EXPERIMENTAL VALIDATION FOR TWO STAGES HUMIDIFICATION- DEHUMIDIFICATION (HDH) WATER DESALINATION UNIT

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ABSTRACT

This paper demonstrates the preliminary experiments for two stage water desalination by humidification-dehumidification HDH process. An experimental set-up consists of two stages of closed air humidification dehumidification units. In this design, the saline water was heated by evacuated tube solar water heater integrated with electrically heated tank. A series of tests were performed in outdoor environment, in order to assess the effect of mass flow rate of the feed water, and initial water temperature on the productivity of the system. Solar radiation, wind speed, relative humidity, mass flow rate of the feed water, process air and cooling water, mass of condensate water and temperatures at various locations were obtained during the experiments. The results showed that maximum flow rate was 18.5 L/h obtained from two stages at inlet water temperature of 80^{o}C. If we consider flow rate of saline water of 4 L/min, average sunshine in summer of 10 h, and evacuated tube area of 9.53 m^2 the maximum water production will be 19.4 L/d/m^2 of solar energy. Comparison between theoretical and experimental yield of fresh water indicated that the condensation efficiency is 24.6% indicating that the most challenging step in HDH process in the dehumidification step. The energy consumption 12.8 kWh/m^3 could be obtained if we involve photovoltaic cell. Also, water production could be further improved if we utilize the spent saline water in a subsequent desalination stage.

Keywords: Desalination, Humidification, Dehumidification, Solar.

1. INTRODUCTION

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination as a highly reliable and non-conventional source of fresh water. So, desalination market has greatly expanded in recent decades and expected to continue in the coming years.

In the developing world, water scarcity led to the pressing need to develop inexpensive, decentralized small scale desalination technologies which use renewable resources of energy.

The humidification-dehumidification desalination (HDH) process is an attractive desalination process because of its simple layout and it can be combined with solar energy. Also, it can be designed to minimize the amount of energy discarded to the surroundings[1]. The HDH process is based on the fact that air can be mixed with important quantities of vapor. The temperature of air affect the amount of vapor carried by air; in fact, 1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature increases from 30°C to 80°C [2]. When air stream is brought in contact with salt water, air carries a certain quantity of vapor at the expense of sensible heat of salt water, provoking cooling. On the other hand, the condensed water is recovered by maintaining humid air at contact with the cooling surface, causing the condensation of a part of vapor mixed with air. Usually the condensation occurs in another exchanger in which salt water is preheated by latent heat recovery. An external heat contribution is thus necessary to compensate for the sensible heat loss. Energy consumption is characterized by this heat and by the mechanical energy required for the pumps and the blowers.

There are numerous studies on the HDH desalination process, most of which focus on performance evaluation and efficiency improvement [3, 4, 5,6]. Younis et al. [7] studied the performance of an HDH system with feed water extracted from a solar pond. It was demonstrated that fresh water production rate strongly depends on air flow rate and is weakly dependent on the rate of saline water. Farid et al. [8] studied the performance of a solar driven humidification– dehumidification system and reported a daily fresh water production rate of 12 $L/m^2_{collector}$ day. No information on the incident solar flux was reported other than experiments were done on a “typical day” in Basrah, Iraq. Al-Hallaj et al. [9] studied a solar driven HDH desalination system operating in Irbid, Jordan during the month of October, and the daily fresh water production rate ranged from approximately 2.25 to 5.0 $L/m^2_{collector}$, depending on the average daily solar flux. Muller-Holst et al. [10] fabricated a solar HDH desalination system for operation in Munich, Germany. The system performance showed a strong seasonal variation. The average daily fresh water production in June was approximately 7.5 $L/m^2_{collector}$ while that in January was approximately 1.2 $L/m^2_{collector}$. A.H. El-Shazly et al. [11] investigated the possibility of using pulsating liquid flow for improving the performance of humidification– dehumidification desalination unit. The results showed that the unit productivity has been increased by increasing the off time i.e. decreasing the frequency of pulsed water flow up to certain levels, a frequency of 20/60 on/off time was found to have the highest productivity of the unit. The productivity of the unit was found to be in the range from 1.5 to 2.5 l/h for each m^2 solar collector depending on the operating conditions.

Orfi et al. [12] described a unique solar driven HDH desalination system where both the saline water and air were heated within solar collectors. The evaporator consists of water and air channels separated by spongy absorbent material, and the air and water flow counter-currently through the channels. The experimental performance is difficult to judge since the water solar collector was replaced by an electric water heater. Guofeng Yuan et al. [13] investigated a 100 L/day HDH desalination unit. This system was composed of a 100 m^2 solar air heater field, a 12 m^2 solar water collector. the results showed that water production of the system could reach 1200 L/day (10.7 L/day/m^2 solar collector), when the average intensity of solar radiation got to 550 W/m^2. While all of these prior investigations have made significant contributions toward the development of solar driven HDH desalination, the electric specific energy consumption was not reported. The electric specific energy consumption is an important performance measure, especially when comparing with PV-RO desalination systems. Also, limited studies focused on the enhancement of air water contact system to improve efficiency of humidification step.

In order to increase the efficiency of humidification process, heating of saline water is necessary to boost mass transfer and fortify evaporation. In this paper, desalination system using HDH technique with closed air open water was tested, where evacuated tube solar water heater was used to preheat the saline water. An efficient contact between water and air will be accomplished by atomizing the hot saline water through air stream.

2. METHODOLOGY

An experimental setup was built to study the heat and mass transfer characteristics in desalination process using HDH technique. Figure 1 illustrates a schematic diagram of the experimental setup. It consists of evacuated tube solar water heater, storage tank equipped with make-up heater, and two stage humidification dehumidification units. The evacuated tube bundle consists of five tubes with dimensions listed in Table 1. The evacuated tubes were fitted with U tube copper pipe and were enclosed by rubber stopper. The evacuated tube bundle was fixed facing south with a tilt angle of 28^o in summer season. The saline water passes through copper pipe in series, and the temperature was monitored by thermocouples connected with a data logger. The water storage tank is made from a galvanized steel and isolated from outside in order to reduce the heat loss; also it is supplied with electrical heater to adjust the temperature of hot saline water to the desired feed temperature. As indicated in Fig. 1, water pass with a different flow rates once through the heating pipe where it is heated by the solar energy then directed to the storage tank.
Air was circulated through each HDH system by a blower, where a hot wire anemometer was used to measure the inlet air velocity and average velocity of air can be calculated by:

$$u_0 = \frac{\int u dA}{A_{tot}} \qquad (1)$$

The average flow rate was adjusted by an electrical current controller to be in the range of 5: 19.3 m/s. The fresh water is collected through a header channel mounted below condensers. The rotating disc sprayer is placed inside the unit and 0.2 m in front of the blower inlet to perform the misting of saline water to get droplets of about with diameter in mm range. The unit has discharge weir for recycling of miscarried water to the storage tank, and is covered by transparent plastic cover to keep the air inside. In both HDH stages, the exhaust air coming out of the condenser is recycled to the blower (closed loop of air). The studied parameters include the sprayer rotation speed, the air speed and the feed water temperature. The concentration of salt was measured by AZ 86555 laboratory bench top meter supplied by AZ Instrument Corp. The temperature of hot feed water and air and the humidity at the inlet and the outlet of each part of the unit and the water and air mass flow rates are measured.

Table 1: Parameters of heating system, humidification and dehumidification units.

Experimental part	Property	Value
Evacuated tube (Water heater)	Length	200 cm
	Outside diameter	5.80 cm
	Inside diameter	4.33 cm
Copper tube	length	400 cm
	Outside diameter	0.93 cm
	Inside diameter	0.67 cm
Humidification unit (Evaporator)	length	80 cm
	Width	50 cm
	Height	50 cm
Dehumidification unit (Condenser)	length	60 cm
	Width	30 cm
	Height	7 cm

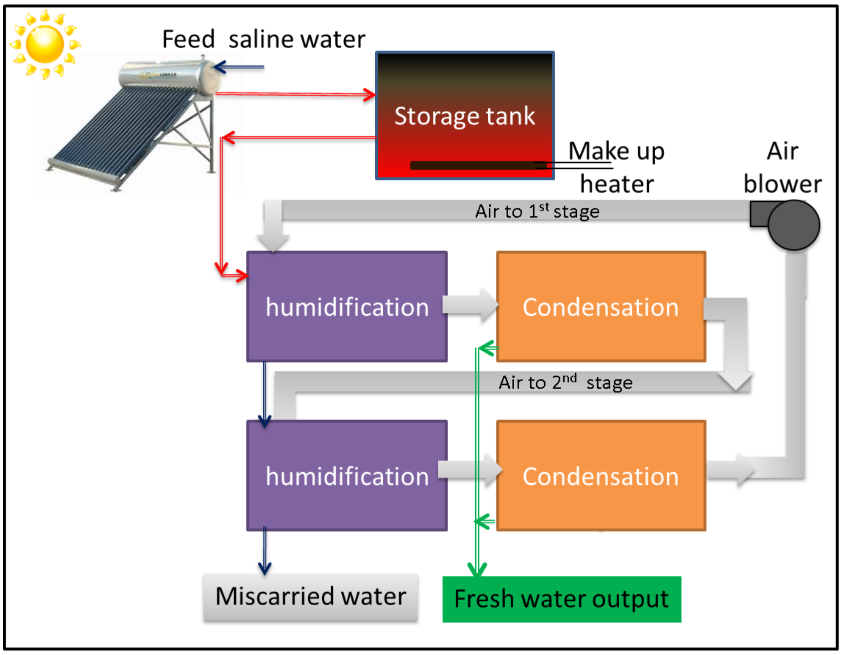

Fig. 1: Block diagram for the arrangement of desalination system using HDH technique.

3. THEORITICAL CONSIDERATION

To enhance heat recovery, Muller-Holst [14] proposed the concept of multi-effect HDH. Fig. 2 illustrates an example of this system. Air from the humidifier is extracted at various points and supplied to the dehumidifier at corresponding points. This enables continuous temperature stratification resulting in small temperature gap to keep the process running. This in turn results in a higher heat recovery from the dehumidifier. In fact, most of the energy needed for the humidification process is regained from the dehumidifier bringing down the energy demand to a reported value of 120 kWh/m^3. This system is being commercially manufactured and marketed by a commercial water management company, Tinox GmbH. This is, perhaps, the first instance in which the HDH concept has been commercialized.

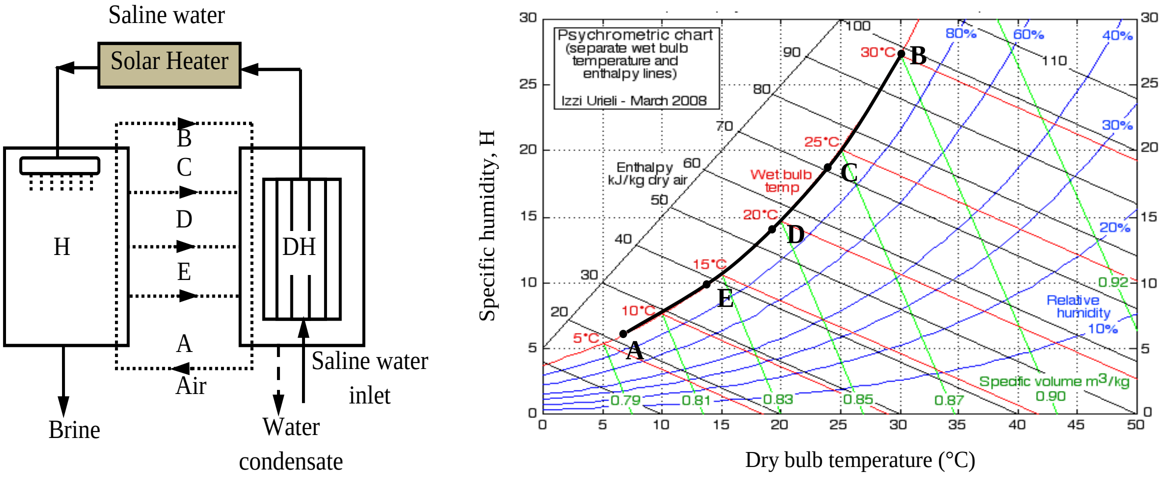

Fig. 2: Multi effect closed air-open water, water heated (CAOW-WH) system and its Psychometric chart.

The performance of desalination process using HDH techniques is evaluated by different ways, parameters, these parameters are defined as follow:

Gained-Output-Ratio (GOR): the ratio of the latent heat of evaporation of the distillate produced to the total heat input absorbed by the solar collector(s). This parameter is, essentially, the efficiency of water production and an index of the amount of the heat recovery effected in the system. This parameter does not account for the solar collector efficiency as it just takes into account the heat obtained in the solar collector. For the HDH systems to have thermal performance comparable to MSF or MED, a GOR of at least 8 (corresponding to energy consumption rates of 300 kJ/kg) should be achieved.

Specific water production: the amount of water produced per m^2 of solar collector area per day. This parameter is an index of the solar energy efficiency of the HDH cycle. This parameter is of great importance as the majority of the capital cost of the HDH system is the solar collector cost: 40 – 45% for air-heated systems [14] and 20 – 35% for water-heated systems [15].

Recovery ratio (RR): is the ratio of the amount of water produced per kg of feed. This parameter is also called the extraction efficiency [16]. This is, generally, found to be much lower for the HDH system than conventional systems. The advantage of a low recovery ratio is that complex brine pre-treatment process or brine disposal processes may not be required for this system.

Energy reuse factor (f): the ratio of energy recovered from the heated fluid to the energy supplied to the heated fluid [17]. This is another index of heat recovery of the system.

4. MATHEMATICAL MODEL

The temperature of water exiting from cupper U tube pipe could be calculated based on energy balance through a small slice. The following assumptions should be considered:

1- Constant heat flux model prevails.
2- Physical properties remain constant and calculated at mean temperature
3- Change in kinetic and potential energy are negligible

The inventory rate equation for energy balance through small slice of Copper pipe becomes

$$q_{in}+h_{w-in}-\left(h_{w-in}+\frac{d}{dx}\,(h_{w-in}\,)dx\right)=\frac{dh}{dt} \qquad (2)$$

At steady state the rate equation for energy reduces to

$$q_{in}=\frac{d}{dx}(h_{w-in})dx=\frac{d}{dx}(\dot{m}\,c_{p-water}dT_f\,)dx \qquad (3)$$

Assuming that the incident energy from solar radiation is homogeneously distributed over the surface of the evacuated tube solar collector:

$$q_{in}=\grave{q}_{in}A=\grave{q}_{in}\pi d_o dx \qquad (4)$$

Substitute of (4) in (3) gives:

$$\grave{q}_{in}\pi d_o dx=\frac{d}{dx}(\dot{m}\,c_{p-water}dT_f\,)dx \qquad (5)$$

By rearrangement

$$q_{in}^{`} = \frac{\overset{\bullet}{m} c_{p-water}}{\pi d_o} \frac{dT_f}{dx}$$
$$\frac{dT_f}{dx} = \frac{q_{in}^{`} \pi d_o}{\overset{\bullet}{m} c_{p-water}} \tag{6}$$

by integration of (6)

$$T_f(x) = \frac{q_{in}^{`} \pi\, d_o}{\overset{\bullet}{m} c_{p-water}} x + c \tag{7}$$

The initial conditions is ($x = 0 \quad T_f = T_{ew}$)

$$T_f(x) = \frac{q_{in}^{`} \pi\, d_o}{\overset{\bullet}{m} c_{p-water}} x + T_{ew} \tag{8}$$

The evaporation rate of water from solution depends on the geometry of contact between water and air. In the case of spherical water droplets sprayed in air stream, the rate of evaporation depends on the particle diameter as follows [18]

$$K_c^{`} = \frac{2D_{AB}}{d_p} \tag{9}$$

It is notable that decreasing particle diameter will increase the mass transfer coefficient and accordingly the rate of evaporation will increase. Therefore, the recommended way for efficient evaporation is to produce very fine droplets, which fly very fast through dry air. We can estimate the condition by boundary layer theory. The rate of mass transfer (N_A) for flow of air across water droplets is obtained by: [18]

$$N_A = K_c^{`}(c_{A1} - c_{A2}) = K_G^{`}(p_{A1} - p_{A2}) \tag{10}$$

The mass transfer coefficient (k_c) can be obtained from the following formula for Reynolds number (*Re*) range (1-480000) and Schmidt number (*Sc*) of (0.6-2.7) [18]

$$Sh = 2 + 0.552\,\mathrm{Re}^{0.53} Sc^{0.33} \tag{11}$$

We can compute the evaporation rate (*W*) by using N_A

$$W = N_A M_{wt} \frac{A_w}{v_w \rho_w} = N_A M_{wt} \frac{4\pi R^2}{4/3\pi R^2 \rho_w} \tag{12}$$

5. RESULTS AND DISCUSSION

5.1 Solar Water Heating System

The theoretical prediction of water temperature exiting from the copper pipe is obtained from Eqs. (2-8). Fig. 3 represents the average emerging water temperature with the inlet water temperature at different flow rates of saline water, where both theoretical and experimental values for difference of two temperatures are represented in Fig. 4. It can be noticed that there is little divergence between theoretical and experimental water temperature difference ranging from 0 to 20 %. This is mainly attributed to the assumption that the solar energy is only transferred through the surface of the evacuated tube. It is also assumed that all energy conducted through the copper pipe is perfectly used to heat water, yet the experimental results showed that there are losses in energy at higher flow rates. The experimental data represented in Fig. 3 indicates that in order to heat water to the desired temperature for HDH experiment, it is necessary to use electric heater or increase the number of tubes to 82 [9.53 m^2 of solar water heater]. Accordingly, the solar water heating could be further improved by increasing the area of solar water heating system [19] or utilization of more efficient scheme to heat water such as linear Fresnel lens [20].

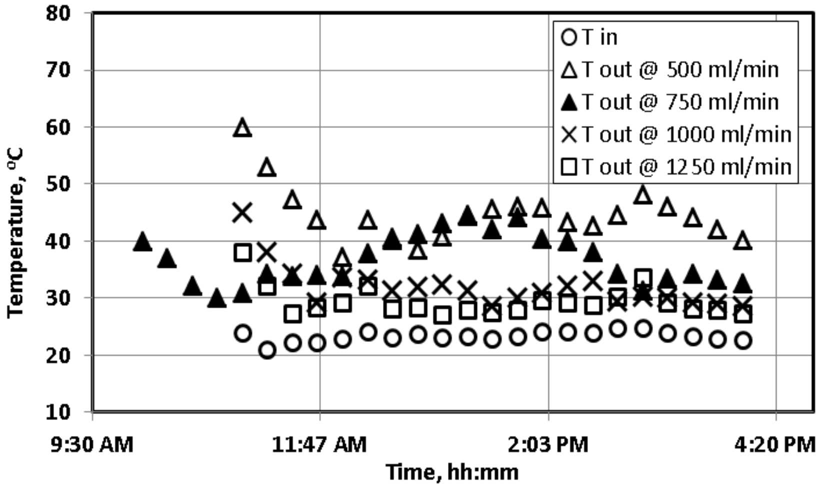

Fig. 3: Inlet and outlet water temperature at different flow rates of saline water; experiments ware done from 23 to 28 September, 2012, average solar intensity was used for Minia Governorate of 581 $kWh/m^2/day$

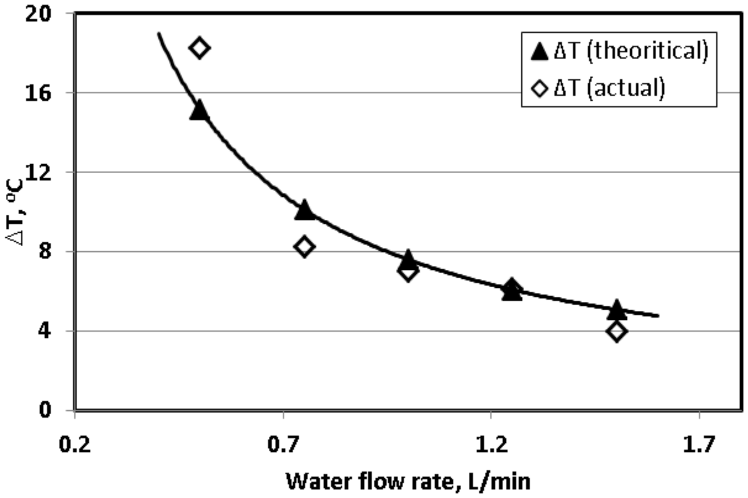

Fig. 4: Comparison between experimental and the predicted values of temperature difference at different flow of saline water; experiments ware done from 23 to 28 September, 2012; average solar intensity was used for Minia Governorate of 581 kWh/m^2/day

5.2 Humidification- Dehumidification Process

Equations (9-12) predict the evaporation rate corresponding to average water drop diameter $\overline{D_p}$. By ploting of the calculated values of evaporation rate againest $\overline{D_p}$ as depected in Fig. 5, It can be noticed that water drop diameter has significant effect on the rate of evaporation, furthermore, the effect of air speed on the rate of water evaporation is mild. This figure also indicates that if water droplet of 1 mm radius flies with speed of 5~25 m/s, it will evaporate nearly in 1 second. The water spraying is thus crucial for enhancement of evaporation rate. To verify this effect we propose to spray hot saline water by subjecting stream of water over rotating disc sprayer. A dimensional equation for the volume-surface mean diameter $\overline{D_p}$ of the drop from a disc sprayer [21] is:

$$\overline{D_p} = 12.2 \times 10^4 R \left(\frac{\Gamma}{\rho_w n R^2} \right)^{0.6} \left(\frac{\mu}{\Gamma} \right)^{0.2} \left(\frac{\sigma \rho_w L_p}{\Gamma^2} \right)^{0.1} \qquad (13)$$

The air flow rate effect on the fresh water productivity was studied at constant feed of saline water of 5 L/min and inlet temperature of 80°C. Figure 6 show the effect of changing air mass flow rate on productivity of fresh water. It is noticed that fresh water productivity increases by increasing air speed with a maximum production of 7 L/h.

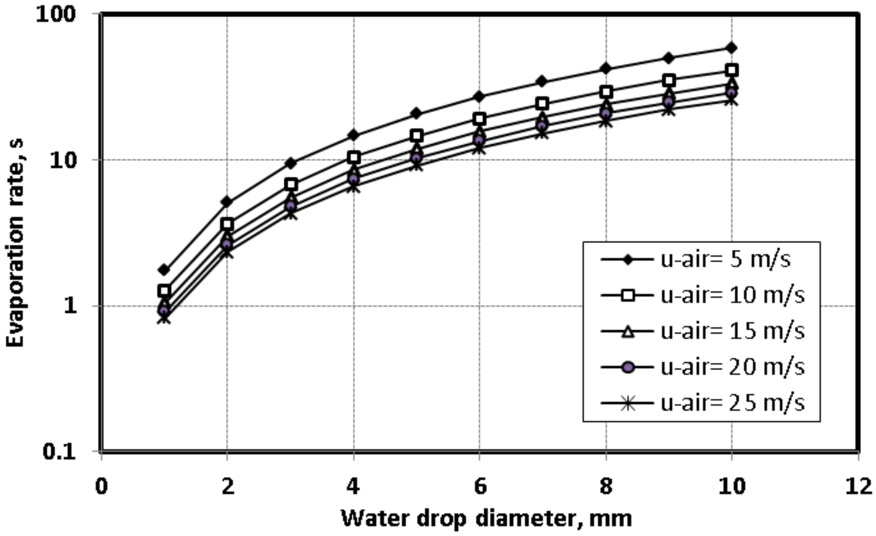

Fig. 5: The relation between water drop diameter and the evaporation rate.

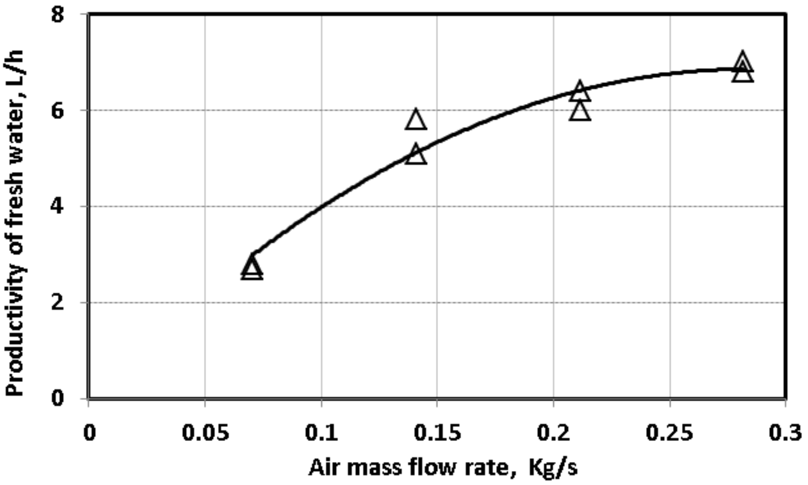

Fig. 6: the effect of air velocity on productivity of fresh water.

The theoretical prediction for the amount of fresh water carried by air could be obtained from psychometric chart. Figure 7 represents the theoretical yield of fresh water at different air mass flow rate and different air temperature, in this figure, isothermal dehumidification was assumed in order to maximize the theoretical yield. It indicates that both air temperature and flow rate have important effects on fresh water yield in dehumidification section. Comparing our results depicted in Fig. 6 with the theoretical data in Fig. 7 showed that at saline water temperature of 80^{o}C and air mass flow rate of 0.28 kg/s, the closed loop air temperature reaches 40^{o}C , this corresponding to both theoretical and actual yields of 28.4 and 7 L/h respectively. Thus the efficiency of dehumidification was 24.64% which is reltievely higher that our previously published data [22] indicating that the most challenging step in HDH process in the dehumidification step.

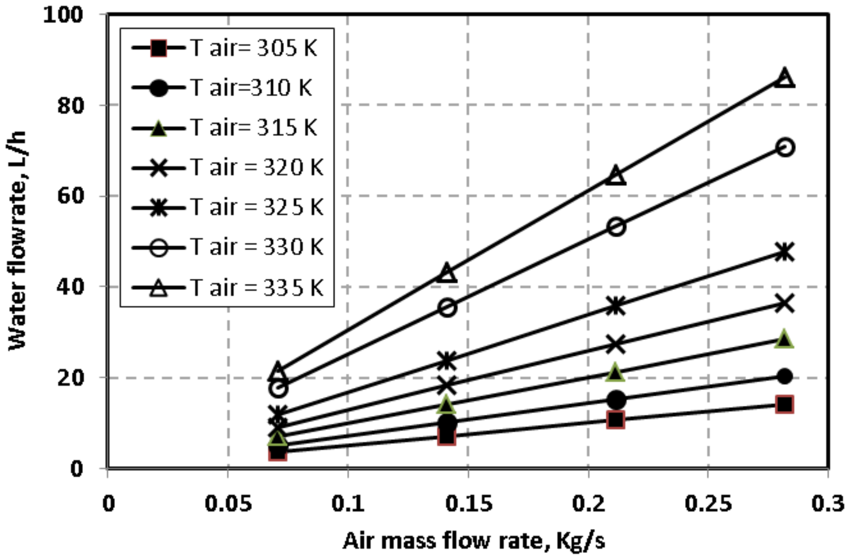

Fig. 7: Theoretical yield of fresh water at different air mass flow rate and different air temperature

Theoretically, the more dominant parameter is the inlet water temperature; its effect on evaporation rate is pronounced. To verify its importance, experiments was done to obtain fresh water yield at different inlet water temperature. Figure 8 shows the fresh water yield of both stages. It can be noticed that by increasing the saline water temperature, the fresh water productivity increases, and at inlet water temperature of 80°C, the maximum attainable water flow rate was 18.5 L/h. On the other hand, the yield per solar collector area could also be calculated from data shown in Fig. 7. The calculation is based on the theoretical predictions of evacuated tube solar collector performance discussed previously. The maximum yield of 19.4 L/d/m^2 of solar collector is predicted which is relatively higher than previously published data of 7.5~12 L/d/m^2 of solar collector [8, 10]

Furthermore, it is noticable that the temperature of miscarried water is sufficiently high to be further used. In this experiment we recycled this water to be reused, however this design could be further enhanced by introducing miscarried water to third humidification stage to increase the fresh water yield.

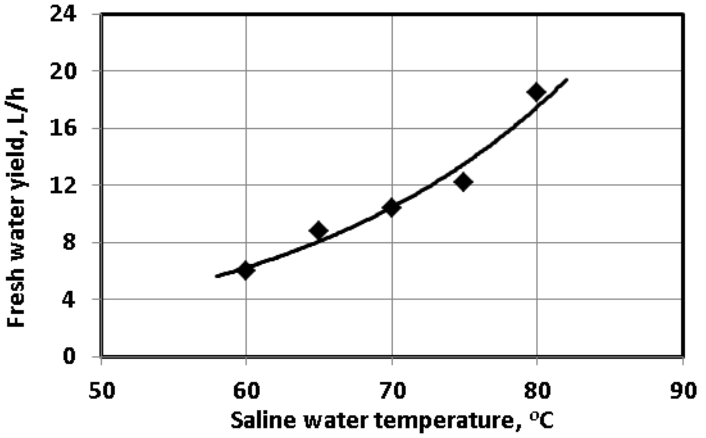

Fig. 8: Effect of inlet water temperature on the fresh water yield at sprayer speed of 2200 rpm.

5.3 Energy Consumption

The energy consumption per liter of fresh water is calculated based on the maximum rate of desalination at 80°C, where the power consumption is the summtion of power required for both blower and atomizer [$P_{total} = 236.5$ W]. For a production rate of 18.5 L/h ($18.5*10^{-3}$ m^3/h) the energy consuption for desalination is calculated as 12.8 kW.h/m^3. Although this energy still higher than energy required for desalination by reverse osmosis system (2.5-7 kWh/m^3) [23], this energy could be supplied by photovoltaic cell. The Gained-Output-Ratio (GOR) is defined as:

$$GOR = \frac{\dot{m}_w h}{\dot{Q}in} \tag{14}$$

This parameter is, essentially, the efficiency of water production and an index of the amount of the heat recovery effected in the system. John H. Lienhard, et. al. [24] invoked that For the HDH systems to have thermal performance comparable to MSF or MED, a GOR of at least 8 (corresponding to energy consumption rates of ~300 kJ/kg) should be achieved. Calculation of GOR for our system gives value of 4.2 indicating that our system has thermal performance lower than other major desalination system but may be more efficient after considering the energy efficiency utilization in our system.

6. CONCLUSION

The main results for this paper can be short noted as follows

- Mathematical modeling of water evaporation sowed that we could enhance the rate of evaporation by decreasing water drop diameter, which could be attained by high rotation speed sprayer.
- At inlet water temperature of 80 °C, fresh water yield was 18.5 L/h [19.4 L/day/m^2 solar collector] where energy consumption per liter of fresh water is calculated as 12.8 kW.h/m^3.
- Comparison between theoretical and experimental yield of fresh water showed that the condensation efficiency was 24.64% indicating that the most challenging step in HDH process in the dehumidification step.
- The GOR for the system studied was calculated to be 4.2 indicating that our system have thermal performance lower than major desalination system and will be considered in the future development.

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NOMENCLATURE

A_o = outer area of steel pipe, m^2
A_{tot} = the total area of the air flow, m^2
A_w = the area of water drop, m^2
$C_{p\text{-}water}$ = Heat capacity for water, J/kg K
D_{AB} = The diffusion constant, i.e. $D_{Air\text{-}H2O}$ is the diffusion coefficient of air relative to water vapor, m^2/s
d_i= inner diameter of copper pipe, m
d_o= outer diameter of copper pipe, m
d_p= water drop diameter, m
h= enthalpy of water, kJ/kg
$h_{w\text{-}in}$= enthalpy of water entering the studied small slice, kJ/kg
h_o= heat transfer coefficient based on outer area of steel pipe, W/m^{2}K
Kc=mass transfer coefficient, m/s
K_G= mass transfer coefficient for gases, kg mol/(s m^{2}Pa)
$\dot{m}$ = water mass flow rate, kg/s
N_A = the rate of mass transfer per unit time and unit area, kg/m^2 s
$q_{\grave{i}n}$ = thermal flux intensity, W/m^2
$q_{\ in}$ = thermal intensity, W
P^*_{H2O} = vapor pressure of water, Pa
r= the droplet radius, m
Re = Reynolds number, $\mathrm{Re} = \dfrac{\rho D u}{\mu}$
Sc= Schmidt number $Sc = \dfrac{\mu}{\rho D_{AB}}$
Sh= Sherwood number, $Sh = \dfrac{K_c^{\grave{}} d_p}{D_{AB}}$
T_{ew}= temperature of water entering steel pipe, K
T_f= temperature of water exiting the studied copper slice, K
T_{ow}= temperature of water exiting copper pipe, K
$T_{w\ in}$= temperature of water entering HD unit, ^{o}C
$T_{w\ out}$= temperature of water exiting HD unit, ^{o}C
T_x = temperature of the bulk of liquid, ^{o}C
u_{air} = average velocity of the air, m/s
V_w = is the volume of water drop, m^3
W= rate of evaporation, kg/s
x= thickness of the studied copper slice, m
η_{hu}= humidification efficiency
ρ_{water} = the density of water, kg/m^3

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