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 humidification–dehumidification desalination process, and it include 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. [13] gave a method of exergy analysis of solar multi-effect humidification dehumidification desalination (HDD) process. From exergy analysis, the solar collector has lowest exergy efficiency, humidification–dehumidification desalination (HDD) process has lower exergy efficiency, and the water rejected has large exergy loss. Solar multi-effect humidification–dehumidification desalination (HDD) process has much room to improve. Three ways to enhance fresh water 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 humidification dehumidification desalination (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 fresh water. For example, to use solar distill method to desalinate.

In order to enhance the fresh water output per square meter area of solar collector, this paper presents a two-stage solar multi-effect humidification–dehumidification desalination process plotted from pinch analysis. The purpose is to reduce exergy loss and to enhance energy recovery rate and GOR.

2. Pinch technology

Pinch technology is a graphical method of identifying technically and economically interesting energy efficiency measures. The minimum cooling and heating demands in the system can thereby be determined, together with the net heat for each temperature level. The concepts and methodology of pinch technology are well explained in the works of Linhoff et al. [14], Eastop and Croft [15], Linhoff [16] and Mubarak Ebrahim [17]. The benefits of pinch technology application in industrial applications are several

and include the identification of the maximum thermal energy recovery, the optimum heat exchanger network design and the minimum thermal utilities required.

3. System process model

The two-stage solar multi-effect humidification–dehumidification desalination process consists of two closed loops for air circulation as showed in Fig. 1. One is the higher stage, the high temperature circulation, and another is the lower stage, the lower temperature circulation. The low temperature circulation is operated in a forced draft mode by using a fan. A large surface condenser

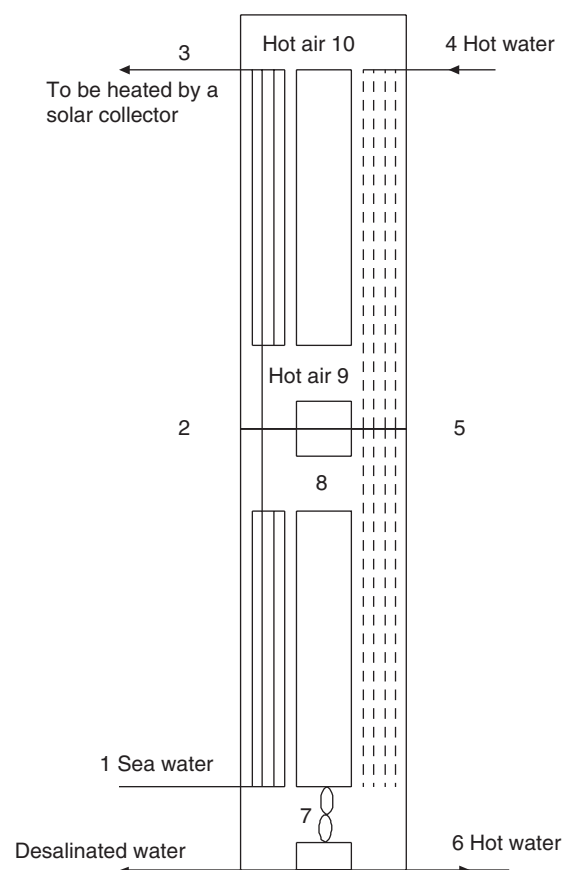


Fig. 1. A sketch of the two-stage solar multi-effect humidification–dehumidification desalination process.

is fixed in one side of the duct, while wooden packing is used in the other side of the duct for efficient humidification of the air. In the lower stage, firstly, the saline water at 1 is fed to the condenser to condense partially the water vapor from the air at 8. The latent heat of condensation is used to preheat the feed water to 2. The air at 7 is finally got at the bottom of the condenser. Then, the saline water at 2 is further heated in upper stage. Last, the feed water at 5 from the upper stage 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 the warm brine at 6 is rejected from the bottom of the humidifier. In the upper stage, the structure is the same as the lower stage. Firstly, the saline water at 2 from lower stage is fed to the condenser to condense partially the water vapor from the air at 10. The latent heat of condensation is used to preheat the feed water to 3. The air at 9 is finally got at the bottom of the condenser. Then, the saline water at 3 is further heated in a solar collector. Lastly, the feed water at 4 from the solar vacuated tube collector is sprayed over the wooden packing in the humidifier. The air is continuously heated and humidified. The desalinated water drops to the lower stage, while the warm brine at 5 drops to the lower stage.

4. Methodology

Pinch point technology is based on process thermodynamic analysis. The methodology used in this work has therefore as fundamental points mass and energy balances and the optimum use of the heat flows in the processes and consist of the following steps:

- (1) Obtaining the process diagram of the thermal system of HDD process that is shown in Fig. 1.
- (2) Obtaining thermodynamic data of the thermal system (temperatures, enthalpies, mass flows and specific heats). In this work, we assume the dry air mass flow rate in the lower stage

is 1 kg/s, the mass flow rate ratio of feed sea water to dry air is ratio and the dry air mass flow rate in the upper stage is $1/x$ kg/s, the sea water flow ratio is the same as that in lower stage. The spraying water mass flow rate is considered unchanged when we calculate the enthalpy of spraying seawater.

For both feed sea water and spraying seawater:

$$H_{\text{water}} = 4.1868 \dot{m}_{\text{water}} T = 4.1868 \text{ Ratio } T \quad (1)$$

For the saturated air:

$$H_{\text{sat}} = \text{Exp}(2.39329 + 0.10648T - 0.00135T_2 + 0.000010058T_3) \quad (2)$$

This formula is obtained from data of reference [18].

- (3) Identification of the hot and cold streams in the HDD process. In humidification process, the hot stream is hot seawater from T_4 to T_5 , and then to T_6 and the cold stream is the saturated air from T_7 to T_8 in the lower stage, from T_9 and to T_{10} in the higher stage. In dehumidification process, the hot stream is the saturated air from T_{10} to T_9 in the lower stage and from T_8 to T_7 in the lower stage, and the cold stream is seawater from T_1 to T_2 , and to T_3 . The details are illustrated in Tables 1 and 2.
- (4) Determination of the ΔT_{min} (minimum approach temperature) for both processes.
- (5) Construction of the hot and cold curves of humidification process and dehumidification process on one chart. The data of the curves obtained from computer code in this work.
- (6) Elaboration of the problem table. This is also acquired from computer code.
- (7) Determination of the minimum energy added, recovered and rejected in the unit.

$$E_{\text{added}} = E_{\text{rejected}} = H_6 - H_1 = H_4 - H_3 \quad (3)$$

$$E_{\text{rec}} = H_{10} - H_7 \quad (4)$$

Table 1
The hot and cold stream in humidification process

Stream	Fluid	Start temperature	Target temperature	Mass flow rate
Hot 1	Seawater	T_4	T_5	Ratio
Hot 2	Seawater	T_5	T_6	Ratio
Cold 1	Saturated air	T_9	T_{10}	$(1 + d_{\text{sat}})/x$
Cold 2	Saturated air	T_7	T_8	$(1 + d_{\text{sat}})$ kg

Table 2
The hot and cold stream in dehumidification process

Stream	Fluid	Start temperature	Target temperature	Mass flow rate
Hot 1	Saturated air	T_{10}	T_9	$(1 + d_{\text{sat}})/x$
Hot 2	Saturated air	T_8	T_7	$(1 + d_{\text{sat}})$ kg
Cold 1	Seawater	T_2	T_3	Ratio
Cold 2	Seawater	T_1	T_2	Ratio

(8) Evaluation of the thermal energy recovery rate.

$$k = \frac{E_{\text{rec}}}{E_{\text{rec}} + E_{\text{added}}} \quad (5)$$

5. Results

The best hot and cold curves of both humidification and dehumidification process of a single stage HDD when the seawater temperature at inlet is 25°C, the spraying sea water temperature is 80°C, ratio = 3.6 and $\Delta T_{\text{min}} = 1^\circ\text{C}$ at pinch point given by reference [10] is illustrated in Fig. 2. The temperature after heat exchanger in Fig. 2, T_2 , is the highest in single stage unit, and thermal energy recovery rate, about 0.67, is the highest. It means that is the best plan for a single stage unit. From the Fig. 2, one can find that the reason why the thermal energy recovery rate of a single unit is low is the curve of the saturated wet air. If the curve could be flattened, the temperature difference between the spraying seawater and the cooling water could plot smaller, and the thermal energy recovery rate could be higher.

To solve this problem, author bisects the single unit and form two circles and lessens the air flow rate in the higher stage. So, the saturated air curve could be flattened, and the thermal energy recovery rate could increase.

Fig. 3 gives the hot and cold curves of both humidification and dehumidification process of

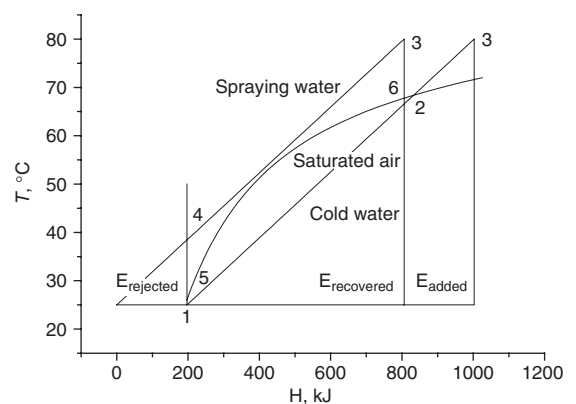


Fig. 2. The best hot and cold curves of both humidification and dehumidification process of a single stage HDD when the seawater temperature at inlet is 25°C, the spraying sea water temperature is 80°C, ratio = 3.6 and $\Delta T_{\text{min}} = 1^\circ\text{C}$ at pinch point given by Ref. [10].

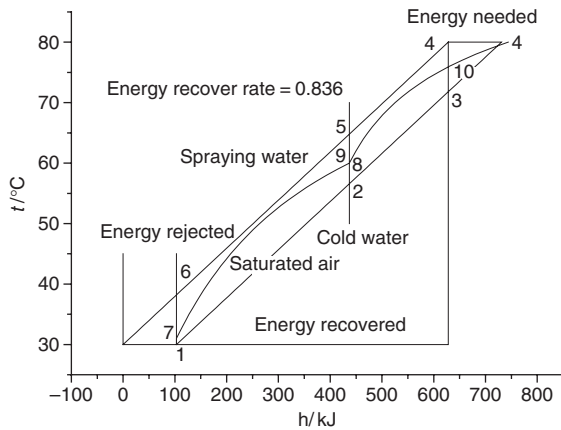


Fig. 3. The hot and cold curves of both humidification and dehumidification process of a two-stage solar multi-effect humidification dehumidification desalination process.

a two-stage solar multi-effect humidification–dehumidification desalination process. In Fig. 3, in the lower stage, the dry air mass flow rate is 1 kg/s, the mass flow rate ratio of feed sea water to dry air is Ratio (=3) and $\Delta T_{\min} = 1^\circ\text{C}$ at pinch point, the seawater temperature at inlet is 30°C , the spraying sea water temperature is T_5 , the saturated air at 7 is 60°C . In the higher stage the sea water flow rate is the same as that in lower stage, the dry air mass flow rate in the upper stage is $1/x$ kg/s ($x = 4$), and the spraying seawater temperature is 80°C . It is though changing the value of x that we change the curve of saturated air. The energy recover rate under the above conditions is 0.836. From the Fig. 3, one can see that if the spring seawater increase to 100°C and using multi-stage, the energy recover rate would increase. If the energy recover rate could reach 0.9, the GOR would increase greatly.

6. Conclusions

This study gives a two-stage solar multi-effect humidification–dehumidification desalination process plotted from pinch analysis. The study shows

that the two-stage solar multi-effect humidification–dehumidification desalination process has a higher energy recover rate than the one stage does. In an extreme case, the minimum temperature difference at pinches are 1°C , the energy recovery rate could reach 0.836. If using multi-stage, the energy recover rate would be higher, and that leads a higher GOR. The multi-effect HDD has much room to be improved.

Notation

Ratio	Mass flows rate ratio of water to dry air
H	Enthalpy, kJ/kg
T	Temperature, $^\circ\text{C}$
E	Energy, kJ/kg
\dot{m}	Mass flow rate, kg/s
k	Energy recovery rate
d	Humidity ratio of wet air, g/kg (d.a.)
c_p	Specific heat, kJ/kg/K
x	Dry air flow rate ratio of the low stage to the high stage

Subscripts

added	Added by thermal source(solar collector or others)
rec	Recovered by heat exchanger
rejected	Rejected by the unit
da	Dry air
sat	Saturated wet air
water	Sea water
1	Seawater inlet to the condenser of the lower stage
2	Seawater outlet from the condenser of the lower stage
3	Seawater outlet from the condenser of the higher stage
4	Seawater inlet to the humidifier of the higher stage
5	Seawater outlet from the humidifier of the higher stage
6	Seawater outlet from the humidifier of the lower stage

- 7 Air at the bottom of the lower stage
- 8 Air at the top of the lower stage
- 9 Air at the bottom of the higher stage
- 10 Air at the top of the higher stage

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