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Improvement of Solar Humidification-Dehumidification Desalination Using Multi-Stage Process

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Solar humidification-dehumidification (HD) desalination is a suitable choice for fresh water production when the demand is decentralized and solar radiation with high intensity is available. This paper evaluates multi-stage technique to improve the efficiency of the solar HD process through mathematical programming method. Result shows that multi-stage HD has good potential in process improvement. Also it is concluded that according to modeling results and construction cost, two-stage process is the most suitable choice for fresh water production when multi-stage technique will be used.

1. Introduction

Air humidification dehumidification desalination is a suitable choice for production of fresh water when the demand is decentralized. Conventional desalination methods such as MSF, ME, VC and RO are suitable for large and medium capacity of fresh water production. But most remote arid areas need low capacity desalination systems. Simplicity of the process and possibility of using a wide range of thermal energies such as solar, geothermal, exhaust waste and fossil fuel are advantages of HD method with compare to conventional methods. Also because of low temperature demand of this method and availability of solar energy in areas that need drinking water, it is very compatible with solar energy and total required thermal energy can be obtained from solar radiation.

Most of investigations on HD desalination process have concerned about productivity and efficiency improvement and have been done after 1990 and several units have been built. These units are similar in base but different in type of equipments.

In 1990 Farid and Hamad (1993) constructed a HD desalination unit in Basrah, south of Iraq. The unit produced 12 $L/(d.m^2)$ of solar collector surface which was about three times of production of a single-basin solar still under similar solar conditions. However the pressure drop in the condenser and the humidifier was too high, increasing the electrical power consumption by the blower to a level that makes such a process uneconomical.

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Then, two unit of different size were constructed and operated in Jordan described by Al-hallaj et al.(1998) and Farid et al.(1995). They found that effect of water flow rate is more significant on the heat and mass transfer coefficient than air flow rate. Also they concluded natural circulation of air have preferred over force circulation.
Ben Bacha et al. (1999) presented a perfect work included modeling, simulation and experimental validation of a solar HD system. They concluded that perfect insulation of the unit, high water temperature and flow rate at the entrance of evaporation tower, low temperature of water at the entrance of condenser and hot water recycling by injection at the top of evaporation tower can improve operation and production of system.
Because of plurality of effective parameters and their simultaneous effects on HD performance, parametric analysis and try and error method does not guide the designer to the optimal design. Hou et al. (2005) used pinch technology to optimize performance of HD process. They maximize condenser heat recovery through composite curves. They found that there is an optimum value for water to air flow rate ratio (L/G). But effect of humidifier inlet temperature and solar collector efficiency has not studied. In another study Hou (2008) evaluates a two-stage solar HD desalination process using pinch technology. His research proves that the HD desalination has much room to be improved.
First global optimization of HD process was developed by Soufari et al. (2009). With a perfect simulation of the process, effects of different parameters were analyzed and a mathematical programming model was presented to optimize the process with different objective functions. Then the model was developed by adding the solar part and finally a low cost design for solar HD desalination was obtained (Zamen et al., 2009). In the next step a unit with capacity of 10 lit/h based on optimization results was constructed which has been located at Iranian Research and Development center for Chemical Industries (IRDCI), Karaj, Iran (Soufari et al., 2009). In comparison with previous works, distillation percent and production per volume of unit have been improved and are quite satisfactory. However, because of novelty of the HD method, it seems more improvements could be gained with some changes in the process. Evaluation of the T-H diagram of the process results more improvement with multi-stage HD process that its effects will be analysis in this paper through mathematical modeling method.

2. Process Description

As shown in Fig. 1, a single-stage HD desalination unit has three main sections: humidifier, dehumidifier and heat source. In humidifier hot water which heated by an external heat source such as solar collectors, is in contact with air on a packed bed and a certain quantity of vapor is extracted by air. Then hot and humid air leaves the humidifier and enters to dehumidifier. In this section, water vapor is distilled by bringing the humid air in contact with a cooled surface which causes the condensation of the water vapor and production of fresh water. Latent heat of condensation is used for preheating the salt feed water. Fig. 2(a) shows temperature-enthalpy (T-H) curves for water streams and saturated air in the humidifier and dehumidifier towers.
The main purpose of this article is to improve efficiency of the HD process and to enhance the energy consumption per unit of fresh water production. Decrease of

temperature difference between point 3 and 6 in Fig.2 (a) and increase of heat recovery in dehumidifier can be improves the specific energy consumption. The main reason of low thermal energy recovery rate of a single-stage HD unit is the shape of the saturated air curve. If the curve could be flatten, the hot and cold water lines could be closer, and the thermal energy recovery rate could be higher as graphically presented in Fig. 2(b). The shape of air curve could be improved if the mass flow rate of the air will be variable. Base on this fact Fig. 3 shows the new process with some closed air loops named multi-stage HD desalination. Feed salt water inters to the first stage and after passing through first condenser, enters to the second stage and so on. Salt water temperature increases after each stage. Hot water enters to the upper stage and cascade in lower stages to exit from first stage. Temperature of the hot water outlet could be controlled with design of packed bed and condenser. Mass flow rate of air could be change for each stage and set in an optimum value. So, the heat recovery section is extended and energy consumption will be reduced as shown in Fig. 2(b).

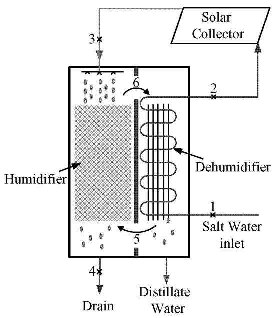

Figure 1: Single-stage solar HD unit

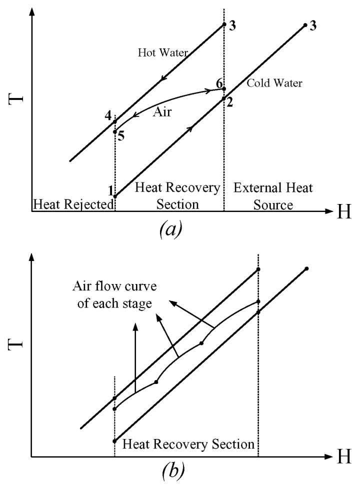

Figure 2: T-H diagram of HD process (a) single-stage;(b) multi-stage

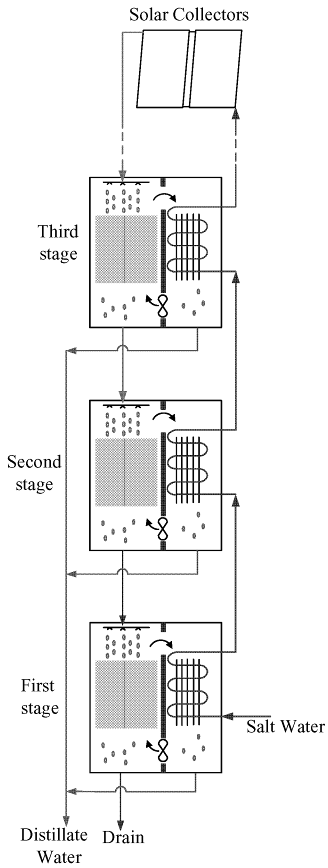

Figure 3: Multi-stage HD desalination unit

In this paper the effect of multi-stage process in efficiency and operation of the system will be evaluated through mathematical programming method. So, related equations that used in previous studies for single-stage HD, will be developed and adjusted for multi-stage process.

3. Model Development

Main equations of each stage are based on heat and mass balance in humidifier and dehumidifier towers that presented in reference [12]. Also additional equations for solar collector and packed bed are used according relations presented in reference [13]. Based on Fig.3 hot water outlet of each humidifier is the humidifier inlet of the lower stage. Also the outlet of the dehumidifier feed to the upper stage. These condition inserted to the model as new constrains and by adding the related constraints to closed air cycle and inlet and outlet conditions of hot and cold water between stages, mathematical model of the system would be completed. The mathematical programming model is solved for one to four-stage processes with mentioned constrains to achieve the minimum energy consumption per kg of fresh water production.

4. Results

The model was solved for one to four-stages HD process. One of the important parameters is the minimum approach temperature for both humidification and dehumidification processes that will be considered in results. In initial calculation minimum approach temperature seems to be fixing and equals 4 ºC.
Fig. 4 shows effect of increasing number of stages on minimum specific thermal energy consumption of the process. The humidifier inlet water and cooling water enter to the dehumidifier temperature seems to be 70 ºC and 20 ºC respectively. It is shown that increasing number of stages from one to two reduces energy consumption by more than 35 %. But this reduction will be small for systems with more than two-stage. In the two-stage process the optimum value of mass flow rate of first and second stage seems to be 1.3 and 0.5 times of the single-stage process respectively. A same effect will be seen for productivity that shown in Fig. 5. Productivity improved with increase of number of stages. But the most enhancements obtain in two-stage rather than single-stage process.

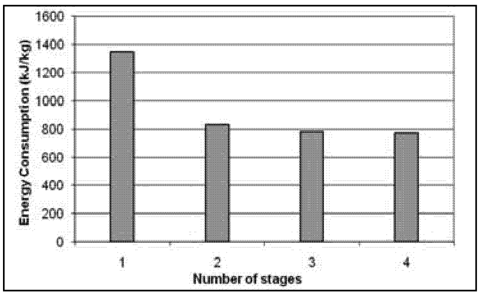

Figure 4: Specific energy consumption as a function of number of stages, $T_{wc}^{in} = 20\,°C;\ T_{we}^{in} = 70\,°C;\ \Delta T_P = 4\,°C$

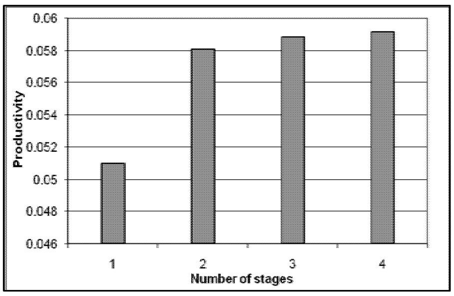

Figure 5: Effect of number of stages on productivity of the process $T_{wc}^{in} = 20\,°C;\ T_{we}^{in} = 70\,°C;\ \Delta T_P = 4\,°C$

Also, as shown in Fig. 6, daily production per solar collector area increases more than 40 % with two-stage process but this incensement will be 4 % and 1 % for 3 and 4-stage process respectively. Generally when number of stages increases, energy consumption per kg of fresh water, productivity and daily production per solar collector area enhance but the main enhancement accurse from one to two-stage process.
As mentioned above, minimum approach temperature in humidifier and dehumidifier is an important parameter that affects energy consumption of desalination process. Fig. 7 shows minimum specific thermal energy consumption as a function of minimum approach temperature. It is shown that reduction of this parameter reduces energy consumption of the process intensively. But required heat transfer area is very increased with reduction of pinch temperature difference. Therefore an economical trade off is needed between energy cost and initial investment.
More results can be summarized as follow:

- Stages with higher temperature have higher productivity.
- In the multi-stage process higher temperature stages need lower air mass flow rates. In other words liquid to gas flow rate ratio (L/G) reduces with reduction of humidifier inlet water temperature. So in low temperature stages, a forced draft made by a fan may be required.

It should be noted that increasing number of stages increases investment cost. Therefore according to above explanations, it seems that two-stage process is the most suitable choice. Also with increase of the stages and efficiency improvement of the process, temperature of the hot water outlet from the lowest stage will be reduced. So, it could be partially recycled to the inlet of the dehumidifier that causes more productivity enhancement up to 15 %. Based on these results a unit is under construction in an arid region in Iran.

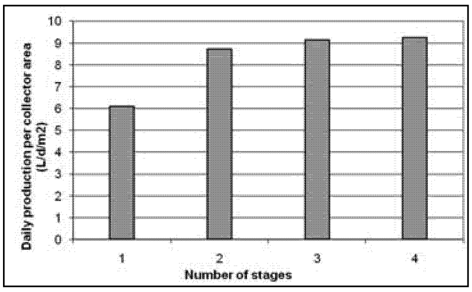

Figure 6: Daily production per collector area as a function of number of stages $T_{wc}^{in} = 20\,°C;\ T_{we}^{in} = 70\,°C;\ \Delta T_P = 4\,°C$

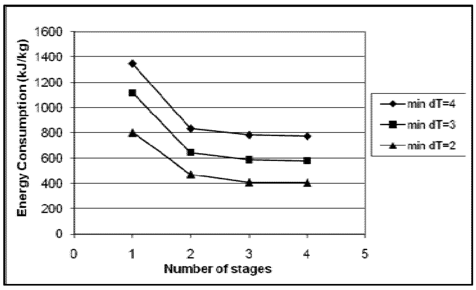

Figure 7: Effect of pinch temperature difference on specific energy consumption $T_{wc}^{in} = 20\,°C;\ T_{we}^{in} = 70\,°C$

5. Conclusion

The multi-stage HD process for desalination was introduced and its performance was analyzed through mathematical programming. Results show that important parameter of the process such as specific energy consumption, productivity and daily production per solar collector area improved when two-stage process used instead of one-stage process. But this reduction is neglected when number of stages is increased. So, according to construction cost, it seems that two stage unit is the most suitable choice. Also hot water outlet could be recycled and cause productivity improvement up to 15 %. A system based on this process is under construction and experimental results of a solar two-stage HD desalination unit will be introduced in near future. This unit will be constructed in an arid region in Iran.

References

Al-Hallaj S., Farid M.M. and Tamimi A.R., 1998, Solar desalination with humidification-dehumidification cycle: Performance of the Unit, Desalination, 120, 273-280.

BenBacha H., Bouzguenda M., Abid M.S. and Mallej A.Y., 1999, Modeling and simulation of a water desalination station with solar multiple condensation evaporation cycle technique, Renewable Energy, 18 , 349-365.

Farid M.M. and Hamad F., 1993, Performance of a single-basin solar still, Renewable Energy, 3, 75-83.

Farid M.M., Nawayseh N.K., Al-Hallaj S. and Tamimi A.R., 1995, Solar desalination with humidification dehumidification process: Studies of Heat and Mass Transfer, In Proceeding of the Conference: SOLAR 95, Hobart, Tasmania, the Australia, 293-306.

Hou S., Ye S. and Zhang H., 2005, Performance optimization of solar humidification-dehumidification desalination process using pinch technology, Desalination, 183, 143-149.

Hou S., 2008, Two-stage solar multi-effect humidification dehumidification desalination process plotted from pinch analysis, Desalination, 222, 572–578.

Parekh S., Farid M. M., Selman J. R. and Al-Hallaj S., 2004, Solar Desalination with a humidification-dehumidification technique - a comprehensive technical review, Desalination, 160, 167-186.

Soufari S.M., Zamen M. and Amidpour M., 2009, Performance optimization of humidification-dehumidification desalination process using mathematical programming, Desalination, 237, 305–317.

Soufari S.M., Zamen M. and Amidpour M., 2009, Experimental validation of an optimized solar humidification-dehumidification desalination unit, Desalination and Water Treatment, 6, 244–251.

Zamen M., Amidpour M. and Soufari S.M., 2009, Cost optimization of a solar humidification-dehumidification desalination unit using mathematical programming, Desalination, 239, 92–99.