Performance Enhancement of a Small Scale Solar Driven Humidification-Dehumidification Water Desalination Unit

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Abstract

The present article reports on parametric analysis of the performance of solar driven humidification-dehumidification (HDH) small scale water desalination unit (WDU). Mathematical models of unit components are constructed in MATLAB environment. The effects of solar field hot water supply temperature and flow rate, WDU air flow rate, and water/air flow rate ratio on the performance of the plant have been investigated. A heat recovery system using hot rejected saline water is introduced to enhance the plant performance. The proposed heat recovery system is found to increase the plant gained-output ratio (GOR).

Keywords *Desalination, Humidification, dehumidification, solar, heat recovery*

I. INTRODUCTION

Solar powered humidification–dehumidification desalination systems (HDH) has attracted much attention in recent years. The basic components of HDH cycle include a heat exchanger with a heat source, air humidifier, and dehumidifier. In closed air open water (CAOW) HDH system, the saline water is heated in the heat exchanger and then sprayed into the path of a flowing dry air. The dry air gets humidified and then passes over a cooling coil where the water moisture is extracted by condensation to produce fresh water. The raw saline cold water is initially introduced in the cooling coil before entering to the heat exchanger section. The saline water passing over the humidification section is ultimately rejected outside the unit.

In solar driven HDH units, the heat source for heat exchanger of the HDH unit is powered by hot fluid, usually water, coming from the field of solar collectors. The mass flow rate and output temperature from the solar field control the quantity of fresh water production. Other parameters that may affect the unit performance include the air flow rate and the water/air flow rate ratio inside the WD unit. The solar field needs to be optimized and controlled to guarantee the required values of supply water flow rate and temperature. These values are function of the solar radiation, ambient conditions, collector size, type, as well as storage tank dimensions. Understanding the effect of these parameters will certainly help in optimizing the unit operation and selection of set points for control of the solar field and the HDH unit. The HDH desalination units generally works at ambient pressure with salt water temperature in the heat exchanger between 70 °C and 95 °C. Also, it can be designed to minimize the amount of energy discarded to the surroundings [1].

K. Bourouni et al. [2] showed that the HDH unit production first increases with increasing water flow rate to an optimum value. Beyond that value the unit production decreases with increasing water flow rate. This is due to the increase in heat and mass transfer coefficients as well as the solar collector efficiency. However, the evaporation and condensation decreases due to the decrease of operating temperature of the unit. Nawayseh [3] theoretically showed the dependence of fresh water production on the air flow rate. They showed that the use of natural air draft is more favourable than the forced draft. E. Hassan [4] studied numerically the performance of a solar-driven HDH unit and reported no effect on the fresh water production by increasing the temperature and the entering water flow rate. H. Shaobo et al. [5] using pinch analysis, showed that the thermal energy recovery rate increases with the decrease of temperature difference of the pinch point.

Yamal and Solmus [6] studied a model of an HDH desalination unit consisting of double pass flat plate solar air heater with two glass covers, humidifier, condenser and water storage tank. The unit is based on closed water and open-air cycle (CWOA). The fresh water production is found to be affected by increasing the inlet water and air mass flow rates to the humidifier. The authors indicated that the productivity of the unit improved up to 8% by using the double -pass solar air heater compared with a single pass solar air heater.

Orfi et al. [7] studied a solar-driven humidification-dehumidification desalination unit consisting of two solar collectors; one for heating the water and the other one for heating the air, humidifier and dehumidifier. The theoretical results showed that there was an optimum mass air to water mass flow rate ratio for maximum fresh water production.

Zhani and Ben Bach [8] carried out a theoretical and experimental study to investigate and validate the feasibility of a solar-driven HDH prototype with pad humidifier. The unit consisted of two flat plate solar collectors one for heating the air and the other one for heating the water, a pad humidifier and a condensation tower. Based on the authors report, the system was very efficient but the cost of water production was very high.

Yuan and Wang [9] investigated experimentally the feasibility of a solar-driven HDH unit with both solar air and water collectors. The solar air heater has been shown to have an important role in reducing the fresh water production cost. T. Farrag et al. [10] carried out an experiment study to investigate the performance of a two-stage water desalination unit by HDH process. Their unit consisted of two stages of closed air HDH units. According to the authors, the more dominant parameter is the inlet water temperature. It has been found that both air temperature and flow rate have important effects on fresh water yield.

It was reported in [11] that the effects of some parameters such as water flow rate, air flow rate and solar intensity on the fresh water production rate is complicated by its combined effects on the performance of the solar collector, condenser and humidifier.

It is evident from the previous survey that modelling and simulation of solar driven HDH desalination plants are important tools in the design and operation phases of HDH plants. In the present article, mathematical model for a closed air open water (CAOW) HDH desalination plant driven by vacuum tube solar collectors is developed in MATLAB environment. The model has been validated by comparison with experimental and theoretical data of a typical plant. The model has been utilized to investigate the effects of different design and operating parameters on the unit performance. Also, a model for a heat recovery system to use the waste heat of the high temperature rejected brine temperature to preheat the salt water is constructed. The model is implemented to perform a parametric study of plant performance. The effect of proposed heat recovery system on the overall efficiency of the system is investigated.

II. HDH DESALINATION PLANT DESCRIPTION

Figures 1 shows a schematic diagram of the HDH desalination plant and WDU considered in the present study [12, 13].

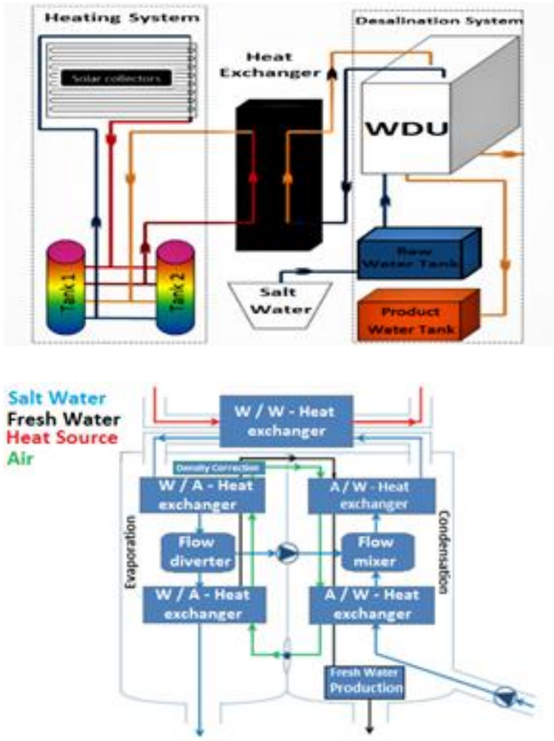

Figure 1: HDH desalination plant components [12, 13]

The plant parameters are typical of the plant constructed in the framework of SUNWATER Project [12, 13]. The main features of the plant include: vacuum tubes solar collectors of 240 m^2; two storage tanks with a volume of 5 m^3 each; solar field circulation pump; heat exchanger between the solar field and salt water in the WDU unit; water Desalination Unit (WDU) with a rated capacity of 209 L/h at an input temperature of 95 ℃ and 50 kW_{th} thermal power; raw water tank to supply the WDU with salt water; and product water tank used to collect the produced fresh water.

III.MATHEMATICAL MODELLING

The mathematical model is constructed using the CARNOT toolbox in MATLAB environment. This toolbox can be used to calculate and simulate different components of heating systems [10]. The model of the system consists of different heat exchangers and other components like a flow mixer and a flow diverter. The present model uses the methodology and governing equations suggested in [12]. Figure 1 shows the model components of HDH unit. The saltwater enters the WDU in the condensation chamber in which the saltwater is preheated by the hot air and then passes a flow mixer where it is mixed up with a part of the hot water coming from the evaporating chamber. After passing the flow mixer the water passes again to another heat exchanger to raise its temperature even more before entering the external heat exchanger of the WDU in which the water is heated up with an external heat source to the maximum temperature in the system. It leaves the external heat exchanger and sprays down in the evaporating chamber. In which the energy is transferred from the hot water to the cold air. Then it passes a flow diverter, which splits the saltwater flow into two different volume flows. The heat exchangers are modelled using the following differential equations:

$$\frac{dT_{w,out}}{dt} = \frac{\dot{m}_w}{m_{w,m}}\left(T_{w,in} - T_{w,out}\right) - \frac{kA}{C_{p,w} m_{w,m}} \vartheta_{cond} \quad (1)$$

$$\frac{dT_{a,out}}{dt} = \frac{\dot{m}_a}{m_{a,m}}\left(T_{a,in} - T_{a,out}\right) + \frac{kA}{C_{p,a} m_{a,m}} \vartheta_{cond} \quad (2)$$

$$\vartheta_{cond} = \frac{T_{w,in} - T_{a,out} - T_{w,out} - T_{a,in}}{Ln \dfrac{(T_{w,in} - T_{a,out})}{(T_{w,out} - T_{a,in})}} \quad (3)$$

HDH model parameters are listed in Table 1. The flow diverter and the flow mixer are implemented using CARNOT toolbox. Full details of the mathematical model can be found in [12].

Table1. HDH model parameters

Symbol	Description	Value	Units
$C_{p,w}$	Heat capacity of water	4185.5	J/(kg K)
$C_{p,a}$	Heat capacity of air	1003	J/(kg K)
k	Heat transfer coefficient	20	W/(m^2 K)
A	Surface area of heat exchanger	5	m^2
$T_{w, in}$	Temperature of input water	363	K
$T_{w, out}$	Temperature of output water	Calculated	K
$T_{a, in}$	Temperature of input air	293	K
$T_{a, out}$	Temperature of output air	Calculated	K
$\dot{m}_a$	Mass flow rate of air	0.15	Kg/s
$\dot{m}_w$	Mass flow rate of water	3.33	Kg/s
$m_{w,m}$	Mass of water	5	kg
$m_{a,m}$	Mass of air	1	Kg
ϑ_{cond}	Operation Characteristic	Calculated	K

The above-mentioned models of HDH unit are implemented in MATLAB Simulink. This includes modules for heat exchanger used to heat the saline water by the hot water coming from the solar field, water / air heat exchangers, flow mixers and flow diverters. Other sub modules are used to calculate the density correction of air as function of temperature, water content, and heat transfer characteristic for heat exchanges. The module for fresh water production calculates the fresh water as function of air temperatures and volume flow rates. The flow diverter can be sat in the range from 0 (by-pass in activated) to 1 (the whole flow continues without diverting). A value of 0.5 is used throughout the present study.

Validation of the developed mathematical models has been performed by comparison with the experimental data reported in [13] and theoretical data reported in [12]. The amount of fresh water production of the unit during the first hour is calculated as 173.7 L/h as compared to, experimental results of 209 L/h [13]. The difference can be attributed by transient period of the present model during which the HDH unit temperature needs to reach its steady temperature after starting from ambient conditions. After steady state temperature the amount of calculated fresh water production of the HDH unit is in agreement with the experimental data.

During simulation, different temperature states in the WDU are calculated. The inlet saltwater temperature is 20 ℃. The saltwater reaches its highest temperature value of about 80 ℃ after the main heat exchanger. The temperature of the leaving brine rejected from the WDU reaches 40 ℃. The difference between the inlet slat water temperature and the rejected one represents a good potential to enhance the performance of the unit.

IV. PARAMETRIC ANALYSIS OF PLANT PERFORMANCE

In the present section, the effects of different parameters on the amount of fresh water produced per hour are discussed.

Figure 2 shows the variation of fresh water yield with air mass flow rates at different values of hot water temperatures entering the WD unit from the solar field. It can be observed that the fresh water yield increases with the increase of air mass flow rate and hot water temperature.

Figure 3 shows the variation of fresh water yield with hot water mass flow rate at different values of entering hot water temperature. It can be noticed that the fresh water yield increases by increasing the hot water mass flow rate and entering temperature to the WDU. It can be also observed from Fig. 3 that, the rate of increase fresh water yield with the increase of hot water mass flow rate is not linear and the fresh water yield approaches a maximum value at high values of hot water flow rate. Increasing the hot water flow rate above this limit has a negligible effect on the value of water yield. This can be explained by limitations in the heat exchanger heat transfer effectiveness.

Gained-Output-Ratio (GOR) is a performance indicator of WD units which is defined as the ratio of the latent heat of evaporation of the water produced to the heat input to the cycle, GOR = $\dot{m}_{pw} h_{fg} / Q_{in}$.

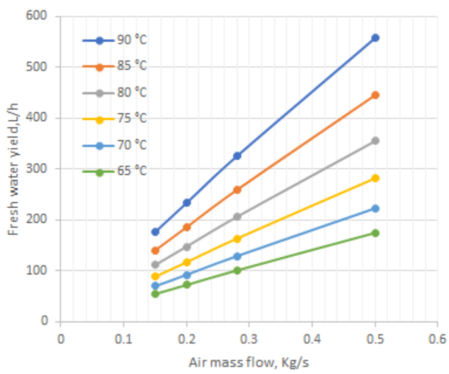

Figure 2: Variation of WD unit water yield with air mass flow rate at different values of hot water inlet temperature

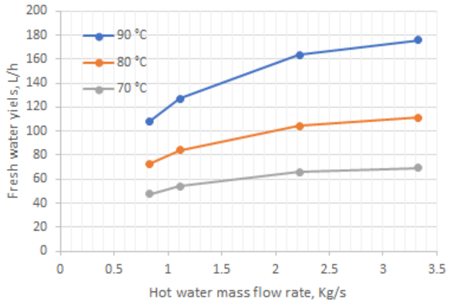

Figure 3: Variation of WD unit water yield with how water mass flow rate at different values of hot water inlet temperature

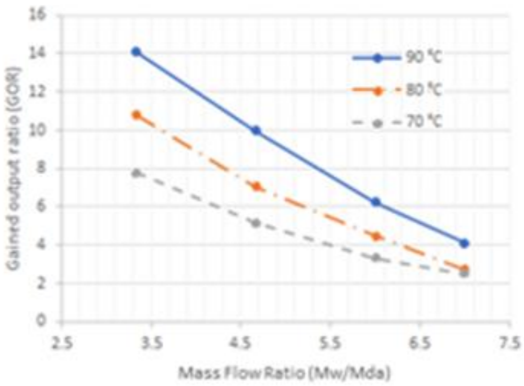

Figure 4: Variation of GOR with water to air mass flow ratio inside the WD unit

Figure 4 shows the variation of GOR with the ratio of saline water/air mass flow rates inside the WD unit. It can be observed that the GOR value increases with the decrease of water to air mass flow rate ratio.

Previous results show that output brine temperature reaches about 40 ℃, while the entering salt water temperature is about 20 ℃. This temperature difference represents a potential for enhancement of plant performance. It was suggested in [13] that adding a heat recovery tank for brine water increases the efficiency of the system. In the present study, the model is modified to integrate a heat recovery tank between the feed cold saline water and the hot rejected brine. The effect of heat recovery tank on the performance of the WD unit has been investigated while keeping all other plant parameters constant.

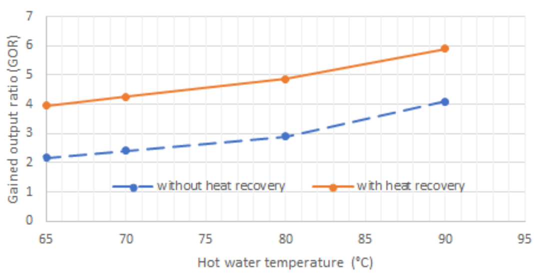

Figure 5: Variation of WD unit GOR with hot water temperature with and without heat recovery tank

Figure 5 shows a comparison of WD unit performance in terms of GOR value with and without integrating the heat recovery tank. It can be noticed that, integration of heat recovery tank, increases the GOR value. The performance of WDU has been enhanced significantly by inclusion of heat recovery tank. Table 2 shows that the percentage increase of GOR is relatively higher at lower values of hot water inlet temperature to the WD unit.

Table 2: Percentage increase in GOR with heat recovery

Hot water inlet temperature	% Increase in GOR
90 ℃	43.9 %
80 ℃	67.5 %
70 ℃	77.1 %
65 ℃	82.5 %

V. CONCLUSION

A complete model for an HDH water desalination unit has been constructed in MATLAB Simulink. The model is capable of predicting the HDH unit performance with reasonable accuracy and can be used for further analysis of plant performance and fresh water production enhancement.

The water yield of WD unit is found to increase with the increase of hot water inlet temperature, increase of air flow rate, and up to a certain limit, with the increase of hot water flow rate. The unit gain to output ratio (GOR) decreases with the increase of water to dry air mass flow rate ratio.

A good potential for heat recovery from the rejected brine water from the unit has been highlighted. Integration of a heat recovery mixing tank between the inlet cold saline water and the rejected hot brine water is found to significantly increase the GOR value. The percentage increase in GOR value reaches a values of 82.5 at low values of hot water inlet temperature. The present results are very useful for setting an operation and control strategy for the WD unit and integration with properly sized solar field.

REFERENCES

[1] Mohammad Al-Sahali, Hisham M. Ettouney, “Humidification dehumidification desalination process: Design and performance evaluation”, Chemical Engineering Journal, 143, 257–264, 2008.

[2] K. Bourouni, M.T. Chaibi, L. Tadrist, “Water desalination by humidification and dehumidification of air: State of the art”, Desalination, 137, 167–176, 2001.

[3] Nawayseh NK, F. M., H.T., "Solar desalination based on humidification process", Desalination 160, 167-186, 2004.

[4] Hassan E.S. Fath, A. G., "Solar desalination using humidification dehumidification technology - Part I A Numerical investigation" Energy Conversion and Management 45(7):1243-1261, 2004.

[5] Hou Shaobo, Ye Shengquan ,Zhang Hefei, “Performance Optimization of Solar Humidification– Dehumidification Desalination Process using Pinch Technology” , Desalination 183 pp. 143–149, 2005.

[6] C. Yamal, I. Solmus, "Heat-transfer enhancement in double-pass flat plate solar air heaters with recycle", Energy, Volume 30, Issue 15, 2796-2817, 2005.

[7] J. Orfi, M. Laplante, H. Marmouch, N. Galanis, B. Benhamou, S. Ben Nasrallah and C.T. Nguyen, "Experimental and theoretical study of a humidification-dehumidification water desalination system using solar energy", Desalination , vol. 168, pp. 151-159, 2004.

[8] K. Zhani, and H. Ben Bach, "Modeling, simulation and experimental validation of a pad humidifier used in solar desalination process", Desalination and Water Treatment, Volume 51, pp. 1477-1486, 2013.

[9] G. Yuan, Z. Wang, H. Li, X. Li, "Experimental study of a solar desalination system based on humidification–dehumidification process", Desalination 277, 92–98, 2011.

[10] Taha E. Farrag, Mohamed S. Mahmoud and Wael Abdelmoez, "Experimental Validation for Two Stages Humidification- Dehumidification (HDH) Water Desalination Unit", Seventeenth International Water Technology Conference, IWTC 17, Istanbul, Turkey, 2013.

[11] M. Ben-Amara, "Efficiency investigation of a new design air solar plate collector used in a humidification–dehumidification desalination process", Renewable Energy Volume 30, Issue 9, Pages 1309-1327, 2005.

[12] Daniel Buschert, "Sun water Project - An Innovative Water Desalination System operated with Solar Thermal Energy", Recklinghausen, Germany, Soest, December 2014.

[13] M. Mostafa, A. Mohammed and A. Bassiuny, "Performance enhancement of solar desalination plant" A M. Sc. Thesis, Helwan University, Cairo, Egypt, 2014.

[14] Carnot Block set, "Conventional and renewable energy systems optimization block set", Solar Institute, 2013.

[15] G. Prakash Narayana, Mostafa H. Sharqawya, John H. Lienhard Va, Syed M. Zubairb, "Thermodynamic analysis of humidifi cation dehumidifi cation desalination cycles", Desalination and Water Treatment, 339–353, April, 2010..