Bulgarian Chemical Communications, Volume 49, Number 2, (pp. 469 – 477) 2017

An inverse approach in designing a humidifier for humidification-dehumidification desalination process

F. Abdel-Hady[1], A.K. Mazher[2], A. Alzahrani[1], M. Hamed[3]

[1] *Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, KSA*
[2]*Nuclear Engineering Department, King Abdul-Aziz University, Jeddah, KSA*
[3]*Mechanical Engineering Department, King Abdulaziz University, Jeddah, KSA*

Received January 3, 2016; Accepted August 14, 2016

The need of small amounts of water daily in desert areas motivates the design of a humidifier-dehumidifier desalination portable unit using solar energy. The objective of this paper is to calculate the humidifier performance parameter (*KaV*) for various values of its exit temperature. *KaV* includes the mass transfer coefficient of the water *K*, the surface area of the packing *a*,and the volume *V* of the humidifier. A numerical method is employed to calculate the *KaV* of the humidifier; and NTU method to calculate the distilled water and exit temperatures of the dehumidifier. The usual approach in analyzing the HDH is to select *KaV* and solve the mathematical model of HDH to find the exit temperatures and amount of distilled water. In this paper, instead of calculating the exit temperature of the water from the HD, we reverse this process. The *KaV* is calculated given the exit temperature of the HD, and the amount of the distilled water. The results of *KaV* variations for a range of 25-40ºC of exit temperature; and the corresponding amounts of the distilled water are presented for four cases of operating conditions of humidifier and dehumidifier: water mass rate, air flow rate; and inlet water temperature to the humidifier. The calculated value of *KaV*, for a given region and amount of water required, will be used to design the evaporator.

Keywords: desalination, humidification, dehumidification, numerical method, design

INTRODUCTION

Humidification-Dehumidification (HD-DHD) process is an efficient method for desalination in remote areas to produce a small amount of water [2-23].The work presented in this paper is the result of a project that aims to design a HD-DHD desalination unit in the Saudi Arabia weather. The goal of the research project is to manufacture a portable unit suitable to the gulf area weather to produce a small amount of fresh water daily. In the gulf region, the solar energy is abundant and it will be employed to power the HD-DHH unit. The research project consists of two parts; the first part concerns the design a parabolic thermal solar collector with control unit to heat the seawater to a specified temperature to produce at least 500 Lit/day of desalinated water. The first part of the project completed the analysis and the design of the solar collector to heat the seawater to a controllable temperature; and the model of the solar irradiance available at Jeddah Saudi Arabia was published [1]. In that paper, the parameters concerning the gulf region, the solar power, ambient temperature were reported. The second part of the research focuses on the sizing and material selection parameter of the HD-DH to produce a small amount of water based on a given inlet water temperature, mass flow rate, air flow rate, and cooling water mass flow rate for a range of HD exit temperature. Our specific goal is to study the effect of HD exit temperature on the performance characteristic parameter *KaV*. This parameter is composed of the mass transfer coefficient *K* of water (kg/m^2 s), the surface area of the packing *a*, and the volume *V* of the humidifier (m^3). The objective of the calculation is to relate the brine exit temperature of the evaporator (HD) to the amount of water produced during the day and the *KaV*.

The research results will help to design a portable HD using the *KaV* value to produce the distilled water required per day in the desert environment. In present paper, the result of the research concerning the procedure to calculate *KaV* to produce a small amount of distilled water is reported under the assumption that the exit temperature of the seawater equals the ambient temperature of the region.

A MATLAB code uses a numerical iterative method was employed to calculate the produced clean water for different exit temperatures of the humidifier; and for different values of airflow and seawater flow rates. The calculation is repeated for the inlet temperature range of 85 – 45 ºC of a humidifier during the day. The amount of the produced water is calculated for 10 hours daily from 9:00 am to 7:00 pm. To produce a minimum of 500 liters/10 hours daily, the designer have different options by selecting the mass flow rate of air; and seawater rates to the HD and the DHD. The main result from the above calculations, are a set of curves that relate the exit temperature of the humidifier

* To whom all correspondence should be sent:
E-mail: faissalhady@gmail.com

versus the *KaV* and the produced distilled water. The calculated results show the effect of exit temperature variation for a given mass flow rates of air and seawater on the amount of distilled water and *KaV*. These results can be used to size and select the packing material of the HD-DHD unit.

A brief review of the methods of analyzing the working of HD-DHD

Researchers used theoretical, computational, and experimental methods to analyze the performance of HD-DHD unit. They studied the effect of different parameters on the amount of distilled water produced. The researchers in references [2, 3] analyzed the HD-DHD hybrid desalination process using solar still. Modeling and experimental validation for the unit is analyzed for different cases in [4]-[7]. Entropy and thermodynamic analysis are used to analyze the performance of the desalination unit [8]-[11]. Experimental researchers [15, 17] used a pilot plant and measured the temperature, humidity and the produced water for different water inlet temperature for units that use solar power. Other researchers[13, 15] used numerical methods and designed experiments to validate the computational results.

The research reported here belongs to the modeling and numerical methods that used to study the HD-DHD process. In papers[16]-[23] numerical methods are used to solve the energy and mass conservation equations for the HD and DHD in addition to enthalpy balance for the humidifier and the LMTD equation for the dehumidifier. For the humidifier the mathematical model is a set of three equations with three unknowns. The humidifier unknowns are the exit water temperature, the mass flow rate, and the exit temperature of the hot humid air. Given a value of *KaV*, an iterative method is used to solve these three equations for the three the unknowns. The results of the published numerical research, used a different empirical formula for *KaV* borrowed from the empirical cooling tower research[20-23].

For the dehumidifier the mathematical model is a set of three equations with three unknowns too. The dehumidifier unknowns are the exit cooling water temperature, the mass flow rate of the distilled water, and the exit temperature of the cooled air. Given a value of *UA*, an iterative method is used to solve the three equations for the three unknowns of the dehumidifier.

The objective of the present study is to solve numerically only the mass and energy conservation equations of the HD to calculate the distilled water as a function of the exit temperature of hot water from the HD. From the solution, the enthalpy balance equation is used to calculate the performance parameter *KaV* needed to produce the amount of distilled water during 10 hours in a desert environment for a given mass flow rates of air and seawater; and for various values of inlet and exit temperatures of HD of the desalination unit. For the dehumidifier, the NTU method [24] is used to solve the dehumidifier equations.

HD-DHD desalination unit

Figure 1 shows the HD-DHD unit for a desalination process using a parabolic trough collector (PTC) as a heat source to produce a minimum of 500 liters of water per 10 hours in Jeddah weather condition [1].Also, figure 2 shows a schematic diagram of the HD-DHD process for desalination.

HD-DHD desalination process

In the HDH unit, a hot seawater is sprayed into the evaporator compartment of the unit (humidifier); and the air passed to the evaporator is humidified and then moved to the condenser (dehumidifier) where water in the humidified air condenses releasing its enthalpy of condensation. In the cooling process of the dehumidifier the heat is recovered, and used to preheat the inlet seawater to the HD; but this amount of heat is not enough and the seawater is heated more by a solar PTC heat source before entering again to the evaporator.

The seawater, with mass flow rate of m_{HD-in}, is heated using the solar energy and flows to the HD at temperature T_{HD-in}. It exits the HD at temperature T_{HD-out} with mass flow rate m_{HD-out}. The air enters the HD at temperature T_1 with a specific humidity ω_1 and mass flow rate m_{air}. It exits the HD at temperature T_2 with saturated air with specific humidity ω_2. In the dehumidifier, the saturated air enters at temperature T_2 with a specific humidity ω_2 and air mass flow rate m_{air}. A cooling seawater, that is used to cool the hot humid air, enters the DHD at temperature T_{SW-in} and mass flow rate m_{sw}. It exits the DHD with the same mass flow rate at temperature T_{SW-out}. The hot air is cooled and exits the DHD with the same air mass flow rate, specific humidity ω_1 and temperature T_1. The condensed water is produced with the rate of m_d at temperature T_d. In this process the condensation temperature T_d is set equal to T_1. It is assumed that the air is saturated at the exit and inlet of the DHD.

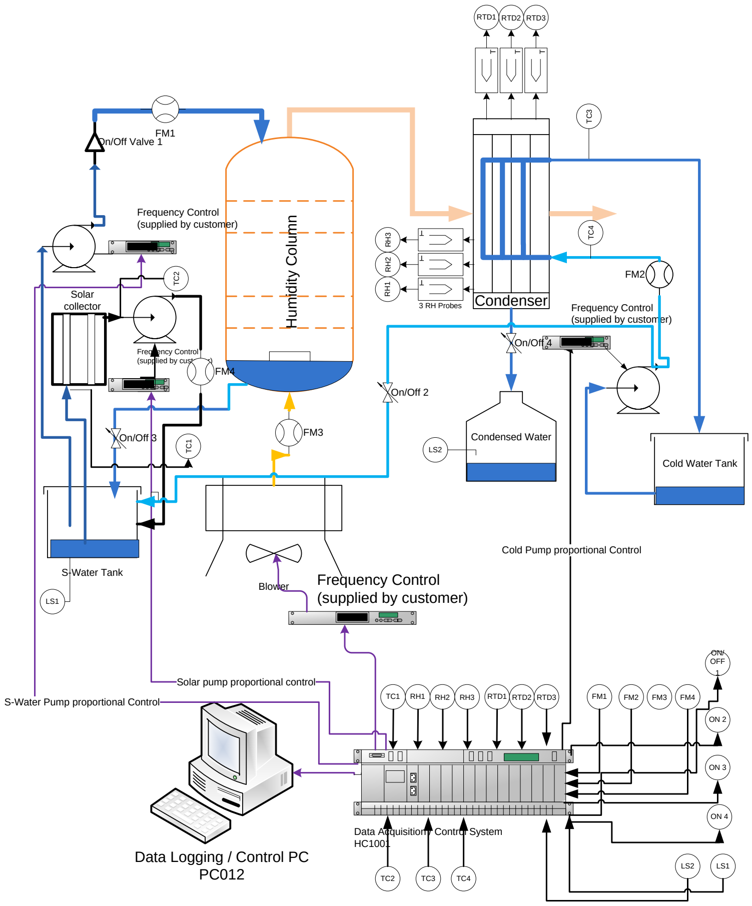

Fig. 1. Complete solar HD-DHD desalinationunit.

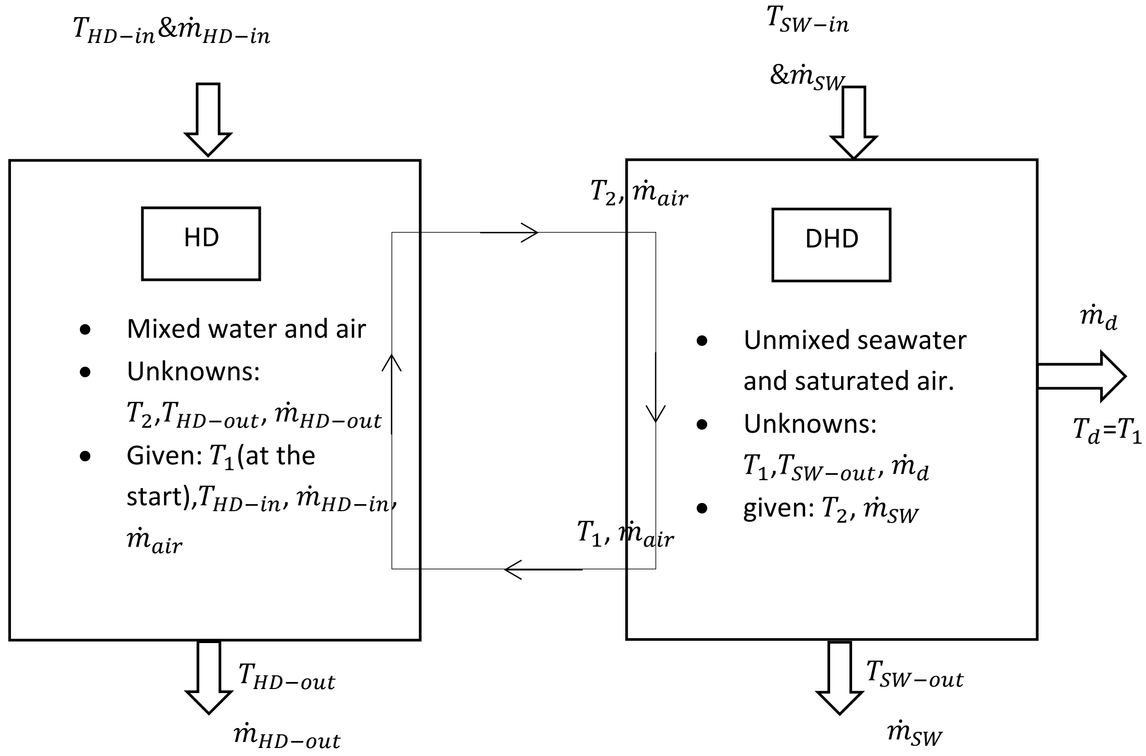

Fig .2. The schematic diagram of the HD-DHD unit.

Sizing the HD depends on the amount of water produced, rate of air and seawater flows, and the exit temperatures of HD and DHD. The objective of this paper is to study the effect of exit temperatures on the amount of water produced during a day for various values of mass flow rates of air and seawater; and compute the corresponding design parameter *KaV*.

Mathematical model

The mathematical model for the HD-DHD unit is derived from the conservation of mass and energy principles. Since the number of unknowns are greater than number of equations, in HD and DHD, the researchers in the references[16-23] used additional equations to close the system.

I. Mathematical model of the humidifier

The solar energy source heats the inlet water to the humidifier to a temperature T_{HD-in}. In the HD, the unknowns are T_2, T_{HD-out}, and m_{HD-out}. The HD parameters are: 1) the mass flow rate of the hot water to the humidifier m_{HD-in}, 2) the mass flow rate of the air to the humidifier m_{air}, and 3) the inlet seawater temperature to the humidifier T_{HD-in}. Since we have three unknowns, three equations are needed. The researchers in references [16-23]used the energy and mass conservation and added an enthalpy balance equation. Hence, the mathematical model of the HD is given by the following equations:

Mass balance:

$$\dot{m}_{HD-in} + \dot{m}_{air} w1 = \dot{m}_{HD-out} + \dot{m}_{air}\, w2 \qquad (1)$$

Energy balance:

$$\dot{m}_{HD-in} h_{HD-in} + \dot{m}_{air} h_1 = \dot{m}_{HD-out} h_{HD-out} + \dot{m}_{air} h_2 \qquad (2)$$

Enthalpy balance analogy equation:

$$\dot{m}_{air}(h_2 - h_1) = KaV \left[\frac{(h_{HD-in} - h_2) - (h_{HD-out} - h_1)}{\ln\left(\frac{h_{HD-in} - h_2}{h_{HD-out} - h_1}\right)} \right] \qquad (3)$$

KaV in equation (3) is used in sizing and selecting material properties of the evaporator. Different values of *KaV* are given in references [20-23]. The selected value of *KaV* affects the exit temperature of the seawater T_{HD-out}. The *KaV* parameter consists of *K*, which represents the mass transfer coefficient, the surface area of the packing *a* ; and *V* which is the volume of the humidifier. To solve the above equations, the following thermodynamic relations are used:

$h = Cp\, T + \omega\, h_g$

$hg = 2500 + 1.8\, T - 1.9 \times 10^{-5} T^2 - 9.3 \times 10^{-6} T^3$

$\omega = 0.662 Pg / (P - \varphi\, Pg)$

$Pg = 0.61 + 0.044\, T + 0.0014\, T^2 + 2.7 \times 10^{-5}\, T^3 + 2.8 \times 10^{-7}\, T^4 + 2.7 \times 10^{-9}\, T^5$

For the saturated air, the specific humidity is given by the formula:

$\omega = 0.002 + 0.00071\, T - 1.95 \times 10^{-5} T^2 + 7.7 \times 10^{-7} T^3$

II. Mathematical model of the dehumidifier

The unknowns of the DHD, are T_1, T_{SW-out}, and m_d.To solve for these unknowns three equations are required. The researchers in references [16-20] used the energy and mass conservation and added heat transfer equation employed in the analysis of heat exchangers. The mathematical model of the DHD is given by the following equations:

Mass balance:

$$\dot{m}_{air} w_2 = \dot{m}_{air} w_1 + \dot{m}_d \qquad (4)$$

Energy balance:

$$\dot{m}_{air} h_2 + \dot{m}_{SW} h_{SW-in} = \dot{m}_{air} h_1 + \dot{m}_{SW} h_{SW-out} + \dot{m}_d h_d \qquad (5)$$

Heat transfer balance equation (LMTD):

$$\dot{m}_{SW} CP_w (T_{SW-out} - T_{SW-in}) = UA \left[\frac{(T_2 - T_{SW-out}) - (T_1 - T_{SW-in})}{\ln\left(\frac{T_2 - T_{SW-out}}{T_1 - T_{SW-in}}\right)} \right] \qquad (6)$$

Equations (4)- (6) are solved for the unknowns of the DHD, which are T_1, T_{SW-out}, and m_d. For the given inlet temperature to the DHD, T_2, the temperatures T_1& T_{SW-out} and m_d are obtained. The solution will vary for different values of the DHD parameters which are: 1) themass flow rate of the cooling seawater to the dehumidifier m_{SW}, 2) the mass flow rate of the air to the dehumidifier m_{air}, and 3) the inlet seawater temperature T_{SW-in} to the dehumidifier.*UA* parameter in equation (6) affects the solution too.

A new approach

In the published method of solution; the unknowns are calculated using iteration to solve equations (1) - (6) for the exit air temperaturesT_2, T_{HD-out}, T_{SW-out}, and the distilled mass flow rate m_d. In the present research, a numerical method is employed to solve equations (1) & (2) for the HD to compute T_2 and m_{HD-out}; and for the DHD, the NTU method [23] is used to calculate T_1 and T_{SW-out}. In solving the evaporator equations an inverse approach is used. Instead of selecting *KaV* and solving equations (1)-(3) for the T_2, T_{HD-out}, and m_{HD-out}, the exit temperature of the HD selected that match the ambient temperature and *KaV* is calculated from equation (3).This calculated value will be used to size and select the material of the HD.

To the knowledge of the authors no one used this approach before. This approach is suitable for the design of evaporator for a portable unit to produce a small amount of water for gulf area. Using this method, the designer can manufacture a customized small units for different areas by changing the size and the material of the HD.

The numerical algorithm

The following are the steps used to calculate the *KaV* and the distilled water for the given specified parameters:

Humidifier

1) Select the inlet temperature of the hot seawater $T_{HD\text{-}in}$, and the mass flow rates $m_{HD\text{-}in}$ &m_{air} to the humidifier.

2) Select the required temperature of the exit water $T_{HD\text{-}out}$.

3) Select the air inlet temperature to the humidifier T_1

4) Solve equations (1) & (2) iteratively to calculate the unknowns T_2andm$_{HD\text{-}out}$.

Dehumidifier

5) Use the calculated value T_2 from the humidifier to calculate the air exit temperature of the dehumidifier T_1 and the exit temperature of the cooling seawater of the dehumidifier $T_{SW\text{-}out}$. Given the mass flow rate m_{sw} and the inlet temperature of the cooling seawater $T_{SW\text{-}in}$ to the dehumidifier, the NTU method[24] is used to calculate T_1 and $T_{SW\text{-}out}$

6) If the computed T_1 in this step is different from the T_1 selected in step 3), the steps 3) - 5)are repeated until convergence.

7) From the converged solution for T_1, T_2, $T_{SW\text{-}out}$, equation(4) is used to calculate the amount of distilled water in the condenser m_d for ten hours. The *KaV* is calculated from equation (3).

8) Steps (2) -(7) are repeated for another values of $T_{HD\text{-}out}$, and the *KaV* and m_d are plotted

8) The procedure (1) - (7) is repeated for different values of$m_{HD\text{-}in}$, m_{air}, and $T_{HD\text{-}in}$

The above algorithm of HD-DHD can be repeated for different values of $m_{HD\text{-}in}$, m_{air}, T_1 , m_{SW} , and $T_{SW\text{-}in}$.

RESULTS AND DISCUSSION

The main objective of this paper is to produce a code to calculate the amount of distilled water per day for HD-DHD unit for any mass low rates of air and seawater. The numerical results of the code is used to analyze the effect of exit temperature on the amount of produced water. Also, the result showed that the *KaV* parameter of equation (3) depends on the exit temperature of the humidifier as expected.

The following results are obtained for two values of the inlet temperature to the HD: $T_{HD\text{-}in}$ = 45 ºC and 85ºC. The amount of water in kg based on the assumption the humidifier works 10 hours/day at the given $T_{HD\text{-}in}$is plotted for all cases considered. For analyzing the humidifier, a range of the $T_{HD\text{-}out}$is selected to vary from the maximum $T_{HD\text{-}in}$ - 5 to a minimum of 20 ºC, and the iteration is conducted for each 5 degrees Celsius.

Case I

Figures 3 -6 show the results for T_1, T_2, m_d, *KaV* variation versus $T_{HD\text{-}out}$ for the following values of the parameters :$m_{HD\text{-}in}$ = .1 kg/s, m_{air}=.2 kg/s, m_{SW}= .1 kg/s, and $T_{HD\text{-}in}$= 45 ºC. Figure 3 shows the variation of the exit air temperatures T_1& T_2as a function of $T_{HD\text{-}out}$. It is observed that the T_2 decreases as the exit water temperature increases. This is physically logical since decreasing the exit temperature allow more water goes to the air. Also, T_1 stabilizes to a fixed temperature 21 ºC.

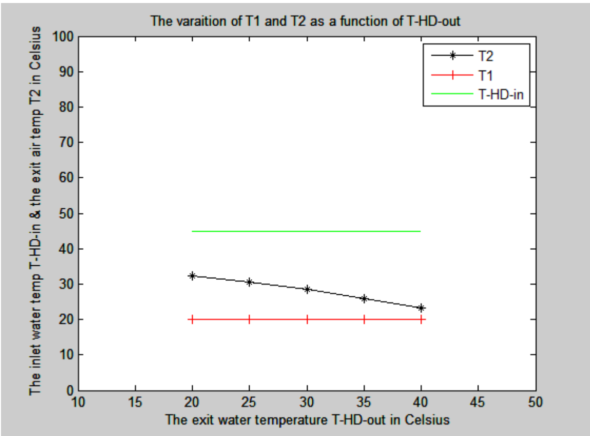

Fig. 3. Thevariation of T_1 and T_2 as a function of $T_{HD\text{-}out}$

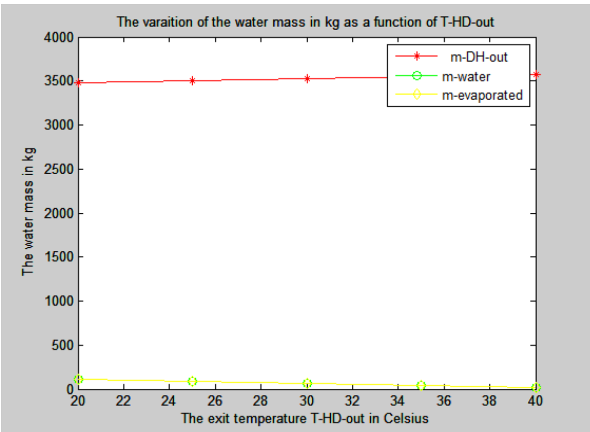

Fig. 4. The variation of the water mass in kg as a function of $T_{HD\text{-}out}$

Figure 4 shows the variation of the mass flow rate of the seawater exiting the HD, and the evaporated air mass flow rate exiting the HD. The figure shows that the water going to the air in HD increases with decreasing the $T_{HD\text{-}out}$, and $m_{HD\text{-}out}$ decreases too.

Figure 5 shows the variation of the total distilled water produced in kg in 10 hours. The curve shows the increase of distilled water with decreasing $T_{HD\text{-}out}$.The maximum occurs when the exit temperature of the water from the HD is minimum.

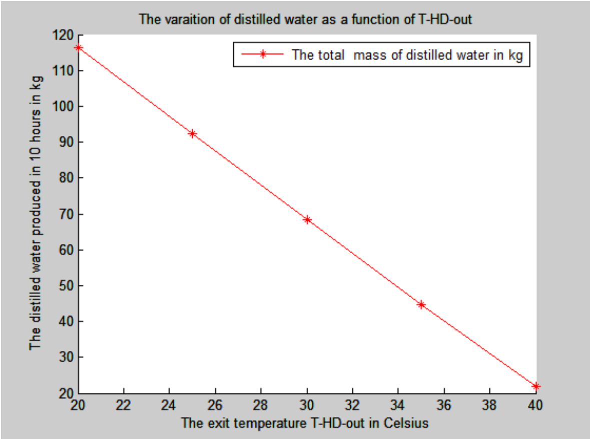

Fig. 5. The variation of distilled water as a function of $T_{HD\text{-}out}$

Figure 6 shows the variation of the exit cooling seawater temperature of the DHD as a function of the exit seawater temperature of the HD. The figure shows that the $T_{sw\text{-}out}$ decreases as $T_{HD\text{-}out}$ increases, which reflect the conservation of heat for the unit.

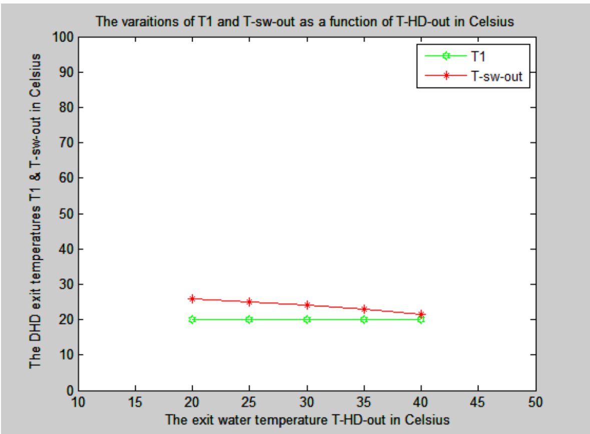

Fig. 6. The variations of T_1 and $T_{SW\text{-}out}$ as a function of $T_{HD\text{-}out}$

Figure 7 shows the variation of the performance characteristic parameter *KaV*of the humidifier as a function of the exit temperature. The calculated resultsare employed in equation (3) to compute *KaV*. Also, the figure shows that *KaV* decreases as the exit temperature increases; and this trend is the same for the other cases presented in this paper. This result for *KaV* means that, for the same mass transfer coefficient *K* and material packing parameter *a*, the volume *V* should decrease as the exit temperature $T_{HD\text{-}out}$ increases.

Case II

Figures 8 shows the produced water variations as a function of $T_{HD\text{-}out}$, while figure 9 shows the variation of*KaV* with the exit temperature of the humidifier. This curve is calculated for the following values of the parameters: $m_{HD\text{-}in}$= .1 kg/s, m_{air}=0.2 kg/s, m_{SW}= .1 kg/s, and $T_{HD\text{-}in}$ = 85 ºC. The behavior of m_d and *KaV* are similar qualitatively to case I but quantitatively are different. The only difference of this case, compared to case I, is the value of the inlet hot seawater to the HD. This reflects an increasing the amount of the distilled water in Fig 8; and an increasing the values of *KaV* in Fig. 9.

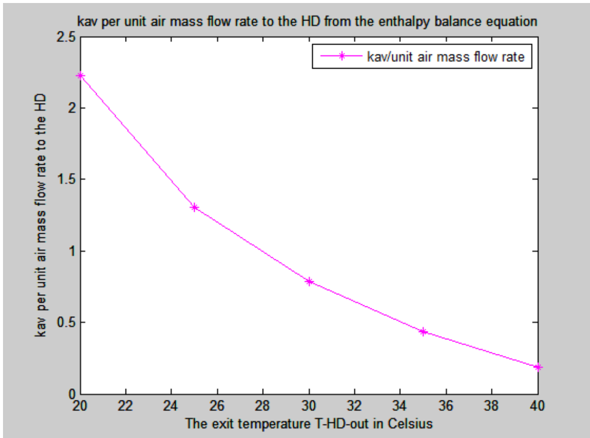

Fig. 7. KaV/m_{air} to the HD from the enthalpy balance equation

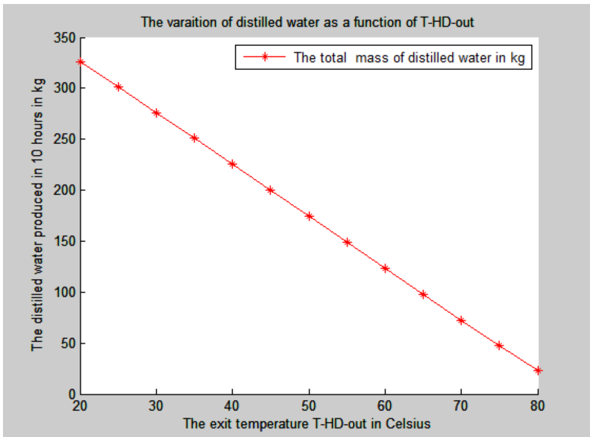

Fig. 8. The variation of distilled water as a function of $T_{HD\text{-}out}$

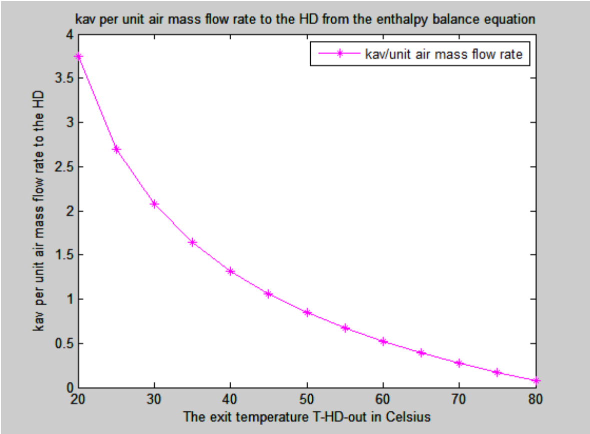

Fig. 9. *KaV* /m_{air} to the HD from the enthalpy balance equation.

Case III

Figure10 shows the variation of the amount of the produced water with $T_{HD\text{-}out}$,while figure 11 shows the variation of *KaV* with $T_{HD\text{-}out}$ for the following values of the parameters: $m_{HD\text{-}in}$= .5 kg/s , m_{air}= 1.0 kg/s , m_{SW}= .1 kg/s, $T_{HD\text{-}in}$ = 45 ºC. Case III shows the same trend of variations qualitatively as cases I and II; but it is quantitatively different. The only difference between this case and case I are the values of $m_{HD\text{-}in}$ and m_{air}. But the ratio of these mass rates is the same and equals 0.5. Figure 10 shows a rise of the m_d vs. T_{HD_out} curve; while Fig 11 shows an increase in the value of *Kav* as $T_{HD\text{-}out}$ increases. In this case, the ratio $m_{HD\text{-}in}/m_{air}$ and the $T_{HD\text{-}in}$ are the same as in cases I and III. The only difference between cases I and III is the amount of hot seawater and air mass flow rate. Here the water rate is increased which reflect the increase in the amount of distilled water.

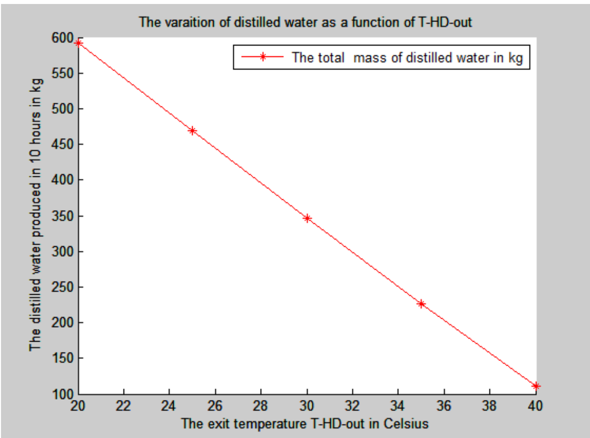

Fig. 10. The variation of distilled water as a function of $T_{HD\text{-}out}$

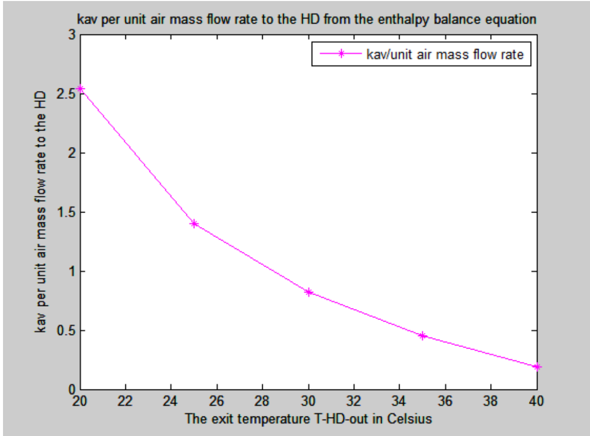

Fig. 11. *KaV*/m_{air} to the HD from the enthalpy balance equation

Case IV

Figures 12shows the variation of the amount of the produced water with THD-out. Figure 13shows the variation of *KaV* with $T_{HD\text{-}out}$ for the following values of the parameters: $m_{HD\text{-}in}$= .5 kg/s, m_{air}= 1.0 kg/s, m_{SW}= .1 kg/s, and $T_{HD\text{-}in}$ = 85 ºC.

This case has the same trend as cases I, II, and II qualitatively, but the values of m_d and *KaV* are different quantitatively. These differences are due to the different values of the seawater, air mass flow rates and the $T_{HD\text{-}in}$. Comparing this case to case III the only difference is the inlet $T_{HD\text{-}in}$, which equals to 85ºC. Figure 12 shows an increase in the total distilled water produced in 10 hours; while Fig. 13 shows an increase in the value of *KaV* as $T_{HD\text{-}out}$ increases. In this case and case II, the ratio $m_{HD\text{-}in}/m_{air}$ and the $T_{HD\text{-}in}$ are the same, but the only difference between cases I and III is the amount of hot seawater and air mass flow rates. In case IV, the water rate is increased which reflect the increase in the amount of distilled water.

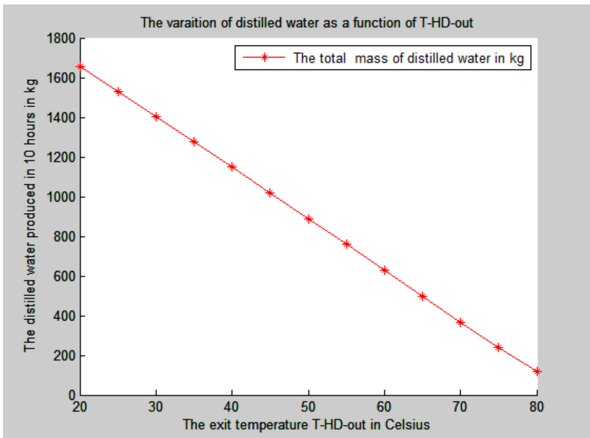

Fig. 12. The variation of distilled water as a function of $T_{HD\text{-}out}$

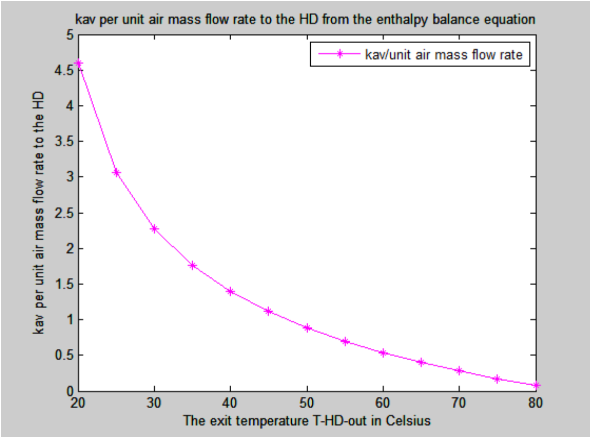

Fig.13. *KaV*/m_{air} to the HD from the enthalpy balance equation.

From the above result, to design a humidifier for a specific amount of distilled water, the designer have many options to select *KaV* to cool the seawater of the humidifier. From this selection follows the selection of the packing area, the material, and the humidifier volume.

CONCLUSIONS

The main objective of the research in this paper is to design a portable HD-DHD unit to produce a minimum amount of 5000 lit/ day in gulf weather using solar energy. To design a portable unit to produce a small amount of water a computational procedure is introduced to calculate *KaV* for a range of the exit temperature of the seawater from the humidifier consistent with the range of the ambient temperature variation of the different areas of the region. This *KaV* will be used to calculate the size and the select the material of the evaporator for any value of the controllable inlet temperature of the seawater to the humidifier. In a remote areas in the gulf regions the ambient temperature varies, so the calculation procedure to design a humidifier take the exit temperature of the HD as input and calculate the performance characteristic parameter *KaV* consequently. The amount of produced water depends also on the inlet temperature of hot seawater to the HD. This temperature is controlled by the design of the solar source and can be selected to control the amount of distilled water.

A computer program using MATLAB was developed to calculate the amount of distilled water in a HD-DHD unit at any hour during the day. The program solves numerically the standard conservation equations of mass and energy. The calculation depends of the given values of the exit temperature of the seawater from the HD. The employed algorithm that solves the mathematical model of the desalination unit can be used extensively to simulate the working of the HD-DHD unit for different ranges of the mass flow rates of air and water as well as inlet temperature to the HD; and seawater cooling temperature. The designer can select the amount of water needed per 10 hours daily based on his selection of $T_{HD\text{-}in}$ and $T_{HD\text{-}out}$; and the best choice, in the above calculations, occurs when the $T_{HD\text{-}out}$ is 20 ºC. The results for four cases are represented to show the usage of the code to generate the designed amount of water. Based on the amount of water needed per day the designer can select the mass flow rate of air and seawater, and the exit temperatures to size the unit. The main result from the above calculations is a bank of data that can be used to design the DH of the unit. To produce the maximum amount of water the exit temperature of the humidifier $T_{HD\text{-}out}$ should be minimum.

Recommendation: Design the solar energy PTC system to produce a constant highest possible temperature, and design the evaporator to cool the water (brine) to a temperature close to the ambient temperature of the region.

Acknowledgement: *This project was funded by the National Plan for Science, Technology and Innovation (MAARIFAH) – King Abdulaziz City for Science and Technology - the Kingdom of Saudi Arabia – award number (11- ENE2004-03). The authors also, acknowledge with thanks Science and Technology Unit, King Abdulaziz University for technical support.*

Nomenclature

A - surface area of the packing (m^2)
C_{pair} - specific heat of dry air (kJ/kg ºC)
C_{pw} - specific heat of seawater (kJ/kg ºC)
h - enthalpy (kJ/kg)
h_g - enthalpyof the saturated water vapor(kJ/kg)
K - masstransfer coefficient of the water in the humidifier (kg/ m^2 s)
m_{air} - air mass flow rate to the humidifier (kg/s)
m_{sw} - cooling sweater mass flow rate to the dehumidifier (kg/s)
m_d - rate of distilled water in the dehumidifier (kg/s)
$m_{HD\text{-}in}$ - water mass flow rate to the humidifier (kg/s)
P - atmospheric pressure (kPa)
P_g - saturation pressure
$T_{HD\text{-}out}$ - outlet temperature from the humidifier (ºC)
$T_{HD\text{-}in}$ - inlet temperature from the humidifier (ºC)
T_1 - inlet air temperature to the humidifier (ºC)
T_2 - exit air temperature from the humidifier (ºC)
$T_{sw\text{-}in}$inlet seawater temperature to the dehumidifier(ºC)
$T_{sw\text{-}out}$ - exit seawater temperature to the dehumidifier (ºC)
UA - heat transfer coefficient of the dehumidifier

V - volume of the humidifier (m^3)
of the water vapor

Greek symbols
ω -specific humidity
φ - relative humidity

REFERENCES

1. F. Abdelhady, H. Bamufleh, M.M. El-Halwagi,·J.M. Ponce-Ortega, *Chemical Engineering Science*, **136**, 158 (2015).
2. A. Ghobeity, A. Mitsos, *Current Opinion in Chemical Engineering*, **6**, 61 (2014).
3. S. Hou, H. Zhang, *Desalination*, **220**(1–3), 552 (2008).
4. Z.M. Omara, M.A. Eltawil, E.A. ElNashar, *Desalination*, **325**, 56 (2013).
5. H.B. Bacha, *Desalination*, **322**, 182 (2013).
6. K.H. Mistry, A. Mitsos, J.H. Lienhard V, *International Journal of Thermal Sciences*, **50**(5), 779 (2011).
7. E.H. Amer, H. Kotb, G.H. Mostafa, A.R. El-Ghalban, *Desalination*, **249**, 949 (2009).
8. Karan H. Mistry, John H. Lienhard V, Syed M. Zubair, *International Journal of Thermal Sciences*, **49**, 1837 (2010).
9. G.P. Narayan, J.H. Lienhard V, S.M. Zubair, *International Journal of Thermal Sciences*, **49**, 2057 (2010).
10. K.M. Chehayeb, G.P. Narayan, S.M. Zubair, J.H. Lienhard V, *International Journal of Heat and Mass Transfer*, **68**, 422 (2014).
11. J. Wang, N. Gao, Y. Deng, Y. Li, *Desalination*, **305**, 17(2012).
12. A.M.I. Mohamed, N.A. El-Minshawy, *Energy Conversion and Management*, **52**, 3112 (2011).
13. C. Yamalı, İ. Solmuş, *Desalination*, **205**, 163 (2007).
14. C. Yıldırım, İ. Solmuş, *Energy Conversion and Management*, **86**, 568 (2014).
15. J. Moumouh, M. Tahiri, M. Salouhi, *International Journal of Hydrogen Energy*, **39**, 15232 (2014).
16. N.Kh. Nawayseh, M.M. Farid, A. Aziz Omar, A. Sabirin, *Conversion and Management*, **40**, 1441 (1999).
17. H. Ettouney, *Desalination*, **183**(1–3), 341 (2005).
18. G. Al-Enezi, H. Ettouney, N. Fawzy, *Energy Conversion and Management*, **47**, 470 (2006)..
19. J.-J. Hermosillo, C.A. Arancibia-Bulnes, C.A. Estrada, *Solar Energy*, **86**(4), 1070 (2012).
20. N.Kh. Nawayseh, M.M. Farid, A.Aziz Omar, A. Sabirin, *Energy Conversion and Management*, **40**, 1423 (1999).
21. G. Franchini, A. Perdichizzi, *Energy Procedia*, **45**, 588 (2014).
22. S. Farsad, A. Behzadmehr, *Desalination*, **278**, 70 (2011).
23. M.M. Farid, S. Parekh, J.R. Selman, S. Al-Hallaj, *Desalination*, **151**(2), 153 (2002).
24. Y.A. Cengel, A.J. Ghajar, "Heat and Mass transfer", 4th edition, McGraw-Hill, USA, 2011, p. 651.

ОБРАТЕН ПОДХОД ЗА КОНСТРУИРАНЕ НА ОВЛАЖНИТЕЛ ЗА ПРОЦЕСИ НА ОБЕЗСОЛЯВАНЕ С ОВЛАЖНЯВАНЕ/ИЗСУШАВАНЕ

Ф. Абдел-Хади[1], А.К. Мазхер[2], А. Алзахрани[1], М. Хамед[3]

[1] Департамент по химично инженерство и материалознание, Университет „Крал Абдулазиз“, Джеда, Саудитска Арабия

[2]Департамент по ядрено инженерство, Университет „Крал Абдулазиз“, Джеда, Саудитска Арабия

[3]Департамент по машинно инженерство, Университет „Крал Абдулазиз“, Джеда, Саудитска Арабия

Постъпила на 3 януари, 2016 г.; приета на 14 август 2016 г.

(Резюме)

Ежедневната нужда от малки количества питейна вода особено в сухи пустинни области ни мотивира да разработим и проектираме овлажнител (DHD), който да произвежда обезсолена питейна вода с помощта на слънчева енергия. Целта на тази статия е да определи ефективния коефициент на овлажняване (*KaV*) за различни изходни температури. *KaV* включва в себе си коефициента на масообмена на водата, повърхността на пълнежа а и обема*V* на овлажнителя. За определяне на *KaV* е използван числен метод както и NTU метод за изчисляване на обема на дестилираната вода и изходящата температура от овлажнителя. Традиционния подход използван за описание на (DHD) е да се избере *KaV* и да се реши математическия модел (DHD) за да се намерят количеството и изходната температура на водата. В настоящата работа вместо да изчисляваме изходната температура на водата от HD, ние обръщаме този процес. *KaV* е изчислен за предварително зададени температура и количество на получената вода. *KaV* е определен за температури в интервала от 25 до 40 ºC за три случая на работни условия: масов дебит на водата, дебит на въздуха, входна температура на водата в овлажнителя. Получените стойности на (*KaV* са използвани за проектиране на овлажнителя.